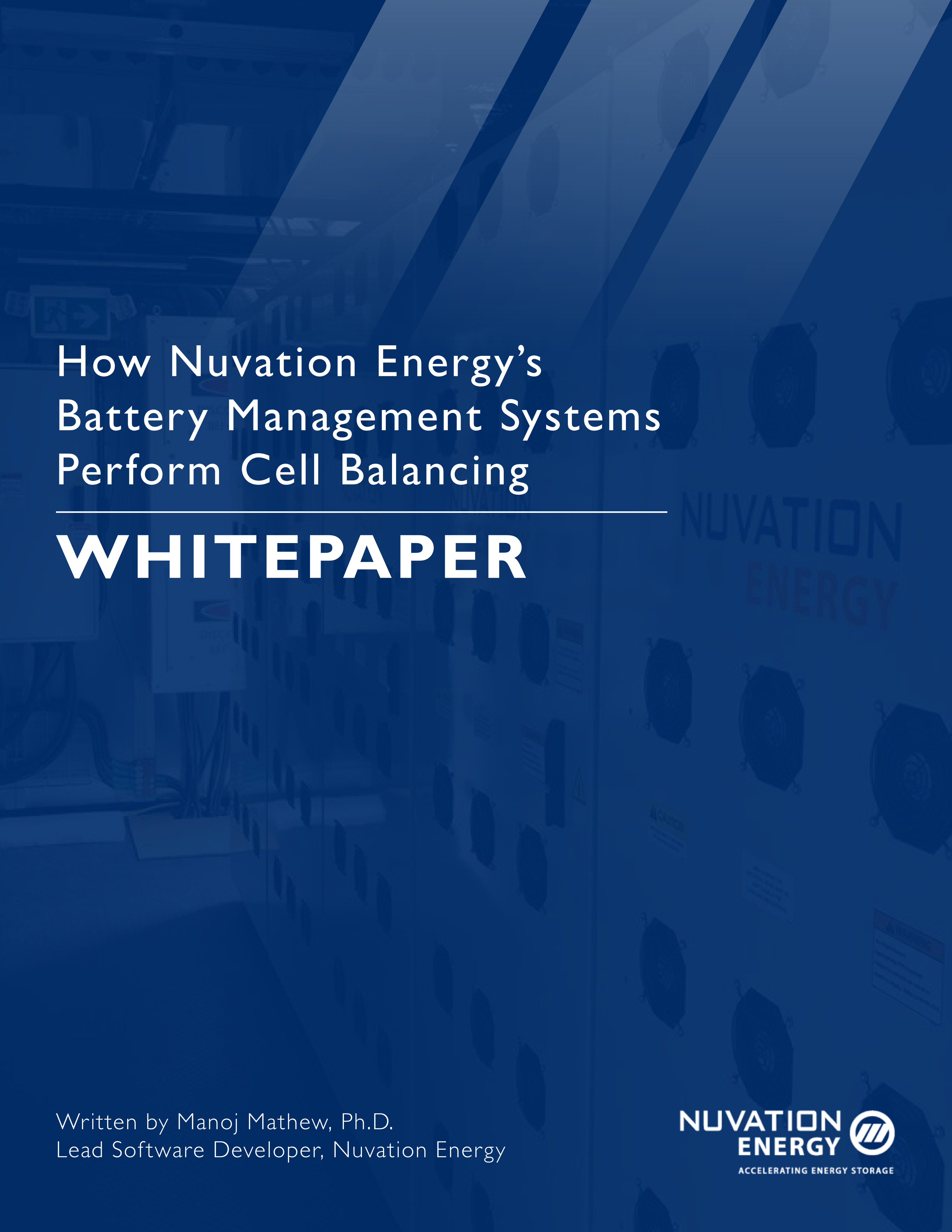

How Nuvation Energy's Battery Management Systems Perform Cell Balancing

WHITEPAPER

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Introduction

The goal of this paper is to describe how Nuvation Energy's battery management systems perform cell balancing in lithium-ion and other battery chemistries. We will also explore how cell balancing can be simulated in software, and the benefits of simulation. This paper will:

- Define cell balancing and explore the causes of imbalance in series-connected cells.
- Describe how Nuvation Energy's battery management systems perform cell balancing.
- Present Nuvation Energy's balancing simulation framework.

