External Cell Balancing in bq3060

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ABSTRACT

This application note describes cell balancing in the bq3060 SBS 1.1-Compliant Gas Gauge and Protection with CEDV. It introduces and explains the theory of what causes cell imbalances and when to perform cell balancing. It details the effects of the parameters of cell balancing in the bq3060 device through examples, and shows how to set up these parameters in the data flash for a particular application to optimize the battery life.

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1   Cell Balance: Cause and Effects

Many portable devices, such as notebooks and power tools, need a high power and high voltage power supply that is achieved by configuring battery cells in series and/or parallel combinations. At a certain time, cells can have different capacities or states of charge (SOC) creating a cell imbalance. This cell imbalance will lead to a rapid degradation of the battery if not corrected. There are three types of cell mismatch:

- Rate of Charge/Discharge—The rate of charge or discharge can be different between the cells. This leads to a different SOC in each cell, which is reflected as a different voltage on each cell.

- Capacity Mismatch—The capacity of a cell may be different from the other cells in the configuration. Regardless that the rates of charge/discharge are the same for all the cells, this leads to SOC differences.
- Impedance Imbalance—When current is flowing through a pack, a difference in impedance will provoke a different voltage in each cell with the same current. This changes the relationship between voltages of the cell vs. SOC, leading to different discharge times for each cell.

Some of the factors that contribute to the development of these mismatches are:

- Manufacturer Variability—Within a same batch, characteristics such as internal impedance and capacity may vary from cell to cell. For example, unused cells may have up to ±15% variations in the value of internal impedance at low frequencies.
- Temperature Gradient—In some applications (for example, notebooks), a battery may be exposed to different temperatures in each cell by being near components' dissipating heat. Because resistance, capacity, and voltage depend on temperature, the cells may be imbalanced by the temperature gradient.

To clearly illustrate the consequences of not correcting cell imbalances, an example can be used. Suppose that we have a 2-series cell configuration with a capacity mismatch. Cell 1 has a capacity of 1000 mAh and Cell 2 has a capacity of 1200 mAh. If both cells are fully charged, discharging the pack will cause Cell 1 to reach the end of discharge voltage (EDV) faster than Cell 2 (that is, if the cells have an End of Discharge Voltage [EDV] of 3.0 V), Cell 1 will reach this voltage first, then Cell 2. Also, Cell 2 will end with a higher voltage than 3 V, meaning that it did not fully discharge due to the higher capacity. As this process continues from cycle to cycle, Cell 1 will degrade faster than Cell 2. This results in the battery pack reaching its end of life prematurely.

2   Issues and Limitations of Cell Balancing

Figure 1 shows the OCV and voltage under load profiles as function of SOC for a common Li-Ion battery.
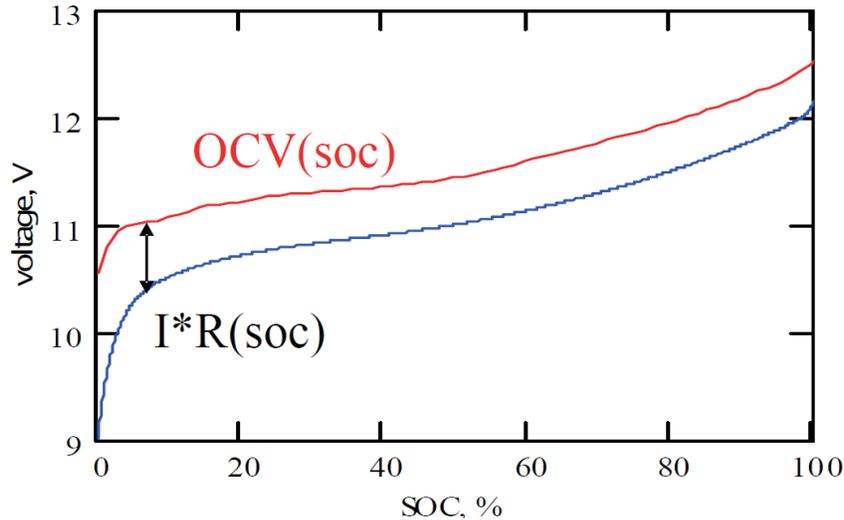

Figure 1. OCV and Voltage Under Load Profiles

The voltage profile of a battery in terms of the SOC is represented by Figure 1. It is evident that the voltage of the battery, also in every cell, will depend on the SOC. Hence, a simple way to balance the cells when they have a different SOC is by equalizing their individual voltages. However, when there is current flowing through the battery, the internal resistance influences how cell balancing should be executed. The following equation represents the voltage of a particular cell N considering the internal resistance R and ignoring temperature (for simplicity):

$$V_N = OCV_N(SOC) + I \cdot R_N(SOC)$$

where *I* is the current flowing through the cell and is positive during charging. As in Figure 1, if you evaluate the rate of change,

$$\frac{dV_N}{dSOC}$$

it will have a higher value at end of charge (EOC) and in the end of discharge (EOD). To understand in detail the effect of the internal resistance to the changes in the voltage of the cell, examine Figure 2 and the following equation:

