Application Report
SLVA155 – March 2004

Cell Balancing in bq208x Advanced Gas-Gauge Designs

Battery management

ABSTRACT

Serial connection of cells in a battery pack can result in reduced-capacity performance if some of the cells have different capacity or charge levels. The problem is that during charging or discharging of the pack, individual cell differences lead to different voltages in each cell. Since the charger monitors only the summary voltage, some cells can be undercharged and others overcharged. Undercharging amounts to a decrease of overall pack capacity, and overcharging can lead to damage of the cells and can create safety issues. To address this known problem of serial battery packs, the bq208x advanced gas-gauge IC in a design with the bq29311 analog front end (AFE) offers a unique capability to monitor the voltage of each cell separately and to bypass part of the charging current of each single cell to achieve a uniform state of charge for all cells.

This application report explains the principles of cell-balancing operation, addresses implementation issues specific to cell balancing, provides a detailed description of a test procedure, gives the results of our testing demonstrating the efficiency of the procedure, and provides a guide for choosing correct values for user-defined registers controlling the cell-balancing algorithm.

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The Need for Cell Balancing

Two types of unequal cell properties can lead to problems during serial charging: total cell capacity and initial charge state.

Consider what happens in a four-series cell battery when one cell has less capacity than the other three, with all starting in the same state of charge. Constant-current/constant-voltage (CC/CV) charging brings the pack to 4.2 x 4 = 16.8 V (typical). However, individual cell voltages are not equal. As shown in Figure 1, the low-capacity cell has a much higher voltage than the remaining cells, while the normal-capacity cells have a lower voltage than achieved in normal charging.

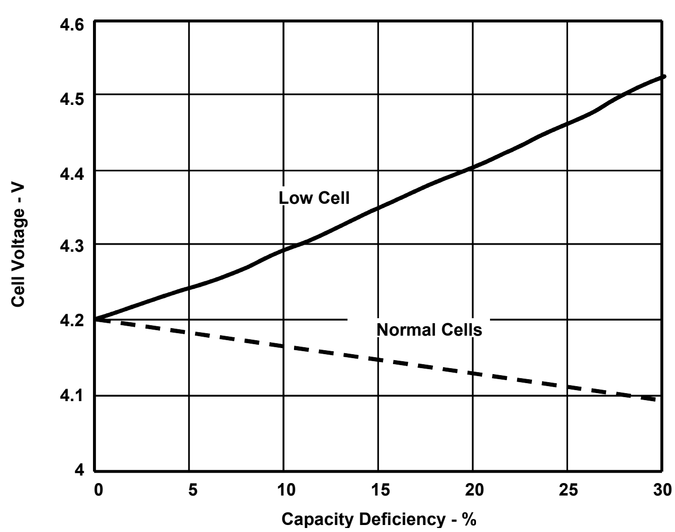

Figure 1. Individual Cell Voltage vs Capacity Deficiency From Nominal

If the lower cell has a capacity deficiency above 10%, its cell voltage begins to rise into the dangerous area above 4.3 V, which can result in additional degradation of the cell or become a safety concern. Safety issues are prevented by additional safeguards present in the bq208x devices such as the *Cell Over Voltage* control parameter. The bq208x terminates the charge cycle if an individual cell voltage exceeds the programmable *Cell Over Voltage* threshold (default 4.35 V). However, terminating the charge at this point leaves the pack severely undercharged; despite prevention of a safety hazard, this indicates that the pack is reaching the end of its useful life. This consideration makes cell balancing one of the most critical issues related to the cycle life of a battery pack.

The effects of cell degradation caused by imbalance is auto-accelerating. Once a cell has a lower capacity, it is exposed to a higher charge voltage which degrades it faster, further reducing its capacity, closing the runaway circle.

New cells are usually graded by cell manufacturers so that their capacity is within a 0.2% voltage tolerance. However, during use, individual cells degrade differently depending on the particular temperature environment and the inherent unpredictability of the degradation process. To prevent initial small capacity differences from growing into large differences, cell balancing during the charging process is essential.

Similar effects occurs when there is a difference in cell charge levels at assembly, or when this condition is acquired during pack operation due to differences in self-discharge rate. The cell that originally had a higher charge is exposed to a higher charge voltage, degrading it faster. In this scenario, a harmless, easily correctable difference in initial cell condition turns into irreversible damage leading to decreased pack performance and premature failure.

Cell-Balancing Operation

Cell balancing is accomplished by connecting a parallel bypass load to each cell depending on its individual charge state. If a cell has a higher voltage than the others during charging, the bypass load to that cell is connected by closing the integrated low-power control FETs in the bq29311 AFE IC so that a fraction of the charging current bypasses that cell.

Specifically, the gas-gauge IC compares all the cell voltages and generates the signal to open or close the control FETs in the bq29311 if the following two conditions are satisfied as shown in Figure 2.

1. A cell voltage is higher than *Cell Balance Threshold* set in DF (see bq208x data sheets for information about writing control variables into data flash). Default for this threshold value is 3.9 V

2. The largest voltage difference between cells is above *Cell Balance Min*. Default is 40 mV.

The gas gauge checks for these conditions at fixed intervals defined by the value stored in *Cell Balance Interval*. Default is 20 seconds.

If any cell voltage is larger than the *Cell Balance Threshold* plus the *Cell Balance Window* (default is 100 mV), the threshold value is incremented by the *Cell Balance Window* value. For example, if one cell voltage becomes 4.01 V, the *Cell Balance Threshold* is changed from 3.9 V to 4 V and so on.

