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Continuous Balancing Guidelines

Application Note

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Please use at your own risk.

The content in this document must be followed in order to ensure safe operation of Nuvation Energy BMS.

> Insulated handling is required of any connector carrying potentials over 60 V DC relative to chassis.

> Please be aware of high voltages present in your system and follow all necessary safety precautions.

> Nuvation Energy BMS relies on your system charger to charge the battery cells; do not leave your charger off while Nuvation Energy BMS is powered from the stack for prolonged periods of time. Nuvation Energy BMS should be shut down when the system is in storage to minimize the drain on the cells.

1. Introduction

Thank you for choosing Nuvation Energy.

Nuvation Energy products are enterprise-grade energy systems components which facilitate fast time to market, exceptional system performance, and flexible custom tuned operation.

1.1. About this Application Note

This Application Note applies to the passive balancing algorithm provided by G5 High-Voltage BMS called continuous balancing. The algorithm increases the operational time of a battery stack and minimizes the time spent balancing cells. This document provides guidelines on configuring the continuous balancing algorithm, specifically:

1. The frequency of conducting maintenance cycles.
2. The time required to conduct balancing.
3. Adjustments that can be made to the LFP OCV curve to improve balancing performance.

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2. Overview

Traditional voltage based balancing requires that the cells are maintained at a specific voltage range for the entire duration of balancing. For this type of operation, the battery stack can be offline for hours to allow cell balancing to complete.

G5 High-Voltage BMS introduces a passive balancing algorithm, called continuous balancing, where the algorithm calculates the exact amount of charge per cell that needs to be removed in order to bring the stack to a balanced state. This estimated charge is referred to as imbalance and this value is used to balance the stack during operation. To generate reliable imbalance estimates for a battery stack, the cells in the stack often need to be within a specific SOC range. This is referred to as the estimation window and the size of this window depends on the battery chemistry. For example, one estimation window occurs between 99% and 100% for LFP. To ensure all the cells get to this region, a maintenance cycle can be conducted, where all the cells are charged to full. Another estimation window occurs between 5% and 0% for LFP and in this case, the entire battery stack needs to be discharged to empty.

Therefore, the frequency at which this type of maintenance cycle is conducted is the key parameter in determining how well the balancing algorithm will perform. The next section will provide guidelines on how to ensure the balancing algorithm converges for a specific application.

3. Balancing guidelines

3.1. Maintenance frequency

There are two key parameters that determine how often charge to full or discharge to empty needs to occur to ensure convergence of imbalance. Note that this type of maintenance cycle should be conducted following the G5 High-Voltage BMS’s current limits.

1. Imbalance per day: For this document, the amount of stack imbalance generated in a single day will be represented by Δ_{SOC}. The value can be determined experimentally and is a result of variation in coulombic efficiency and self-discharge of the cells in the stack. A fairly conservative value of imbalance per day is 0.1%/day.
2. Imbalance estimation region: The value of this parameters is denoted by δ_{SOC} and it represents the change in SOC at the top of the charge cycle or bottom of the discharge cycle, where reliable imbalance estimates can be generated. Some typical values for LFP, NMC and LMO Li-Ion chemistries are shown below. For example, the LFP open circuit voltage is generally flat from 70% SOC to 99% SOC. Therefore, imbalance can be estimated within the top 1% SOC region.

Table 1. Continuous Balancing: OCV curve estimation region

Cell Chemistry	Top imbalance estimation region (%)	Bottom imbalance estimation region (%)
LFP	1	5
NMC	20	20
LMO	20	20

The parameters Δ_{SOC} and δ_{SOC} are a function of the cell chemistry and use-case and

> need to be determined experimentally. Using the typical values provided above might not be appropriate for your specific application.

When estimation occurs at the top of the SOC region, the balancing that is conducted is referred to as top balancing. Top balancing ensures that the SOCs of all the cells reach 100% SOC at the same time. In a similar way, when estimation occurs at the bottom of the SOC region, it is referred to as bottom balancing. Often cells can have slightly different capacities and the SOC range for cells can be different depending on if they are top balanced or bottom balanced. The figure below shows the SOC range for both top and bottom balanced cells.