Battery Management Terms

In the battery industry certain terms can create confusion when not explicitly defined, due to potential variations in interpretation. This paper will begin by explaining how Nuvation Energy defines cell balancing and a few other key terms.

Cell Balancing

Cell balancing refers to the process of maintaining an equivalent amount of charge in series-connected cells. A grouping of series-connected cells is referred to as a battery "*string*" or "*stack*", with Nuvation Energy preferring the term "*stack*". We consider a stack to be *balanced* if all the series-connected cells are at the same state of charge (SOC) when the stack is fully charged. *Balancing* is a charge management process performed by the battery management system to ensure the stack is balanced, and that no cells are overcharged or overdischarged in the process.

Passive balancing and *active balancing* are the two commonly used approaches for balancing cells. Nuvation Energy's battery management systems employ passive balancing.

- *Passive balancing* involves maintaining equal charge across all cells by dissipating energy from cells with a higher charge to ensure that all cells in the pack charge and discharge at the same rate. This enables all cells in the stack to become fully charged at the same time. Since battery cells in a module are usually very closely matched in their State of Health and the rate at which they charge and discharge, imbalance is a condition which tends to gradually build up over a period of weeks.

- *Active balancing* involves transferring energy from a cell with excess charge to one with less charge, as opposed to dissipating it as heat. While active balancing is highly efficient, it is also more expensive than passive balancing because electronics must be connected to every cell. Passive balancing is the dominant type of balancing employed today, largely because of this cost difference. Exceptions are environments where cost is a much lower priority than efficiency and battery lifespan.

Importance of Cell Balancing

To better understand the importance of maintaining a balanced stack, consider Figure 1 and Figure 2 below. In both diagrams, we have three lithium-ion cells connected in series, each having different SOC values before they begin charging and discharging.[1]

In Figure 1, the stack is being charged to full while balancing is disabled. During the charging process, current is usually stopped when any single cell in the stack reaches full, to prevent damage to that cell. This is illustrated in the image on the right side of Figure 1; although cells #1 and #3 can accept additional charge, the charging process has been stopped because cell #2 is full.

Figure 2 helps us understand just how important balancing is to maximize the available energy in all cells in a stack. In Figure 2 the unbalanced stack is being discharged to empty. That process is halted when cell #3 is fully depleted, leaving a significant amount of unused energy in cells #1 and #2. All that unused energy would have been dissipated as heat had balancing been applied, but it is unavailable regardless because the discharge process was stopped when the cell with the smallest charge reached empty. Although energy dissipated during balancing is technically "wasted", the balancing process is essential because it allows all cells to receive equal amounts of energy during subsequent charge cycles, maximizing the total energy available during the discharge cycles.

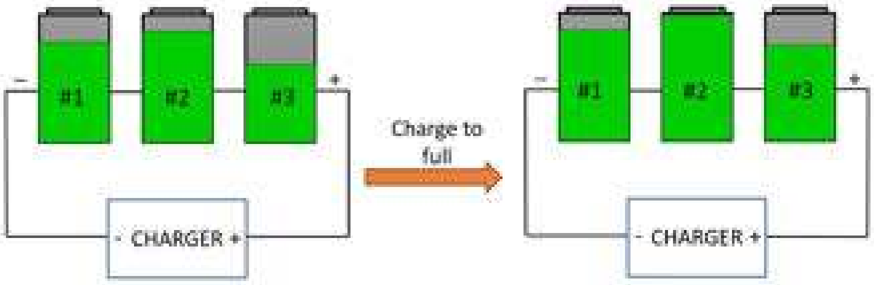

Figure 1 *– Left side: One battery stack with three series-connected cells of different SOC values. The stack is charged to full, with balancing disabled. Right side: Charging has been stopped to protect the cell that has first reached full (#2), leaving the remaining cells not fully charged.*

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[1] Note that the high degree of imbalance shown in Figures 1 and 2 is not commonly observed in practical applications and has been exaggerated in the diagrams for illustrative purposes.