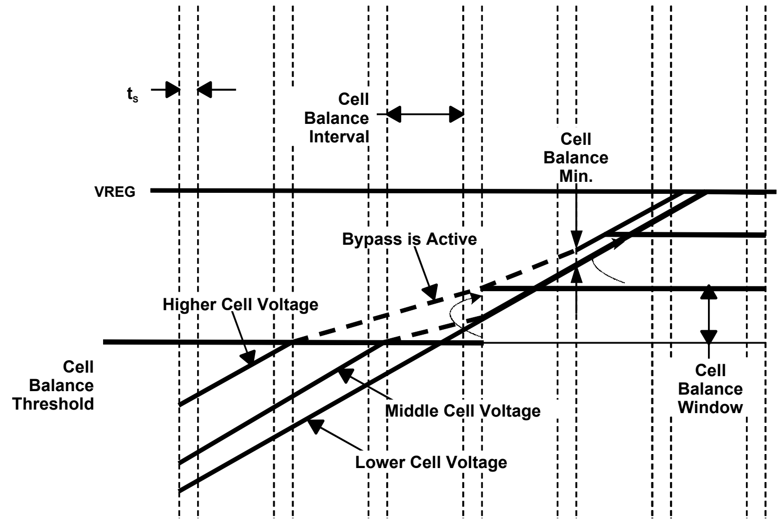

Figure 2. Cell-Balancing Operation

Cell-Balancing Implementation Issues

An effective cell-balancing operation requires the selection of correct resistor values used to bypass the charging current. Exact placement of the resistors (R3–R7) is shown in the reference schematic in Figure 3.

Table 1. Cell-Pack Serial Connection

CELL #	CELL CONFIGURAION	
	4-Series	*3-Series*
1	Bottom	Bottom
2	Middle – Lower	Middle
3	Middle – Upper	Top
4	Top	N/A

Table 2. Connection Sequence

CONNECTION SEQUENCE	
4 – Cell Configuration	3 – Cell Configuration
Cell 1 –ve to VG (X5)	Short VP (X1) to VH (X2)
Cell 4 +ve to VP (X1)	Cell 1 –ve to VG (X5)
Cell 1 +ve to VL (X4)	Cell 3 +ve to VH (X2)
Cell 2 +ve to VM (X3)	Cell 1 +ve to VL (X4)
Cell 3 +ve to VH (X2)	Cell 2 +ve to VM (X3)

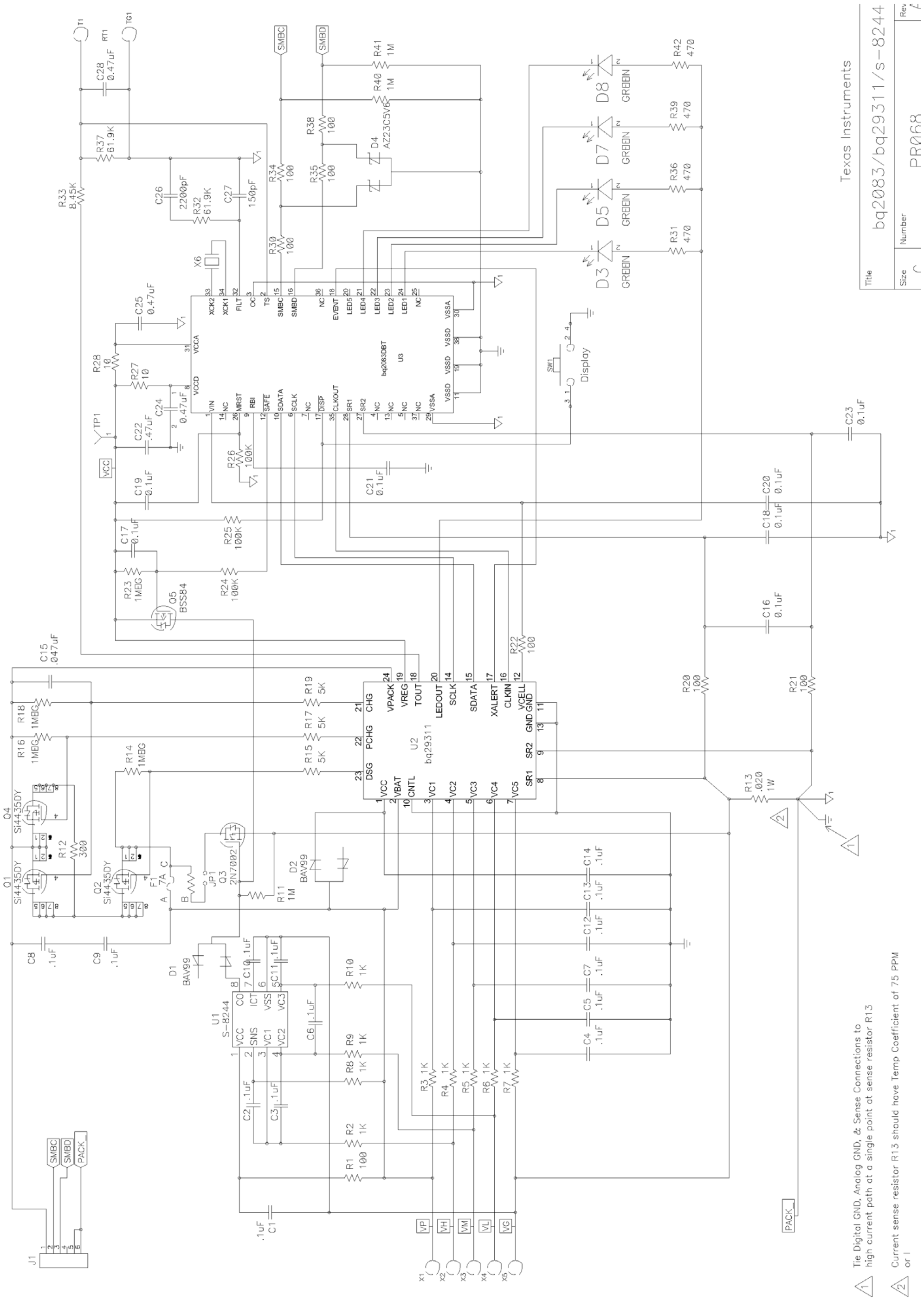

Figure 3. bq208x with bq29311 and S-8244 Reference Schematic

When the integrated bypass FET is on, the bypass current path includes two resistors and the RDS(ON) of the bypass FET (500 Ω typical). Select the resistor value to provide reasonably high discharge current so that cell balancing is performed in a short time. For example, at the default threshold voltage of 3.9 V with a 100-Ω resistor, the bypass current is 5.57 mA. Assuming that 3.9 V is reached after 30 minutes and the usual charging time is 2.5 hours, 0.011 Ah is bypassed during one cycle, which corresponds to 0.55 % capacity correction of a nominal 2-Ah cell.