$$\frac{dV_N}{dSOC} = \frac{dOCV_N}{dSOC} + I\frac{dR_N}{dSOC}$$

From Figure 2, you can see that the internal resistance is dependent on the SOC and will change during a charge or discharge cycle. Care must be taken during balancing because the nonlinearity of the internal resistance can contribute to the voltage reading that is used in voltage-based cell balancing. In summary, during a charge or discharge cycle, the changes in voltage in a cell will not be solely dependent of the charge available, but will also depend on the resistance change in terms of the SOC and the current through the cell.
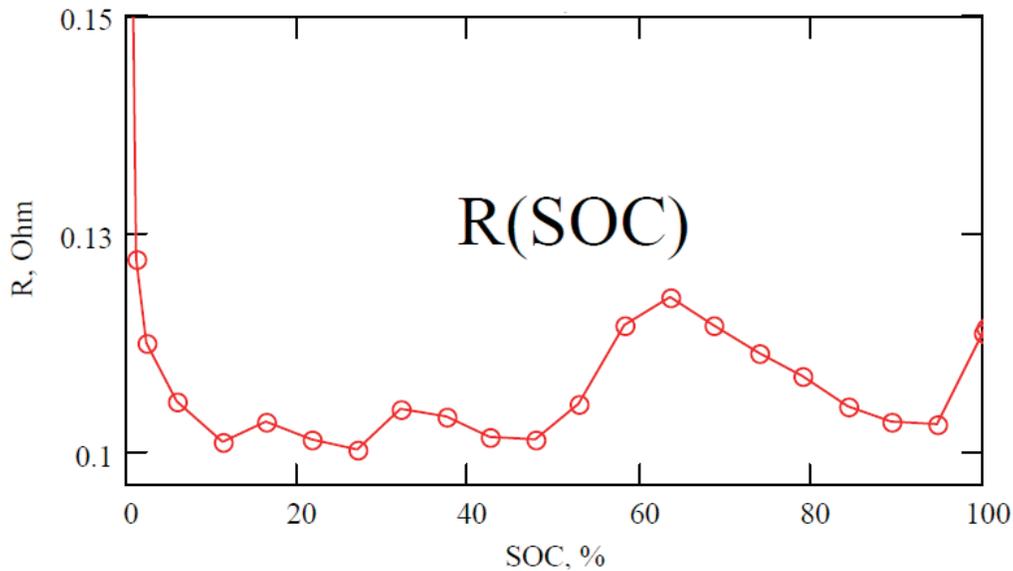
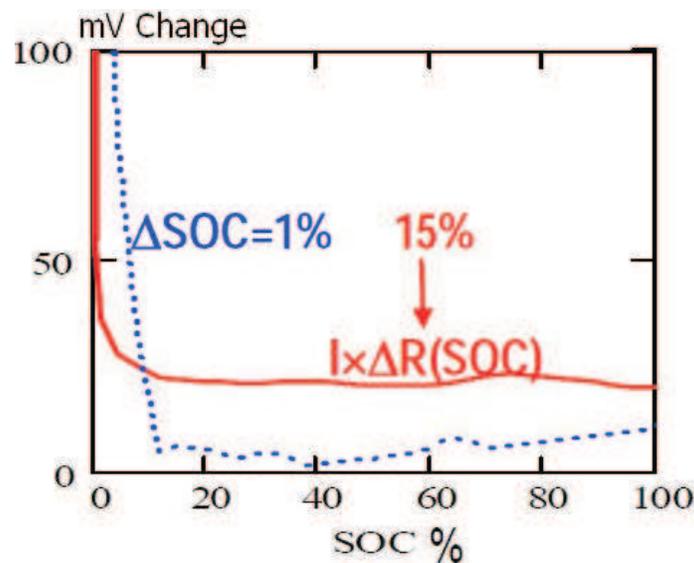**Figure 2. Variation of Resistance of a Battery as Function of SOC**

Figure 3. Contribution of an SOC Change and a Variation with a C/2 Current

Figure 3 shows a representation of a contribution of an SOC change of 1% and a variation of 15% of the internal resistance to the change in cell voltage when a current of C/2 is flowing through the battery.

The impedance between cells may vary from cell to cell. Finding the difference of the voltage between the cells can be written as:

$$\Delta V = \Delta OCV(SOC) + I \cdot \Delta R(SOC)$$

The first term corresponds to the contribution of the SOC imbalance due to the different charge/capacity available and the second by the variability of internal resistance between cells. To perform cell balancing correctly based on voltage, the first term must contribute more than the second. As shown in Figure 3, there are regions where the variability of the internal resistance contributes more to the difference in voltage between cells. Cell balancing cannot be performed during those stages to prevent inducing more imbalances, because the voltage difference between the cells does not represent the real imbalance between the cells.

