Cell-Type Specific Settings for Cell Imbalance Permanent Failure Thresholds

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1 Introduction

Differences between state-of-charge (SOC) of serially-connected cells is called *cell imbalance*. It can cause overcharging of some cells and can create potential safety hazards. To prevent this, the bq20zXX gas-gauge ICs from Texas Instruments have two levels of protection. For a low level of imbalance, the cell-balancing algorithm bypasses some charge energy from the high-SOC cell to correct the imbalance, which in most cases is sufficient. A high level of imbalance is an indication of an anomaly, such as a micro-short in the cell, or a leakage path in the external circuit for some cells. The presence of a micro-short could be an indication of a much more serious problem – particles in the electrolyte, which sometimes lead to catastrophic internal short circuits. Therefore, it is prudent to permanently disable battery packs that exhibit such behavior. This is implemented as a *cell imbalance permanent failure* (CIM PF). Correct settings for the voltage and time thresholds for this feature are critical to avoid disabling packs that have only marginal imbalance or capacity differences.

2 CIM PF Settings

Settings for CIM PF are stored in the *2nd Level Safety* section of the data-flash, in the *Voltage* subsection.

The relevant values are shown in Table 1:

Table 1. 2nd-Level Safety Settings

VARIABLE	UNIT	DEFAULT VALUE	DESCRIPTION	TYPICAL VALUE WHEN ENABLED	COMMENT
Cell Imbalance Current	mA	5	Maximum current to take open-circuit voltage reading for imbalance detection.	5	
Cell Imbalance Fail Voltage	mV	1000	Open-circuit voltage difference between lowest- and highest-voltage cells to trip Gas Gauge permanent failure.	1000 for polymer cells	
				500 for cylindrical cells	
Cell Imbalance Time	sec	0	When Battery Rest Time passes and a voltage difference that exceeds the Cell Imbalance Fail voltage is detected, the Gas Gauge waits for Cell Imbalance Time before setting a permanent failure. A zero value disables CIM PF.	60	
Battery Rest Time	sec	1800	Delay time from when the current falls below Cell Imbalance Current to when the Gas Gauge begins to measure the voltage difference between lowest and highest cells.	1800	
Min CIM-check voltage	mV	3000	If any cell voltage is below Min CIM-check voltage, no voltage-difference checking is performed, and CIM PF does not go into effect.	3000	Only present in bq20zXX v1.15 and higher.

3 Relationship Between Cell Voltage Differences and SOC Differences

The typical settings in Table 1 are for LiCoO2 / carbon type of Li-ion chemistry, and does not represent exact recommendations for all Li-ion chemistries. This is due to the different OCV (SOC) profiles of different chemistries. Depending on the OCV(SOC) profile, the same SOC difference causes a different voltage difference between the cells of different chemistries. Even for the same chemistry, the same SOC difference of 1% has different voltage effect for different states of charge, as can be seen in Figure 1.