This is an acceptable correction value because newly assembled packs typically have their cell capacities balanced with a 0.2% tolerance so initial imbalance can be corrected in one cycle to prevent cell degradation. Additional capacity imbalance would accumulate gradually during cycling, but the accumulation rate is low. The typical specification for Li-ion cell capacity degradation is 30% in 500 cycles, which equates to 0.06% per cycle. Even if a particular cell exhibits 8 × faster degradation, 0.55% balancing per cycle is sufficient to correct it during regular operation.

Although we recommend using 100-Ω resistors for maximum cell-balancing effect, values up to 500 Ω are acceptable. Note that these resistors also serve as protection against a short circuit to ground inside the IC. Therefore, resistors must be chosen so that with a 16.8-V short-circuit, heat dissipation over this resistance does not exceed the value specified in the data sheet.

Additionally, the resistors are used as a part of a low-pass filter for voltage measurement; therefore, the value of these resistors along with corresponding values of capacitors C13,C12,C7, C5, and C4 must generate an appropriate time-constant as shown in the reference design.

Texas Instruments Testing of Cell Balancing

Introduction

This test was run using equipment available only to TI but was only used as an aid to gather data more efficiently and with greater frequency.

No special equipment or changes to the bq208x device are needed to perform, verify, and evaluate cell balancing.

Equipment Setup

This test requires the following equipment

- 4-series cell Li-ion battery
- bq2083 w/bq29311 circuit module (bq208xEVM-001)
  - Resistors R1-4 replaced with 100-Ω value from the 1-kΩ default
  - See the bq2083EVM-001 User's Guide for schematic, layout, connection, and evaluation details.
- Battery charger (DV2054S2)
- Electronic load which capable constant-current mode discharge (PLZ303W)

- Interface program software running on an IBM-compatible PC
- EV2300 (USB) Interface Module to communicate with the gas-gauge module

To set up this test, the battery was calibrated and completed a charge/discharge cycle, so that the battery updated its capacity estimate and was fully charged before starting the test.

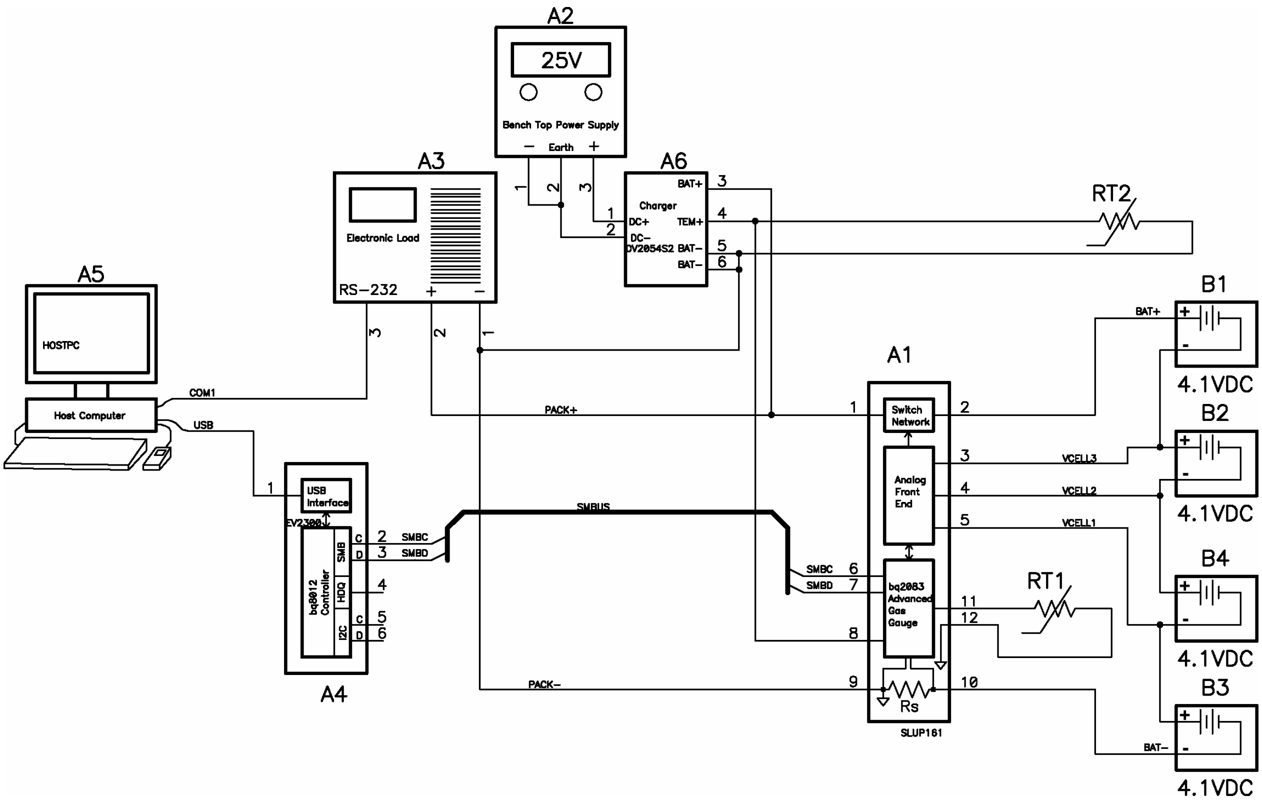

Figure 4. Hardware Setup for Automatic Cell-Balance Cycling

The electronic load (A3) is set up as follows:

- Mode = Constant-current
- Discharge Rate = 3000 mA

The power supply (A2) powers the charger when charging the battery pack and is set up as follows:

- Vout = 25 V (no load)
- Current Limit = 1000 mA

The Data Flash in the bq208x is configured as follows:

- Number of Cells (Pack Configuration, CC0, CC1) = 4
- *Cell Balance Minimum* (Cell Balance Min) = 40 mV

- *Cell Balance Window* (Cell Balance Window) = 100 mV
- Slave Mode (Pack configuration, SM) = enabled (to prevent SMBus broadcasts)

The bq208x in this test contains a modified bq208x program that adds functions to (a) drive or release the charge inhibit pin (A1.8), and (b) provide a method to collect the pack voltage, current, cell voltages, the balance bits (used to control the cell-balancing switches in the bq29311) and the state of the charge inhibit line (denoted as pin A1.8 from the gas gauge). When the charge inhibit line is driven low, it simulates an excessive-temperature condition causing the charger to terminate the charge cycle.