The influence of the resistance variability can be reduced if a small current is flowing through each cell. Because the charge profile of a Li-Ion battery (Figure 4) consists of charging the battery at a constant current until the end of charge voltage of the chemistry and then at constant voltage until the current drops to a certain value (typically 0.04 C–0.07 C), cell balancing should be performed near the EOC. In this way, effects of the internal resistance are minimized, and the rate of change of the voltage with respect to the SOC is mostly contributed by the cell imbalance.
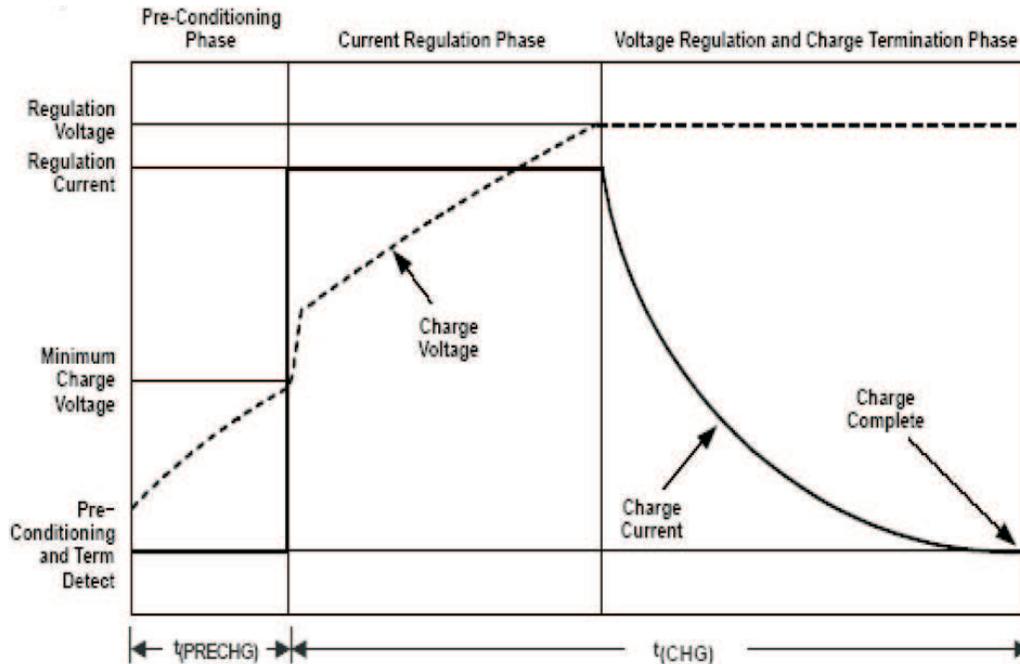
Figure 4. Charge Profile for a Common Li-Ion Battery

3   bq3060 External Cell Balancing

3.1   *Schematic and Functionality Description*

The bq3060 gas gauge is designed to work with an external cell balancing circuit, as shown in Figure 5. Cell balancing occurs during charge and uses voltage based cell imbalance detection. Cell balancing of a particular cell is performed by bypassing a current in the cell. When the bq3060 device triggers a condition to start cell balancing, a small current is drawn by the IC pins VC1–VC4 turning FET transistors ON by creating a voltage across 1-KΩ resistor (as shown in Figure 5) or R1–R4 in the reference schematic (Figure 13). The magnitude of the bypassing current is mostly controlled by the 100-Ω resistor, as shown in Figure 5 or R10–R13 in Figure 13 due to the low $R_{DS(on)}$ of the transistor Q1, shown in Figure 5. Texas Instruments recommends the P-channel SI1023X FET, which has a typical $R_{DS(on)}$ of 1.2 Ω when biased with a V_{gs} of –2.5 V.
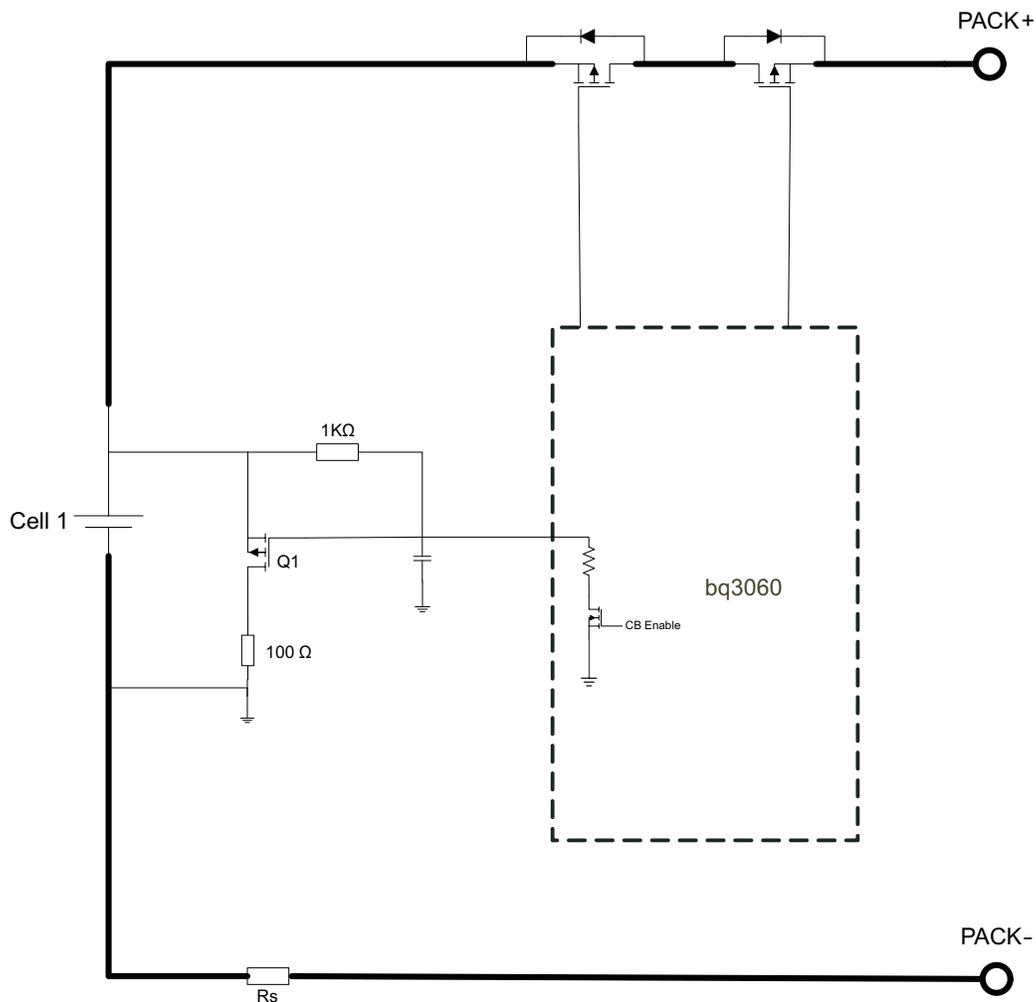
Figure 5. Cell Balancing Circuit