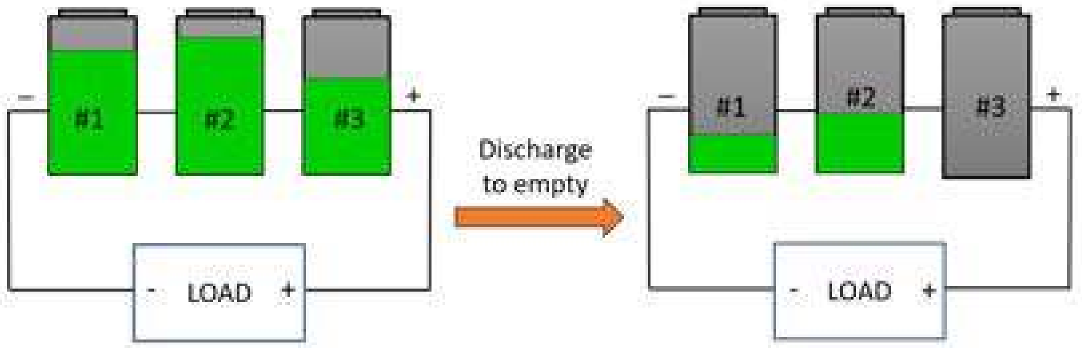


Figure 2 *– Left side: One battery stack with three series-connected cells of different SOC values. The unbalanced stack is discharged to empty. Right side: Discharging has been stopped to protect the cell that has reached empty (#3), leaving unused charge in the remaining cells.*

Causes of Imbalance

If the battery stack is initially balanced, it is possible to become imbalanced again during operation. There are three main factors that can lead to stack imbalance.

- **Coulombic efficiency:** One of the main reasons why a battery stack can become imbalanced during operation is due to differences in coulombic efficiency within cells. The coulombic efficiency (η) is the ratio of the total charge that can be extracted from the battery ($Q_{extract}$) to the total charge required to bring the battery to full ($Q_{required}$).

$$\eta = \frac{Q_{extract}}{Q_{required}}$$

  The difference between $Q_{extract}$ and $Q_{required}$ is caused by unwanted chemical reactions that occur within the cell. Since each cell might have a slightly different coulombic efficiency, imbalance in the stack can grow over time.

- **Self-discharge:** Batteries at rest slowly discharge by themselves due to unwanted chemical reactions that occur within the cell. Self-discharge decreases the SOC even when the battery is at rest. Differences in self-discharge rates of individual cells can contribute to stack imbalance over time.
- **Temperature distributions:** Variability in the thermal and electrical properties of individual cells can often result in cells having different temperature distributions. Although temperature is not a direct factor in creating imbalance, it can significantly affect the self-discharge rate of the cell, which can lead to imbalances in the stack.

It should be noted that if all the cells in the stack were degraded but had the same coulombic efficiency and self-discharge rate, the stack would still remain balanced. It is variability between cells that causes imbalance to occur.

Balancing Using Nuvation Energy’s BMS

Nuvation Energy’s Balancing Solution

Nuvation Energy’s Cell Interface module supports the passive balancing of each cell. Passive balancing involves drawing excess charge from a cell and dissipating this energy as heat. Balancing can be executed continuously regardless of whether the battery is connected to the DC bus or not. An equivalent circuit is shown in Figure 3 to illustrate some of the properties of a passive balancing system.

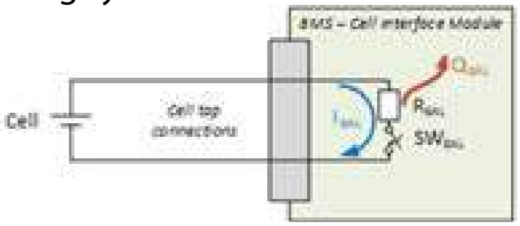


Figure 3 *– Cell Balancing: Equivalent Circuit.*

Cell Interface modules include a balance resistor R_{BAL} which dissipates the balancing energy as heat (Q_{BAL}). During battery operation or while at rest, energy in cells with higher charge is dissipated using the above circuit. The amount of balance current drawn is dependent on the cell voltage.

In addition to bleeding off balancing current, the single cell tap connection shown above is also used to measure cell voltage. To obtain an accurate voltage measurement, the balancing circuit must be disabled and the transient effects associated with balancing current flow allowed to settle. Since balancing current is disabled while the BMS takes voltage measurements, the balancing duty cycle is less than 100%.