The setup shown in Figure 3 allows the DV2054S2 to charge the pack to full. Once the pack is full, the bq208x terminates charge by opening the charge FET and, using modified bq208x firmware, begins a delay. Once the delay expires, the bq208x drives a charge-inhibit bit (A1-8 in Figure 4) low which is wire-ORed into the thermistor inputs of the charger. The delay is timed by the modified gas-gauge firmware and driven by control software which collects data once every 5 seconds. Each time the control software reads data, the modified bq208x increments a delay counter. When the counter accumulates 1000 seconds, the modified bq208x changes the state of the charge-inhibit line.

The control software collects the pack voltage, current, cell voltages, balance-bits status, and charge-inhibit status once every 5 seconds. When the control software detects a 0-to-1 transition in the charge-inhibit line, it commands the electronic load to begin discharging the battery pack. When the control software detects a 1-to-0 transition, it commands the electronic load to stop discharging the pack.

The overall behavior of the system is to:

1)	Charge the battery to full	Charge Inhibit = 0
2)	Wait 1000 seconds	Charge Inhibit = 0
3)	Discharge the pack to empty	Charge Inhibit = 1
4)	Wait 1000 seconds	Charge Inhibit = 1
5)	Repeat 1 through 4	

The control software stores all the collected data in log files that can be imported into programs such as MathCAD™ or Excel™ for analysis.

Unbalancing Procedure

The control software runs with the log file open and already collecting data before unbalancing the battery to capture the condition of the pack before and during the unbalancing procedure.

1. BALANCE PACK: Ensure that the cell voltages are balanced at the end of charge within ±4 mV. If the cells are not balanced, discharge the cells with the highest voltage until they match the lower cells. Allow at least 15 minutes between operations and measurements to allow the cells to return to a resting state.
2. TOP OFF PACK: Charge the pack to full. Disconnect the electronic load so that the discharge cycle does not begin.

3. UNBALANCE: Connect the load to the middle two cells while the battery is fully charged as shown in Figure 5. Do not connect the load to the PACK– terminal; the gas gauge accumulates the discharge activity incorrectly because discharge current is not flowing through all cells. If the load is connected to PACK–, complete another discharge/charge cycle before continuing this procedure.

Figure 5 shows the hardware connections for the cell-unbalance procedure with the charger and power supply used during the procedure omitted to simplify the drawing. Do not perform the unbalance procedure until the charge inhibit bit is set to 1 (indicating that it is ok to discharge).

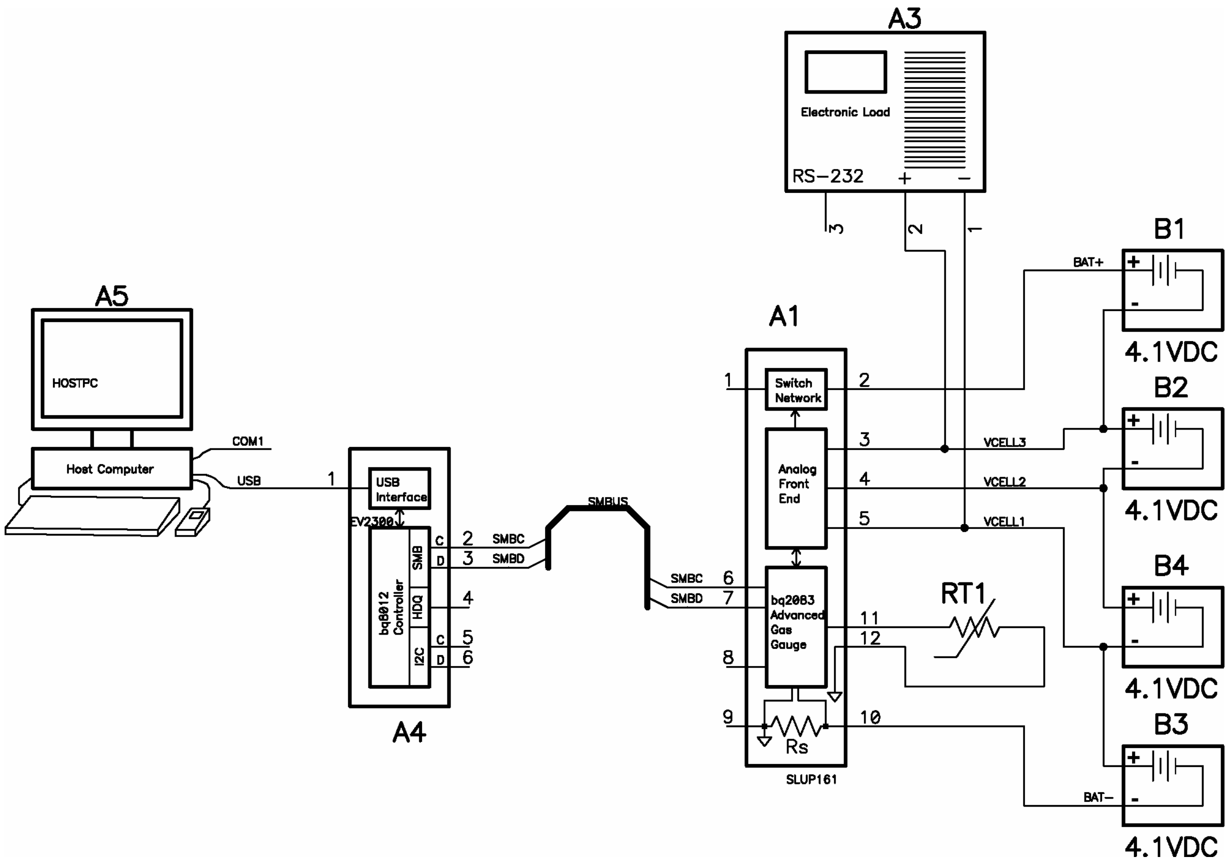

Figure 5. Hardware System for Cell-Unbalance Cycle

Remove 200 mAh of capacity from the cells to unbalance by setting the load to 800 mA for 15 minutes in constant-current mode. If you are not using an electronic load, estimate the time by using the following formula:

$$time_{discharge} = \left[\frac{Cap}{I_{load}}\right] \cdot \left[\frac{1}{60 \cdot 60}\right] \text{ in seconds}$$

where:

Cap = the capacity (in mAh) to remove from the cells for purpose of unbalancing

I_{load} = the discharge current (in mA) used to remove capacity from the cells. Select this parameter to yield a discharge time of approximately 15 minutes (900 seconds).

After allowing the cells to rest for 20 minutes, confirm that the cells are unbalanced by at least 50 mV. If there is a difference greater than the cell-balance minimum (40 mV default), then cell balancing begins on the next charge cycle when the cells rise above the cell-balancing threshold (3.90 V default).

If the cell-voltage imbalance is near the cell-balance minimum, discharge another 50 mAh from the same initial cells. This allows more time in the region where cell balancing is taking place so that the performance can be evaluated easier.

Balancing Procedure

1. Allow the pack to rest for 1000 seconds before beginning the discharge/charge cycling.
2. Configure the system as shown in Figure 4.
3. Manually set the electronic load to discharge the pack at 3.0 A in constant-current mode. When the pack reaches empty, the firmware-modified bq2083 signals the control software to command the load to terminate discharge. Charging commences after a 1000-second resting period.
4. Allow the pack to cycle continuously until the pack is balanced to less than 40 mV of difference between cells. It took about 18 cycles to balance the cells in this extreme imbalance test.

Reference Design Test Results

Description

A 4S2P (4series x 2 parallel) Li-ion battery was fully charged and unbalanced by 200 mAh. The data shows that the cell-voltage imbalance following the unbalancing procedure and a 1000-second rest was between 65 mV and 85 mV as shown in Figure 6.

Since the cell-voltage imbalance at this point was greater than the 40-mV default threshold, cell balancing was necessary. The control software collected data once every 5 seconds during the cell balancing test. The graphs in Figure 6–Figure 10 present a summary of the data.

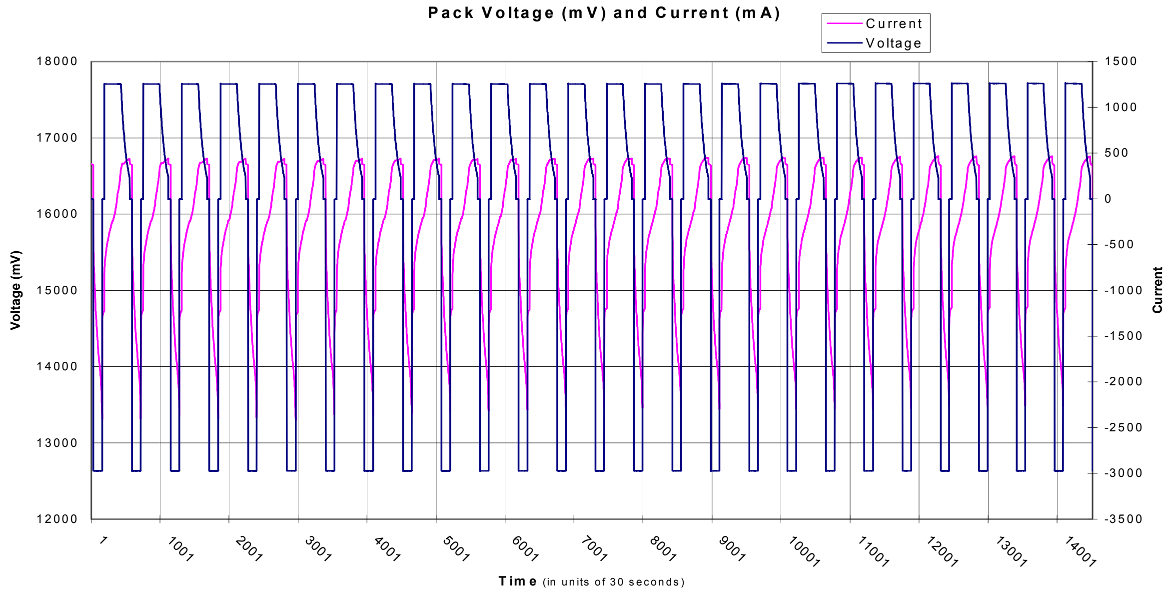

Figure 6. Total Pack Voltage and Current During Discharge/Charge Cycles, Cell Balancing Active