Cell balancing is performed at a 44% duty cycle; therefore, the relationship that approximates how much time it takes to balance a certain amount of charge imbalance A using a bypass current I can be expressed as follows:

$$time_{CB} = \frac{A}{0.44I}$$

From this equation, the influence of the magnitude of the bypassing current to the time needed for cell balance can be seen. For example, for large imbalances, it may take several cycles to balance cells with small currents. This suggests that the bypass current must be fixed accordingly to the application needs by properly choosing values for resistors R_{10}–R_{13}.

3.2 *Parameters Definition*

Figure 6 shows a graphical representation of parameters in the data flash that control the cell balancing process. The following are brief descriptions:

- *Cell Balance Threshold*—Specifies the minimum value that a cell must have in order to initiate cell balancing if the minimum differential voltage between cells exists.

- *Cell Balance Window*—Indicates the voltage that the Cell Balance Threshold can increase in order to help determine which cell to discharge during balancing. Once balancing at a given voltage level is finished, this parameter prescribes the higher voltage where cell balancing can be initiated again if needed.
- *Cell Balance Min*—Specifies the minimum cell differential voltage that must be achieved between any two cells to start the cell balancing.
- *Cell Balance Interval*—The time in which the cell balancing circuit will measure cell voltages to determine the state and the continuation of cell balancing.
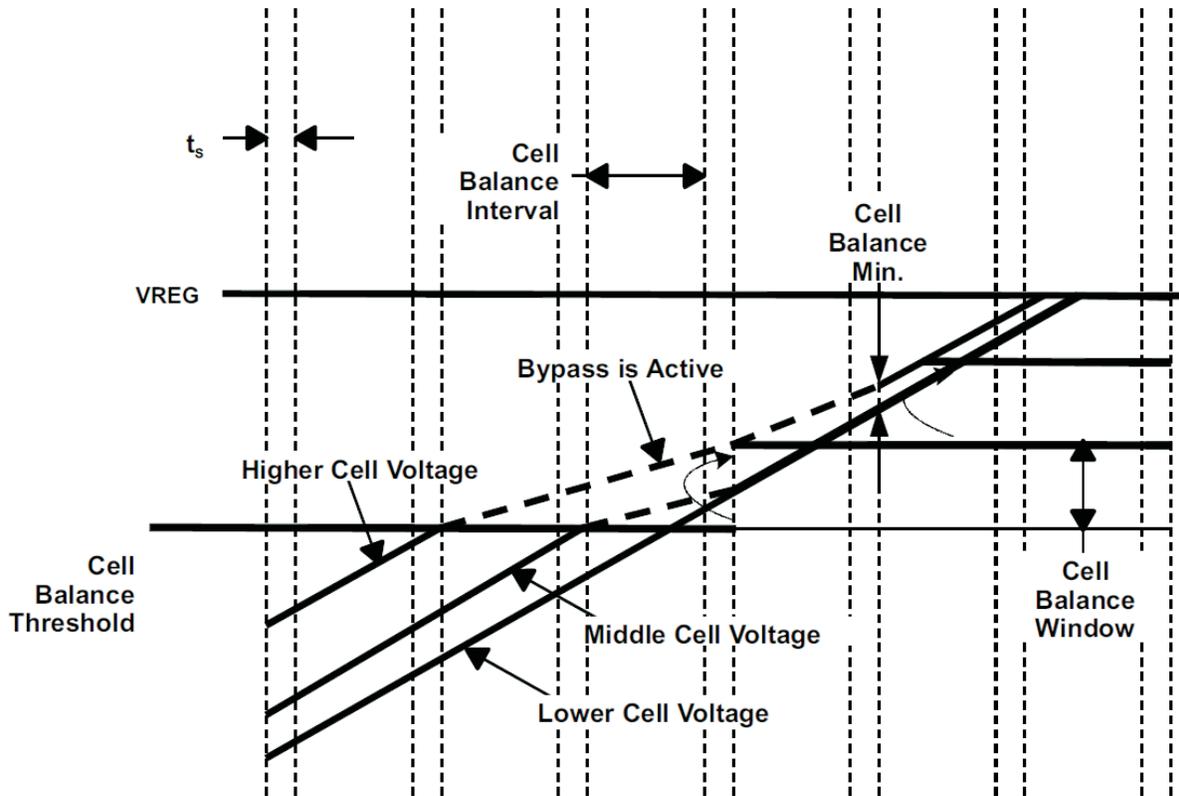
Figure 6. Parameters

3.3   Cell Imbalance Faults

Also, if enabled, the bq3060 device can detect a fault in the cell imbalance and stop any charging/discharging status. The parameters that set the condition for these faults are:

- *Cell Imbalance Current*—If the battery pack current is less than this threshold for the amount of time dictated by Cell Imbalance Time, and the maximum difference in cell voltages is more than the Cell Imbalance Fail Voltage, the condition of the cell imbalance is flagged ([CIM], [XCIM]).
- *Cell Imbalance Fail Voltage*—Specifies the minimum voltage difference between any combinations of cells that, if maintained for at least the Cell Imbalance Time, will trigger the cell imbalance flag.
- *Cell Imbalance Time*—Specifies the time that the *Cell Imbalance Fail Voltage* must be maintained to trigger the cell imbalance flag (use 0 to deactivate the cell imbalance fault).
- *Min CIM-Check Voltage*—Specifies the condition of the minimum voltage that all voltages must have so that the cell imbalance can occur.

4 Influence of Cell Balancing Parameters

The voltage profile of a cell during charging at constant current changes dramatically at the end of discharge and end of charge, but it is reasonably flat in the middle range of the SOC. Therefore, for a same charge imbalance, the differential voltages between the cells is more noticeable in the corners of the voltage profile than in the flat region. This section provides a discussion of parameter influence, along with some experimental examples. Table 1 lists example parameters.

Table 1. Example Parameters

Parameter	Low Value	High Value	Default
CB Threshold	Permits cell balancing from the start of charging cycle	Allow balancing only at later stage of charging, near end of charge	3800 mV
CB Window	Allow balancing in all regions during charging	Favor balancing only at end of charge or end of discharge, excludes flat region	100 mV
CB Min	Will balance cell voltages until they are almost similar values	Increases tolerance of cell imbalance	50 mV
CB Interval	Firmware will evaluate imbalance situation more frequently	Firmware will evaluate imbalance situation less frequently	20 s
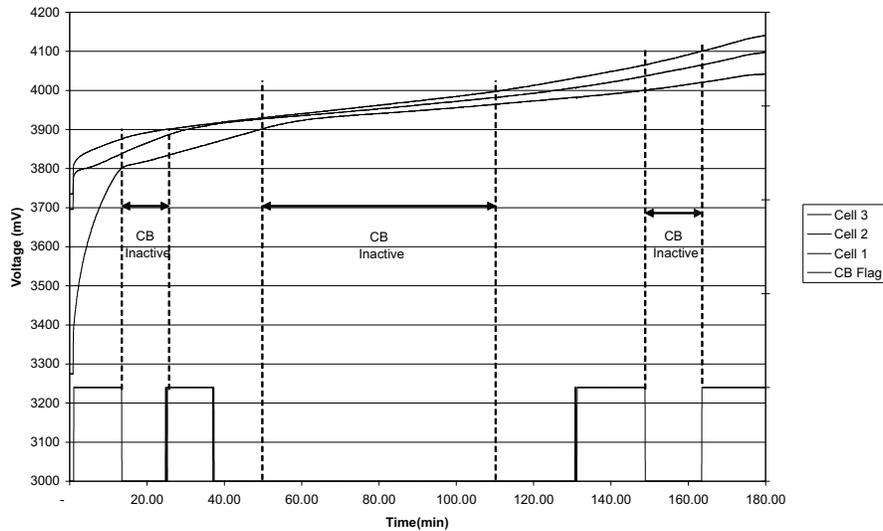
Figure 7. Cell Balancing Controlled in End Regions by CB Window

Figure 7 represents the influence of the parameter *Cell Balance Window*. The cell imbalances, where the time period is marked by CB Inactive, will never be balanced regardless of the value of *Cell Balance Min*. Therefore, this parameter controls the region where cell balancing will occur. Figure 7 shows an example of permitting cell balancing at the end of charge and the end of discharge.

Cell Imbalance Tolerance - CB Min = 50 mV, CB Window = 100 mV
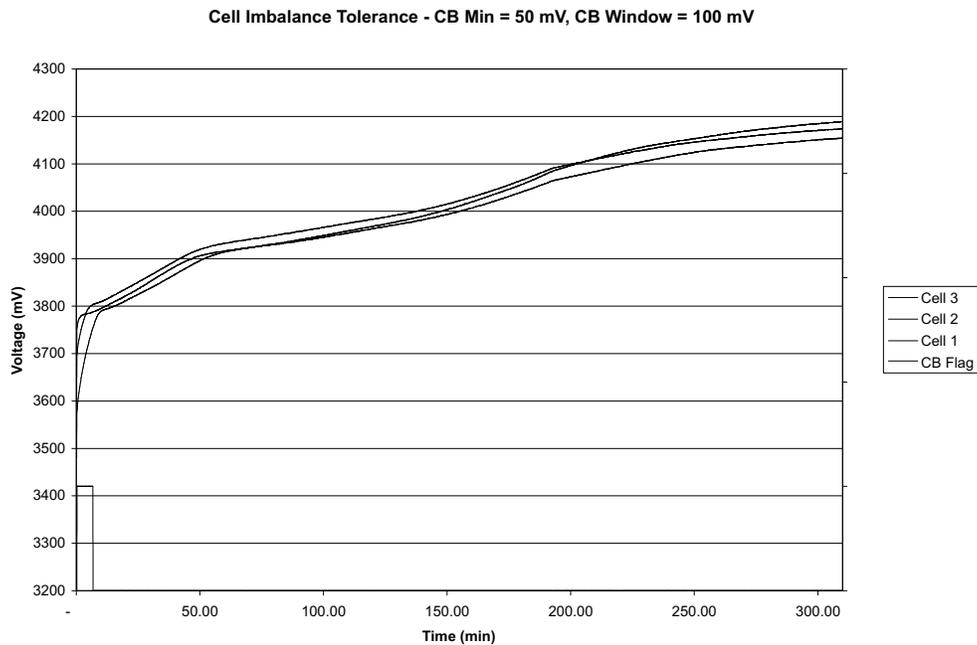
Figure 8. Cell Imbalance Tolerance Fixed by CB Min