Nuvation Energy provides several configurable settings to fine-tune the passive balancing algorithm based on the operating conditions. For example:

- Configuration registers can be set so that balancing will only occur while charging.
- Balancing can be configured to occur during charging or when discharging at a very low current.
- The algorithm can be configured to enable balancing after a specific terminal voltage threshold has been exceeded for an individual cell.
- The balancing duty cycle can be adjusted using a configurable BMS register. A lower duty cycle means a smaller amount of heat is generated during balancing, which can be beneficial for battery systems that have poor thermal management.

These configurable settings provide flexibility in how the balancing algorithm is executed, enabling the Nuvation Energy BMS to be configured for a wide range of battery chemistries and performance characteristics.

Nuvation Energy's Balancing Capabilities

To better understand the balancing capabilities of Nuvation Energy battery management systems, suppose we have *n* cells in a stack, and the deviation between the cells with the lowest and highest SOC is represented as *max SOC deviation*. Assuming no current is flowing (battery stack at rest), and all balancing is performed using a 13 Ohm resistor, the time required to fully balance the stack can be determined as a function of the max SOC deviation and the battery capacity. This is illustrated in Figure 4. For this example, the balancing duty cycle was taken to be 90%.

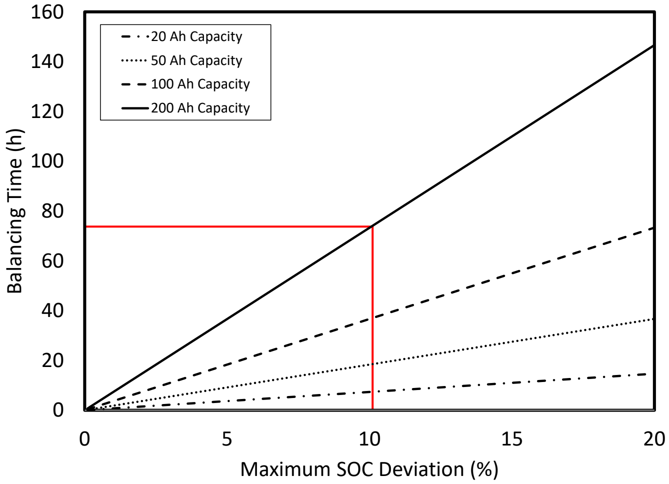


Figure 4 *– Time required for balancing as a function of the SOC deviation for different battery capacities. In this example, balancing is being performed using a 13 Ohm resistor.*

The graph in Figure 4 can be used to determine the balancing capabilities for a specific application. For example, balancing a 200 Ah stack with the maximum SOC deviation of 10% will require around 72 hours (red line in Figure 4).

Simulation Case Study

The hardware balancing solution described above can be simulated in software using a battery model and a BMS simulator. Nuvation Energy has created a software-based simulator that enables our engineers to test different battery management configuration settings without the need for bulky and expensive test equipment. Using this simulation framework enables one to safely validate how the BMS will respond to a range of battery profiles as well as module and stack configurations, and to fine-tune the balancing algorithm configuration settings prior to deployment.

Simulation Set-up

The two key components that make up this simulation framework are the stack BMS simulator and battery model. These two components are described in greater detail below.

Stack BMS simulator

Nuvation Energy has developed a stack simulator that can emulate most of Nuvation Energy's BMS functionality in software. It contains Modbus TCP and HTTP interfaces that accept measurement data such as voltage, temperature, and stack current. The battery measurement data in this case study was generated using the model described below. Upon receiving the measurements, the BMS algorithms in the simulator were executed, and the BMS's simulated output was recorded. The BMS simulator specified which cells should be balanced, and based on this information, the appropriate balancing current was dissipated from those specific cells.

Battery Model

A stack comprised of 8 lithium-iron phosphate cells with varying electrical properties (to guarantee that imbalance will occur) was simulated using one of several battery models developed by Nuvation Energy. The battery voltage response is described by an equivalent circuit model with an open circuit voltage source (V_{ocv}), a single resistor (R_0) in series with a resistor-capacitor pair (R_1 and C_1). The circuit is illustrated in Figure 5 below.