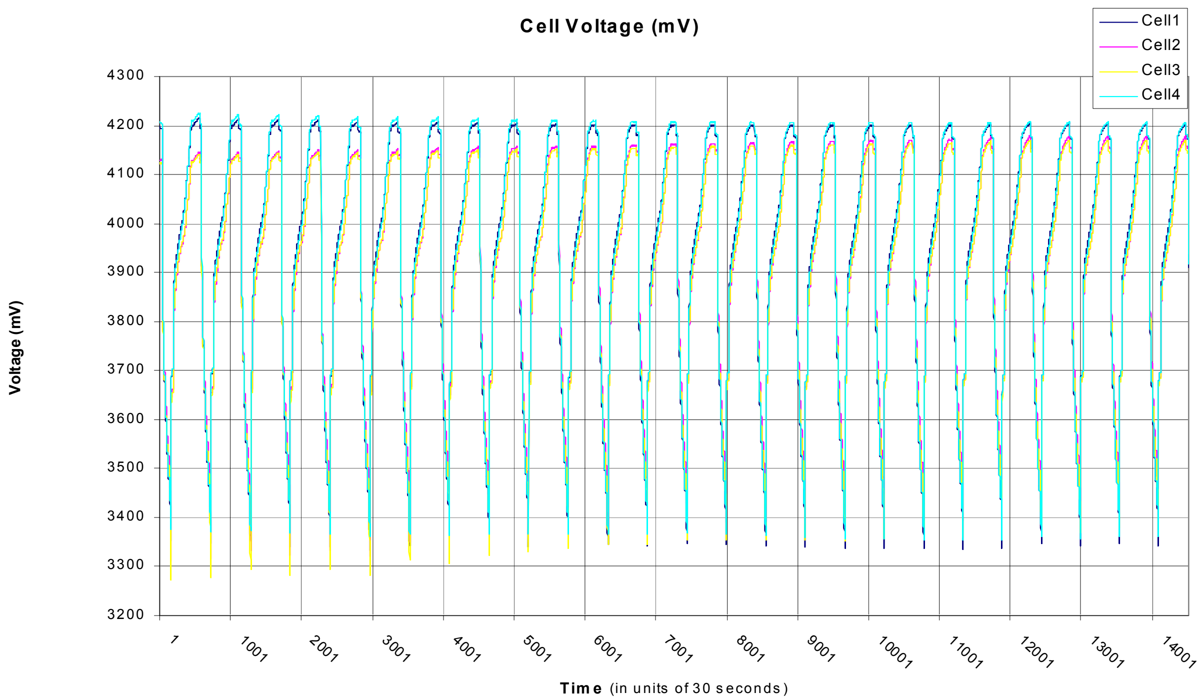

Figure 7. Cell Voltage Over Complete Balancing Cycle

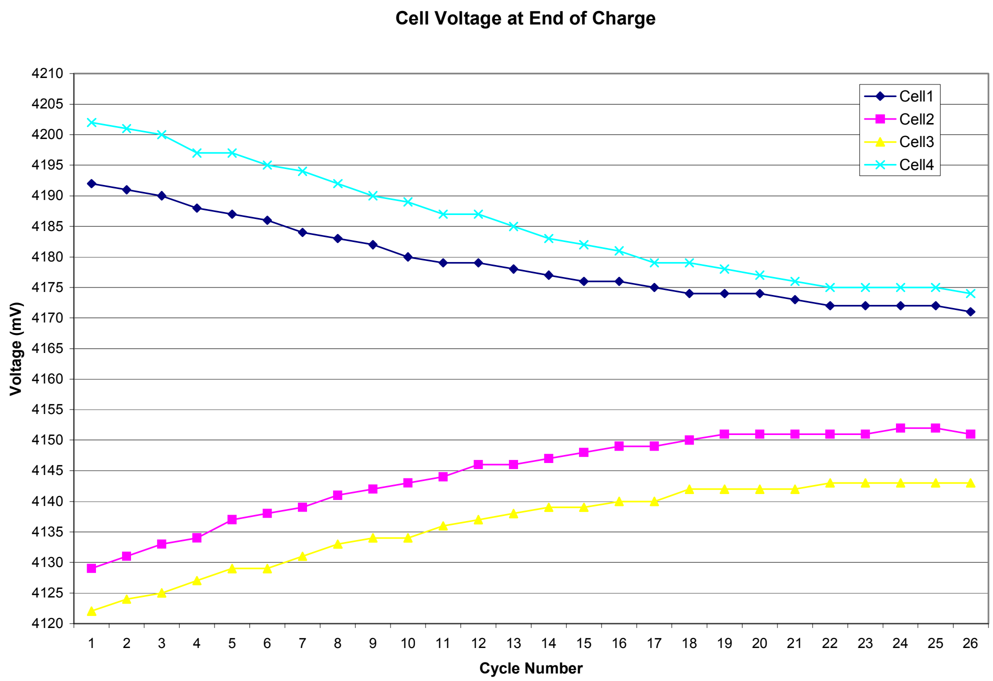

Figure 8. End-of-Charge Cell Voltages After 1000-Second Rest Period

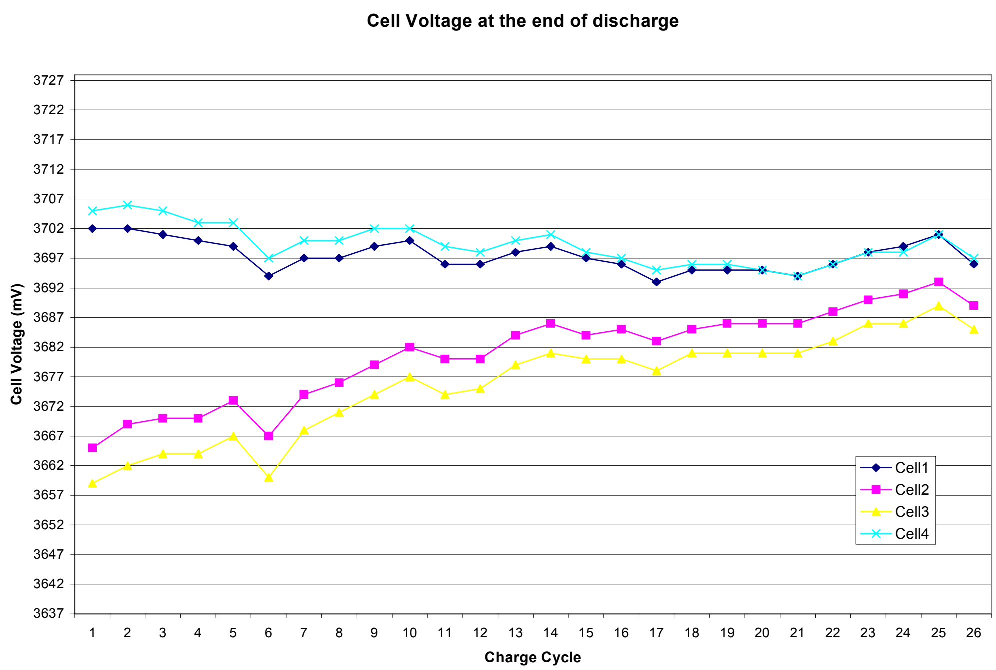

Figure 9. Cell Voltage at End-of-Discharge After 1000-Second Rest Period

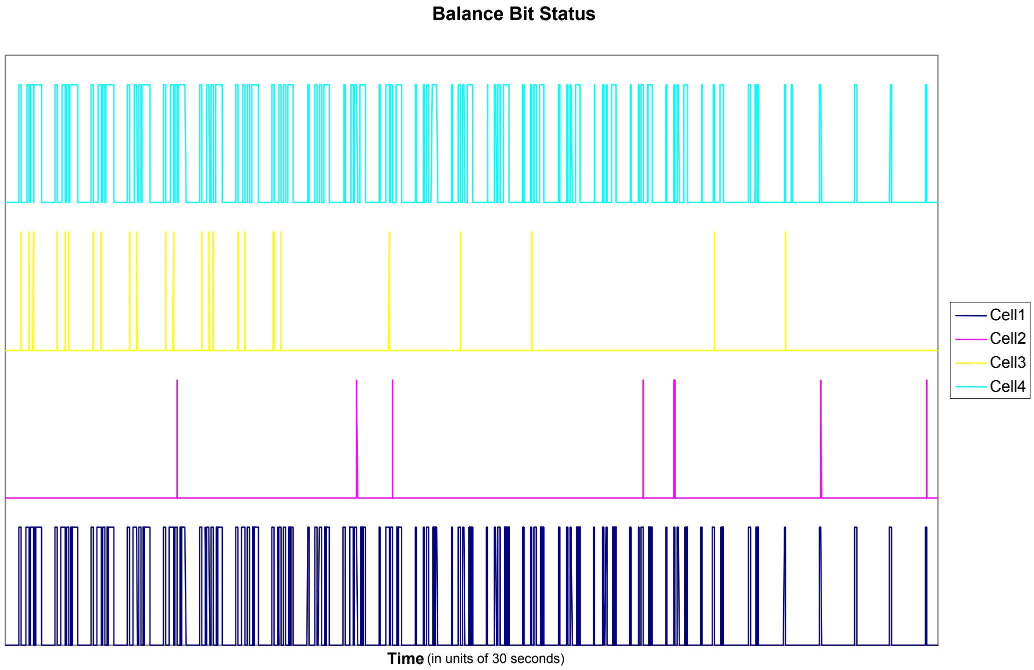

Figure 10. Balancing Activity

Balance bits indicate when each cell is being balanced. When the bit is high the corresponding cell charge rate is reduced. As the cells become more closely matched, the balance-bit density falls.

Summary

As shown in Figure 7, the voltages of unbalanced cells 1 and 4 are significantly higher (85-mV difference) during final stages of the first charge cycle. However, the balancing mechanism reduces this difference after several cycles. This is seen more clearly in Figure 8, which shows only end-of-charge voltages. After approximately 18 cycles, the voltage differences become less than the *Cell Balance Min* value of 40 mV, then changes very little afterward.

An unusually high number of cycles was required to achieve balance in this test due to the artificially induced initial imbalance. This 200-mA imbalance is an extreme value and is unrealistic in an actual industrial pack where initial capacity tolerance is 0.2%. This large imbalance is instrumental for testing purposes to verify the correct behavior of the balancing process. As calculated previously, the cell-balancing correction during one cycle is 0.011 Ah. The expected balancing time to correct a 0.2-Ah imbalance is therefore 18 cycles, which coincides with experimental data and demonstrates that the bq2083 cell-balancing mechanism works as designed.

Cell balancing can be tested in a new design without special equipment or software. First, follow the unbalancing steps described in this section, then proceed with charge/discharge cycling. After each charge, measure the voltage of each cell using the gas-gauge evaluation software. For increased accuracy, wait 15 minutes after the end of the charge before taking measuring. Plot the measured voltage data vs. the number of cycles in a manner similar to this application report, and detect the end of balancing when voltage differences stop changing with subsequent cycles.