When the application permits a certain amount of cell imbalance, the imbalance tolerance can be easily controlled by setting the *Cell Balance Min* parameter to a proper value. As shown in Figure 8, balancing occurs only at the beginning of charging, because after the cells reach the level of 3800 mV, the maximum differential cell voltage is below the value of *Cell Balance Min*. If there is the need to balance the cells with low tolerance, this parameter should be adjusted, as shown in Figure 9. In this graph, cell balancing occurs until the imbalance is almost zero.

Comparing Figure 9 and Figure 10, there is a noticeable difference in the status of the CB Flag, where in Figure 9 it is updated more frequently than in Figure 10. This is controlled by adjusting the parameter *Cell Balance Interval*.

Cell Balacing - CB Window = 2mV, CB Min = 2mV, CB Interval = 20 sec
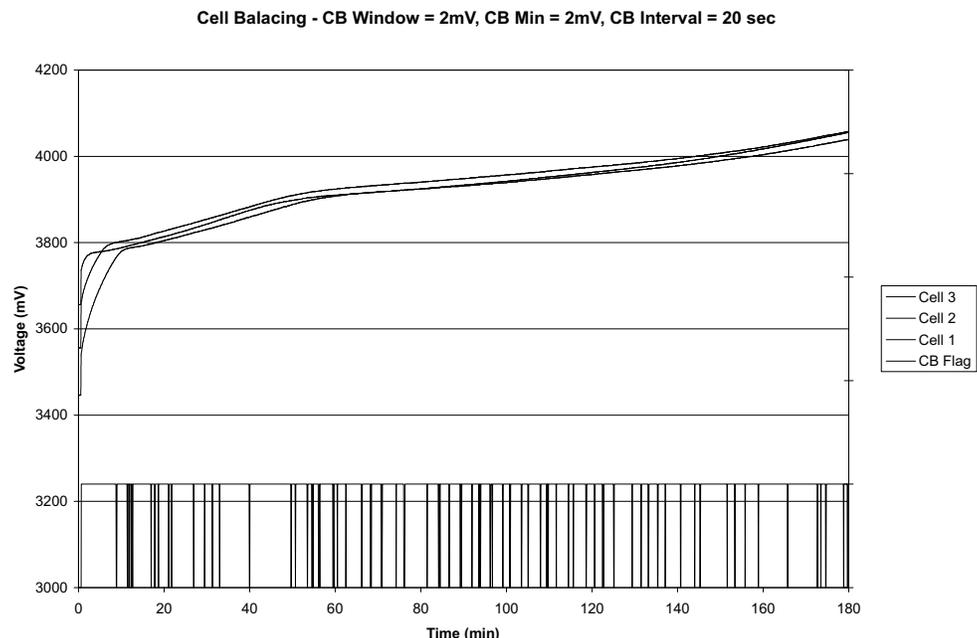
Figure 9. Cell Balancing with Low Imbalance Tolerance and Firmware Algorithm Frequently Updated

Cell Balancing - CB Window = 2 mV, CB Min = 5 mV, CB Interval = 120 sec
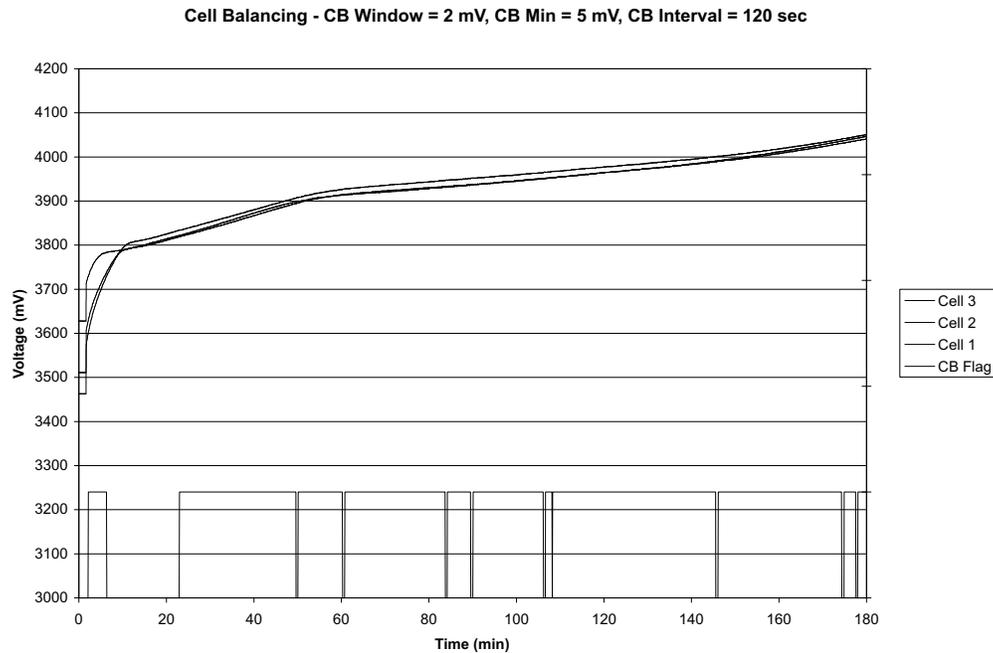
Figure 10. Cell Balancing with Low Imbalance Tolerance and Firmware Algorithm Infrequently Updated

Figure 11 represents cell balancing during a charging cycle with a low charge imbalance.