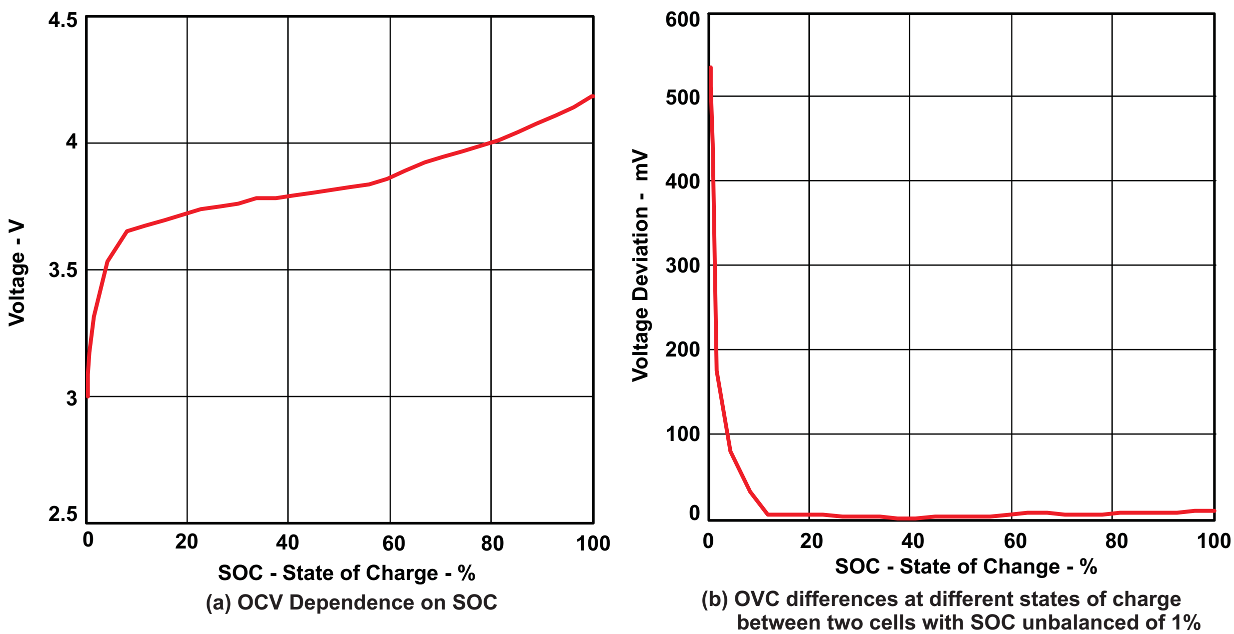


Figure 1.

This means that if we set a voltage threshold of 500 mV, it will actually be detected as CIM PF, even at such small SOC difference as 1%, but only in a deeply-discharged state. If we limit the discharged state at which we check for imbalance, for example by setting DF.Min CIM-check voltage = 3000, we will not detect PF as 1% with a 500-mV threshold. Because DF.Min CIM-check voltage is not available in bq20zXX firmware below v1.15, it is recommended to set the CUV threshold reasonably high to limit the minimal voltage a cell can be discharged to. This will have a similar effect on CIM PF as setting high DF.Min CIM-check voltage.

4 Finding the Exact dV vs dSOC for a Particular Chemical ID

Because OCV(SOC) tables are already used in bq20zXX algorithm, for every chemical ID it is easy to test and find the actual Cell Imbalance Fail Voltage that corresponds to a desired SOC difference. Usually, a SOC difference of 3-5% would be considered critical.

To perform this test, follow these steps:

1. To be able to set arbitrary voltages for each cell, use a resistor divider with four 10-kΩ resistors that emulate the cell stack.
2. Connect the cell-emulating resistance divider to 1N, 1P, 2P, 3P and 4P pins of the EVM the same way as the actual cell stack would be connected.
3. Apply 16.8 V across the resistor divider
4. Program a bq20zXX evaluation model with a given chemical ID (for example using bqEasy in EV Software)
5. Change the value of DF.Avg. I. Last Run to 0. This value will be used for calculating the remaining capacity, and will correspond to the OCV curve because resistance compensation is disabled at zero current.
6. Send a reset command 0041 to manufacturer access to recalculate remaining capacity. Remaining capacity will update according to present voltage and Q_{max}. It will be close to the Q_{max} value if the voltage is close to 4.2 V/cell.
7. Now try several low voltages to determine the Remaining Capacity differences between them. For example, if the cell voltage = DF.Terminate Voltage / number of serial cells, Remaining Capacity = 0.
8. To find the exact voltage difference to cause a given dSOC (%), find a cell voltage that after a reset, the Remaining Capacity = $dSOC \times Q_{max}/100$

5 Effect of Differences in Cell Capacities, Q_{max}

When the full capacities of the cells are not equal, additional complications arise, because SOC differences between cells are not the same at different states of charge. Because cells are typically balanced in a fully-charged state to avoid unsafe overcharging event, the more deeply they are discharged, the higher the SOC differences between the cells become.

$$SOC = SOC0 - = \frac{Q\_discharge}{Q_{max}} \times 100 \tag{1}$$

If we consider the same starting SOC but different Q_{max}, we see that the difference increases with the amount of Q_discharge.