Cell-Balance Configuration Guidelines

Data-Flash Programming

The bq208x allows the user to configure values of several cell-balance settings in data-flash storage. Addresses and default settings for the bq2083/5 are shown in Table 3. For other members of the bq208x family, see their corresponding datasheets.

Table 3. Cell-Balance Parameters

Data-Flash Address		Name	Li-Ion Example	Data	
High Byte	Low Byte			MSB	LSB
0×d7	0×d8	*Cell Balance Thresh*	3900 mV	0f	3c
0×d9	0×da	*Cell Balance Window*	100 mV	00	64
0×db		*Cell Balance Min*	40 mV		28
0×dc		*Cell Balance Interval*	20 seconds		14

Carefully consider all parameters before changing any of the default values. The cell balance can actually diverge when the values are not set properly.

Cell Balance Threshold

Using voltage as the criterion of cell imbalance, we assume a minimal I x R contribution to the cell voltage from cell's internal resistance. This is not true in a highly discharged state where the internal resistance of the battery can be as high as several ohms and I x R drop dominates the overall cell voltage. For this reason, cell balancing is not recommended when the battery is discharged. During a 1-C rate charge, a battery reaches approximately a 50% charged state when its voltage is above 3.9 V. At this charge state the internal resistance drops below 0.2 Ω, a distortion level within acceptable limits. If the charging current is less than 1 C, this threshold can be reduced.

Figure 11 shows how a threshold value set too low can result in diverging cell voltages, causing a greater imbalance than before. Highly undercharged cell1 has a high internal resistance, which drives its voltage high right after charging starts despite its low charge state. Below 4.05 V, undercharged cell1 is subjected to less charge current in an incorrect attempt to balance it with cell2. Since the cell imbalance is more than the *Cell Balance Min* value, the balancing algorithm tries to correct the perceived imbalance starting with the voltage set in *Cell Balance Threshold*, 3.9 V.