Cell Balancing - CB Window = 2mV, CB Min = 2 mV, CB Interval = 20 sec
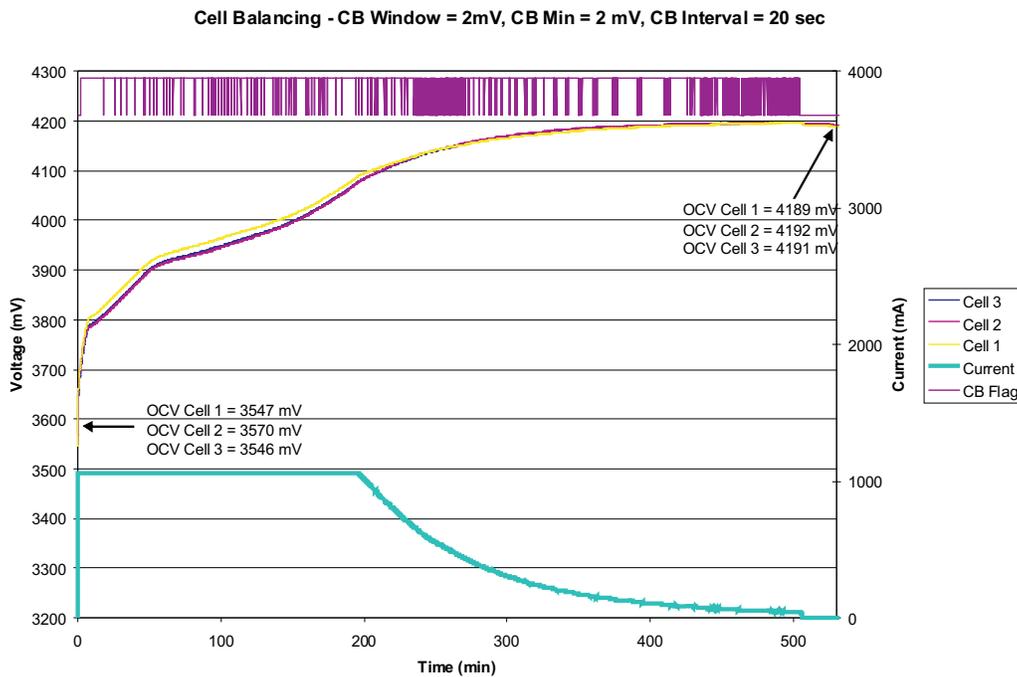
Figure 11. Cell Balancing Example for Imbalance Tolerance Limited by Measuring Accuracy

5   Experimental Results

A 5000 mAh capacity 3-cell old battery was imbalanced by discharging Cell 1 by 200 mAh. The parameters were set as:

- CB Threshold – 4000 mV

- CB Window – 5 mV
- CB Min – 5 mV
- CB Interval – 20 s

The voltage at the end of charge after an appropriate relaxation time was measured and graphed:

End of Charge Voltage and Maximum Cell Voltage Differential
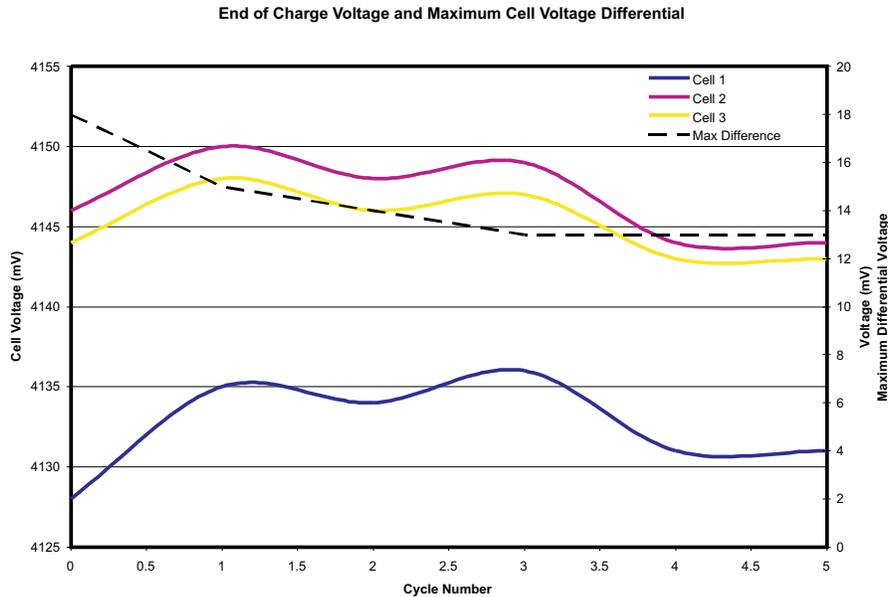
Figure 12. End of Charge Voltages of the Three Cells in Terms of the Cycle Number

The setting used in this example stresses the CB threshold vs. voltage delta tolerance and cell balancing time. It is not necessary a recommended setting for real application. It can be observed in Figure 12 that the maximum differential voltage between cells, represented by the dashed line, decreases through every cycle starting at 18 mV until 13 mV.