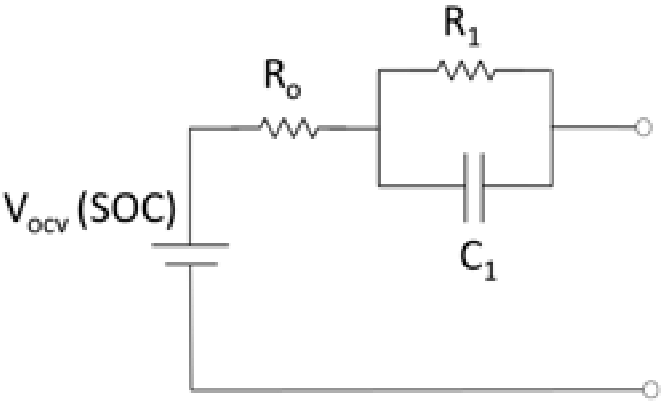
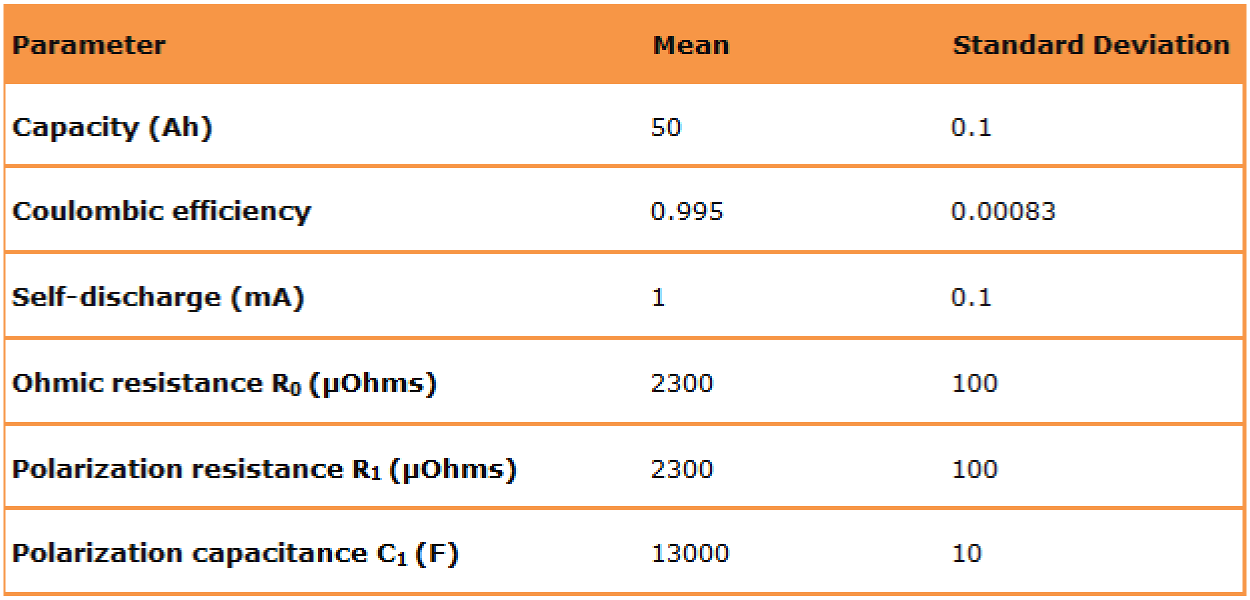


Figure 5 *– Equivalent circuit model used in the closed-loop balancing simulation.*

The electrical properties of the cells were randomly sampled from a normal distribution with a given mean and standard deviation (Table 1).



Parameter	Mean	Standard Deviation
Capacity (Ah)	50	0.1
Coulombic efficiency	0.995	0.00083
Self-discharge (mA)	1	0.1
Ohmic resistance R_0 (μOhms)	2300	100
Polarization resistance R_1 (μOhms)	2300	100
Polarization capacitance C_1 (F)	13000	10

Table 1 *– Mean and standard deviation for variable parameters.*

Note that the value of coulombic efficiency and self-discharge must be determined using carefully designed experiments. In addition, connecting multiple cells in parallel will reduce the variance of coulombic efficiency while keeping the mean value constant. A reduction in the variance means less imbalance for the battery stack.