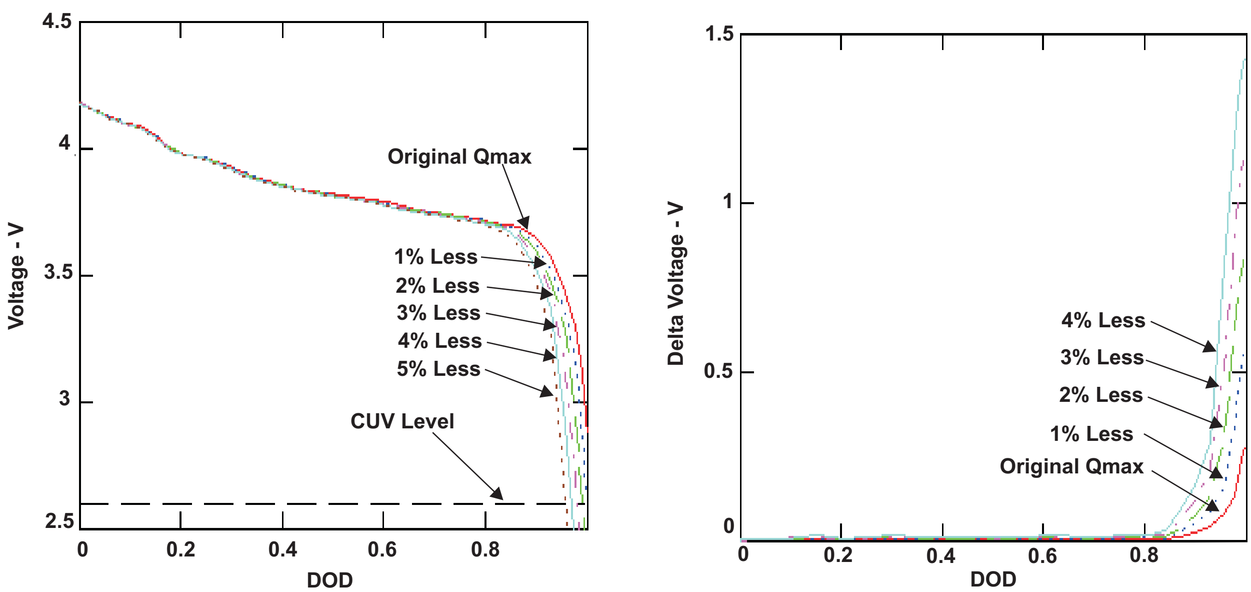
$$SOC_1 = SOC0 - = \frac{Q\_discharge}{Q_{max1}} \times 100 \tag{2}$$

$$SOC_2 = SOC0 - = \frac{Q\_discharge}{Q_{max2}} \times 100 \tag{3}$$

$$dSOC = SOC1 - SOC2 = \frac{Q\_discharge \times \left(Q_{max2} - Q_{max1}\right)}{Q_{max1} \times Q_{max2}} \tag{4}$$

The dSOC is proportional to Q_discharge and the Q_{max} difference. The value reaches the highest value at the end of discharge, so the effective voltage difference is the sum of the initial SOC0 differences between the cells, and the difference resulting from Q_{max} differences.

For example, Figure 2 shows a family of voltage curves for Q_{max} differences ranging from 1% to 5%. The voltage differences increase with the Q_{max} difference.



(a) OCV curves corresponding to different % of decreasing Qmax

(b) Resulting voltage differences between the cells

Figure 2.

6 Effect of Cell Undervoltage (CUV) or Min CIM-Check Voltage Settings

Voltage will not decrease below CUV level, which limits the maximum delta that will be observed (not reflected by above delta Voltage graph). The worst-case scenario is if discharge is at low rate, so that at the moment when CUV is reached, the cell voltage is equivalent to the OCV that will be used for CIM calculations. This worst case scenario is used in the following analysis.