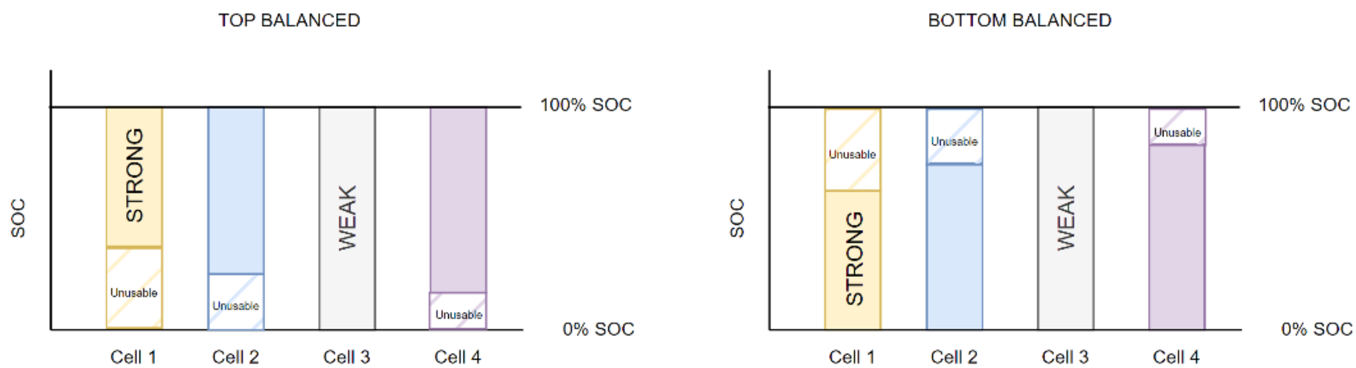

Figure 1. SOC range for top and bottom balancing.

In this example, the stack has four batteries with varying capacities. The cell labeled strong has the highest capacity while the cell labeled weak has the lowest capacity.

> It is important to either use top or bottom balancing. Using both will result in just moving around the reference point for cell SOC and potentially wasting energy.

The minimum requirement of how often the stack needs to be calibrated by charging to full or discharging to empty, represented by $t_{cal\_cyc\_req}$ in days, can be determined using the following equation:

$$t_{cal\_cyc\_req} = \frac{\delta_{SOC}}{\Delta_{SOC}}$$

For example, if the amount of imbalance generated in a single day is Δ_{SOC}=0.1% and SOC window is δ_{SOC}=1%

$$t_{cal\_cyc\_req} = \frac{1\%}{0.1\%/day}$$

$$t_{cal\_cyc\_req} = 10days$$

> The value of $t_{cal\_cyc\_req}$ calculated above is a general guideline and the ESS operator

> can increase/decrease the top-up frequency based on battery operation. For example, if after charging to full, it is determined that all the cells are within δ_{SOC}, then the next top-up period can be increased. On the other hand, if a cell falls below the δ_{SOC} region, then the time between calibration cycles can be decreased.

3.2. BMS balancing time

If a large imbalance in the stack has developed due to not charging up at the frequency described above, you will need to do multiple calibration cycles at a shorter period. The smallest amount of time between consecutive top-up cycles is based on the time required for the BMS to conduct balancing with a imbalance as large as δ_{SOC}. This value is calculated below:

$$t_{bms\_bal} = \frac{C_{stack} \cdot \delta_{SOC}}{\frac{V_{nominal}}{R_{nominal}} \cdot D_{Balance}} \cdot \frac{1}{1 - D_{thermal}}$$

Where:

1. C_{stack} is the capacity of the battery stack in Ampere hours
2. δ_{SOC} is the difference between the highest and lowest SOC values in the imbalance estimation region. For LFP, 1% SOC is a typical estimate at the top of the charge cycle. This would be represented as 0.01 in the actual calculation.
3. $V_{nominal}$ is the average balancing voltage across the range of SOC where balancing is performed. For LFP, 3.3 V is a good estimate.
4. $R_{nominal}$ is the balancing resistance in Ohms. For Gen 5, this is 26 Ohms.
5. $D_{Balance}$ is the balancing duty cycle, typically 0.9 for a 1 second CI scan period. In general, the value is the CI scan period (in ms) minus 100 ms, divided by the CI scan period.
6. $D_{thermal}$ is a factor that accounts for time spent not balancing due to thermal throttling. If balancing is turned off for 10% of the time due to thermal throttling, then the value of $D_{thermal}$ is 0.1.

For example, if C_{stack} = 280 Ah, δ_{SOC} = 1%, $V_{nominal}$ = 3.3 V, $R_{nominal}$ = 26 Ohms, $D_{Balance}$ = 0.92, $D_{thermal}$ 0.1, the time required to conduct balancing is:

$$t_{bms\_bal} = \frac{280Ah \cdot 0.01}{\frac{3.3V}{26Ohms} \cdot 0.92} \cdot \frac{1}{1 - 0.1}$$

If a large amount of imbalance has occurred, then multiple calibration at a period defined by t_{bms_bal} is required to bring the battery to a balanced state.

3.3. Adjustments to OCV curve

The continuous balancing algorithm utilizes a basic cell model to describe the activation and concentration polarization effects in the battery. However, at the very end of the charge cycle, the polarization effects increase significantly, and the model does not capture this effect. Therefore, a minor adjustment can be made to the OCV curve to capture this.

When estimating imbalance at the top of the charge cycle, set:

```
stack_ocv_lut[100].open_circuit_voltage equal to stack_soc[0].vfull
```

When estimating imbalance at the bottom of the charge cycle, set:

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stack_ocv_lut[0].open_circuit_voltage equal to stack_soc[0].vempty
```

The remainder of the OCV curve can be set based on the manufacturer's specifications.

> Additional adjustments to the OCV curve could be made to improve performance based on experimental data. Please contact Nuvation Support for assistance in this process.