Simulation Results/Discussion

A closed-loop balancing simulation was executed using the battery model and stack BMS simulator described above. Multiple charge and discharge cycles were conducted with an applied current of 1C. The cell voltage, stack current and stack SOC for the first 2 cycles are shown in Figure 6. The cycles were repeated 80 times for seven consecutive days.

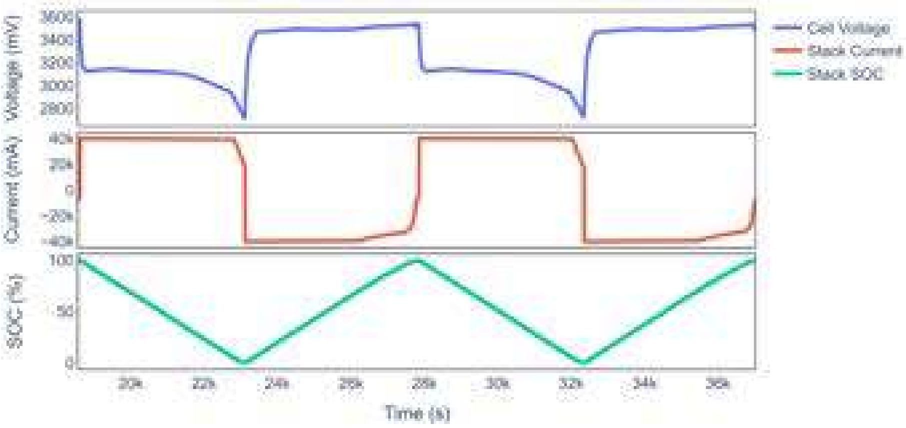


Figure 6 *– Cell voltage, stack current and stack SOC for the first two cycles in the simulation.*

The gradual decrease seen in the applied current as the SOC reaches 0% and 100% is a result of the *current limiting* feature of Nuvation Energy's BMS. The purpose of current limiting is to prevent overcharge/over-discharge by scaling back the current as the cells approach the upper and lower voltage limits.

To illustrate the importance of balancing, consider two simulations: one with the BMS simulator balancing algorithm enabled, and one with the algorithm disabled. The results are shown below.

Balancing disabled

Even if the stack is balanced, it can become unbalanced during operation. With the BMS balancing algorithm disabled, the following voltage response (Figure 7) was obtained for the 8 cells in the stack during the first and last charge cycle out of 80 cycles.

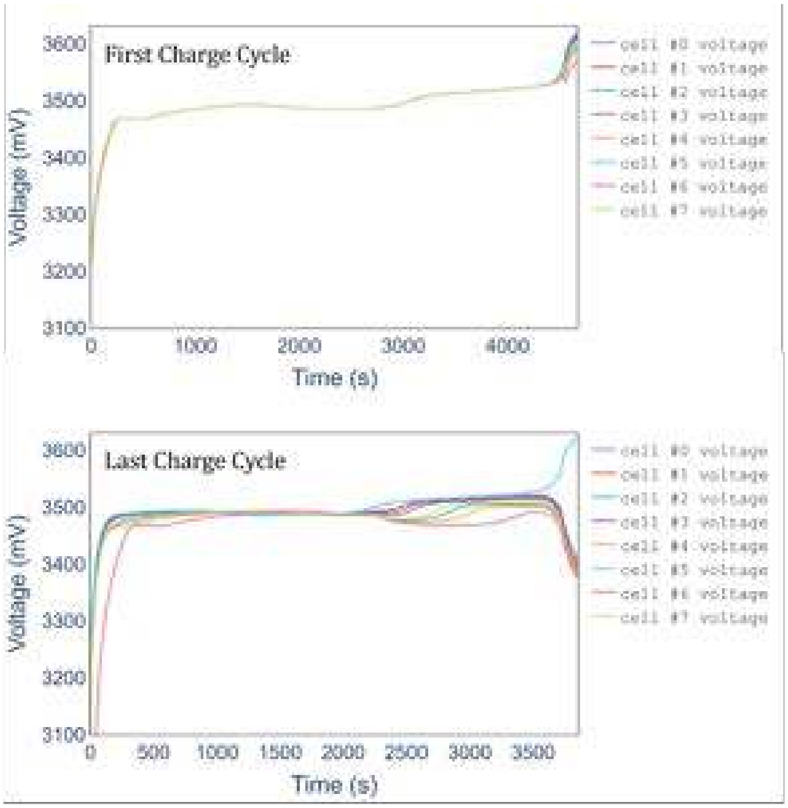


Figure 7 – *The voltage response for all 8 cells in the battery stack for the first and last charge cycle out of 80 cycles, with the balancing algorithm disabled.*