Cell1, without balancing, would follow the cell2 curve, but cell1 while being balanced follows the cell2 balance curve. At the end-of-discharge, the net effect is that cell1 and cell2 are less balanced than they were before. The problem is aggravated if *Cell Balance Min* is set to a value below 40 mV, because in this case the incorrect balancing attempt starts earlier.

This example uses a large charge difference that is unrealistic in an actual battery pack, but the same consideration holds true for the 5–10% imbalances found in typical packs, except that the problem would start below the *Cell Balance Threshold* of 3.8–3.9V.

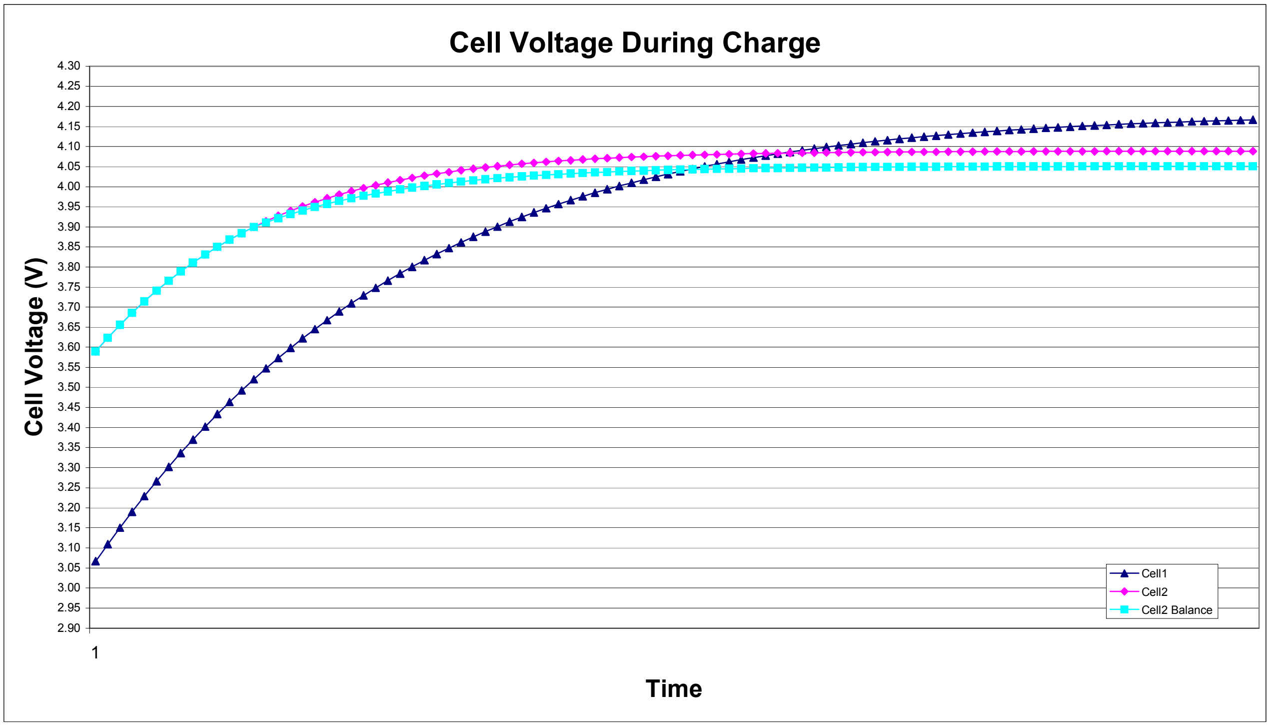

Figure 11. Cell Voltage During Charge, Improper Thresholds

Figure 11 shows a scenario with improperly selected thresholds where the cell-balancing algorithm causes cell voltages to diverge at the end-of-charge.

Cell Balance Window

If the value of *Cell Balance Window* is set below the value of *Cell Balance Window*, the step-up of the threshold would not have an immediate effect. The most reasonable value of this variable is to set it equal to *Cell Balance Min.*

Cell Balance Min

From first impressions, it appears that *Cell Balance Min* could be set to zero to achieve maximum cell balancing (minimum cell imbalance). However, due to effects from battery internal resistance, this is not the case. The low-frequency impedance of a typical Li-ion cell (as an approximation of DC-internal resistance) in a fully charged state is about 0.1 -0.3 Ω depending on the cell manufacturer. The average deviation of impedance value is ±15%. At a nominal 1-C charging current of 2 A, there is (assuming a worst-case 0.3-Ω battery) a ±9 mV deviation during charge for cells having the *same* total capacity and state of charge, due only to the I x R drop. Two worst-case cells in the same pack have an 18-mV difference.

During charging, the cell with a higher impedance (e.g., C1) has a higher voltage, and a cell with lower impedance (e.g., C2) has a lower voltage. But once charging is stopped and after a rest period, they have the same voltage again, because they now have the same charge. If balancing is attempted based on their voltage, C1 receives less charge; so after termination of charge, it has a lower voltage than C2. As a result, an additional charge imbalance was introduced into two cells that had the same initial state of charge.

This effect is exaggerated if resistances of the interconnections between cells are different, because this difference has the same effect as the impedance of the battery itself. The typical interconnect resistance between battery-pack cells is 0.15 Ω, so an additional ±5 mV difference can be expected at 1 A. With this information, 25 mV is the recommended absolute-minimum value recommended for *Cell Balance Min*.

If the *Cell Balance Min* value is reduced without improving cell balance, the reduction can aggravate the problem described in the discussion of *Cell Balance Threshold*. From this point of view, we recommend a safe value of 40 mV. This voltage difference corresponds to a maximum 3% of capacity imbalance between cells and does not risk cell degradation.

Cell Balance Interval

Voltage during the constant current (CC) stage of charging changes rapidly at the beginning, and slowly as it nears the changeover to constant voltage (CV) mode. Because the *Cell Balance Threshold* is usually set to a high voltage near the end of the CC stage, no rapid voltage change is expected. From this point of view, a *Cell Balance Interval* value of 20 seconds is fast enough for all cases. Updating too fast increases the processing load and hence the battery-electronics power consumption without any performance improvement.

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