As shown in Figure 12, Cell 1 voltage was much lower than Cell 2 and Cell 3 voltages. However, at the initial phase of the charging cycle, Cell 1 actually had a higher voltage than the rest of the cell (data was not shown here). This is an example of the effect of IR drop with different CB threshold settings. The resistance difference among the cells will result in a difference in IR drop of each cell. With a lower CB Threshold setting, the voltage-based cell balancing algorithm is less effective compared with a higher CB threshold setting. This is because the charge current was reduced toward the end of the charging cycle, resulting with a less IR effect on each cell. Although a higher CB threshold setting can obtain a smaller voltage difference among the cells, the trade off is longer cell balancing time.

- Low Tolerance
  - CB Threshold – 4100 mV
  - CB Window – 8 mV
  - CB Min – 8 mV
  - CB Interval – 20 s
- High Tolerance
  - CB Threshold – 3900 mV
  - CB Window – 40 mV
  - CB Min – 40 mV
  - CB Interval – 20 s

6   Reference Schematic

Figure 13 shows the bq3060 device's reference schematic.
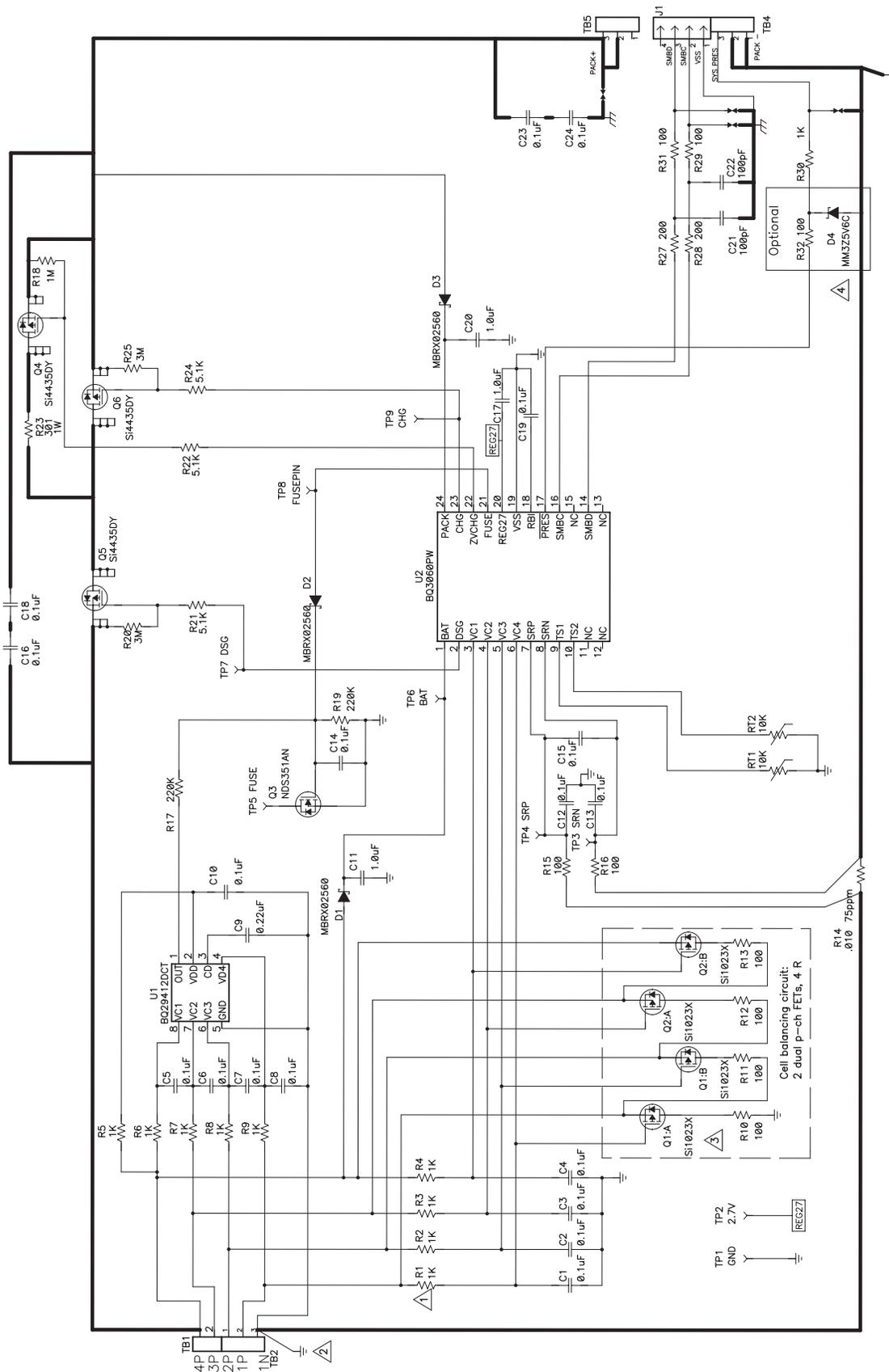
Figure 13. bq3060 Reference Schematic

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