Figure 3 shows the relationship between the cell voltage difference at cell undervoltage and the total-capacity Q_{max} difference. Here are calculations of delta Voltage at CUV level:

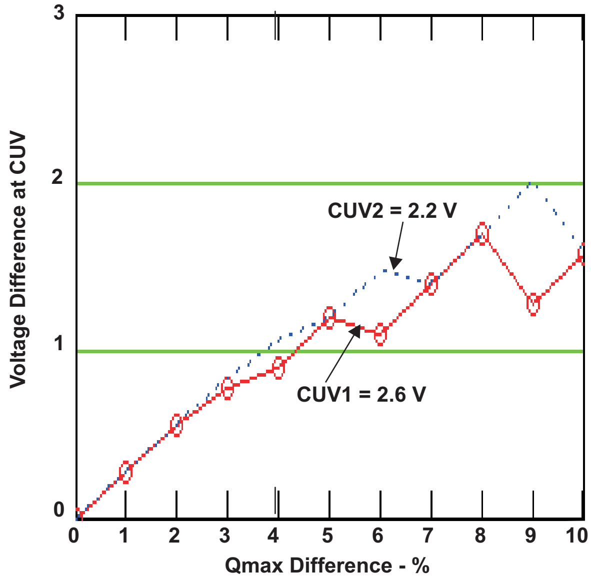


Figure 3. The Relationship Between the Cell Voltage Difference at Cell Under Voltage and Q_{max} Difference

It can be seen that increasing CUV from 2.2 to 2.6 makes the voltage difference somewhat lower above a 4% Q_{max} difference level, and has no effect below this level.

This graph can be used to select a CIM threshold that reflects a Q_{max} difference at which packs should be disabled. Actual test data about Q_{max} deviations in particular cells is required to determine an optimal threshold which will not occur with normal, non-defective cells.

For example, a level of 1 V corresponds to a Q_{max} difference of approximately 3.6% (blue line). Increasing the CUV to 2.6 V (red line) will change that to a Q_{max} difference level of approximately 4.3% (the graph is irregular because of the large sampling interval of the example data).

If a high number of CIM events occur in the field (and high Q_{max} differences are observed) it means that the present CIM voltage level is set too low for a given Q_{max} distribution of a particular cell manufacturer.

Increasing the CUV to 2.6 V will not radically change this situation (while it might still be beneficial for other reasons).

To decrease the number of CIM failures, there are two approaches:

1. Require cell manufacturers to decrease the tolerance on cell Q_{max} differences.
2. Increase the CIM voltage threshold to fail cells at higher Q_{max} differences. For example, to fail it at 7% according to Figure 3 (with CUV 2.6 V), you would need to set threshold to 1.5 V.

7 Effect of Battery Rest Time

When discharge is terminated, the IR drop caused by the discharge is not immediately eliminated, as can be seen in Figure 4.

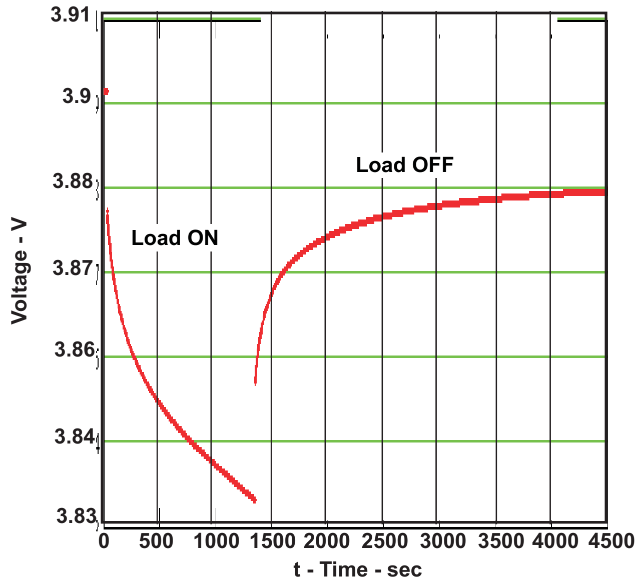


Figure 4. Battery Cell Voltage Waveform During Discharge and Relaxation Mode

A battery behaves like an RC circuit with a very long time constant. The IR-drop differences between different cells are up to 15%, and so can have a significant additional cell-voltage difference if not fully eliminated. The recommended Battery Rest Time of 1800 is sufficient for typical cells, but if a particular chemistry shows longer relaxation time to achieve a stable voltage, it is recommended to increase this value.