As illustrated in Figure 7, when balancing is disabled the cell voltages for individual cells in the stack will continue to diverge over time; examining the last charge cycle in Figure 7, it is evident that the voltage profiles of the cells are significantly different from each other after 2200 seconds. This deviation in the voltage profile is also reflected in the stack capacity, since its value is limited by the first cell to charge to full and the first cell to discharge to empty. The stack capacity will continue to decrease over time, as illustrated in Figure 8.

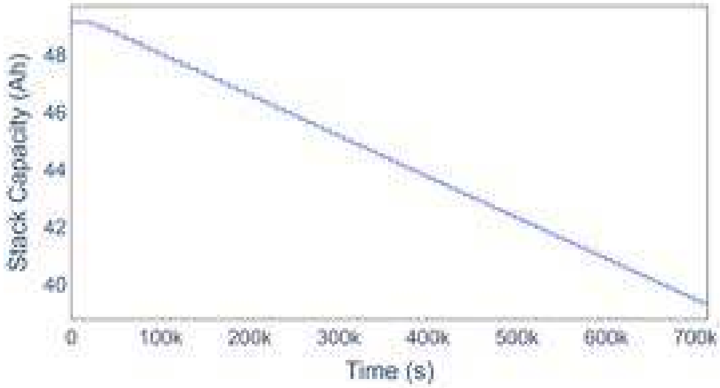


Figure 8 – *The total capacity of the battery stack over time during a simulation of 80 cycles run with the balancing algorithm disabled.*

These simulations illustrate why a balancing algorithm is essential for ensuring that each battery stack in the ESS delivers the amount of energy it has been designed to provide.

Balancing enabled

The same simulation was then re-run, this time with the BMS balancing algorithm enabled.

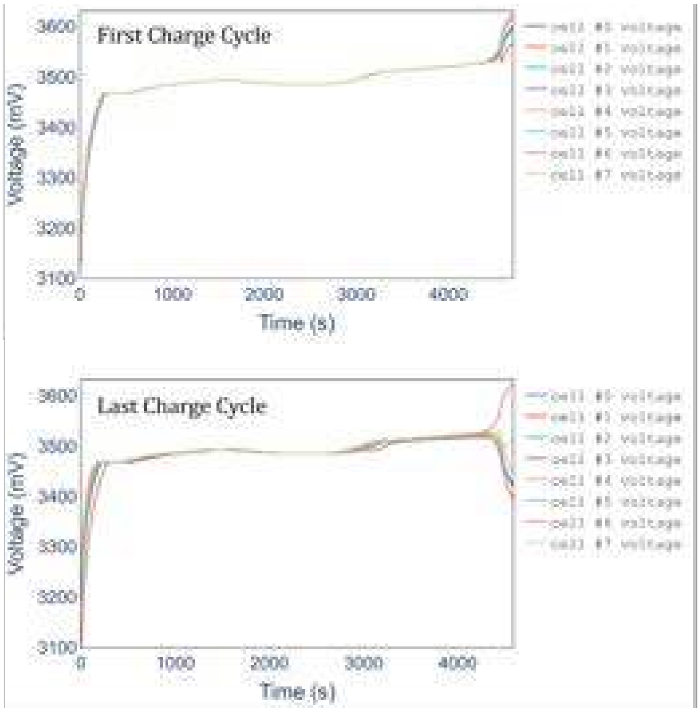


Figure 9 – *The voltage response for all 8 cells in the battery stack for the first and last charge cycle, with balancing enabled.*

With balancing enabled while running 80 cycles over 7 days, there were only minor deviations in the voltage profiles of all 8 cells. During operation, the level of charge in the cells with a higher SOC was gradually reduced by the BMS to ensure that all the cells in the stack eventually reached a similar SOC. Figure 10 below shows that unlike the unbalanced stack in Figure 8, when balancing was enabled the battery stack capacity did not gradually decrease over time, and instead reached a steady state.

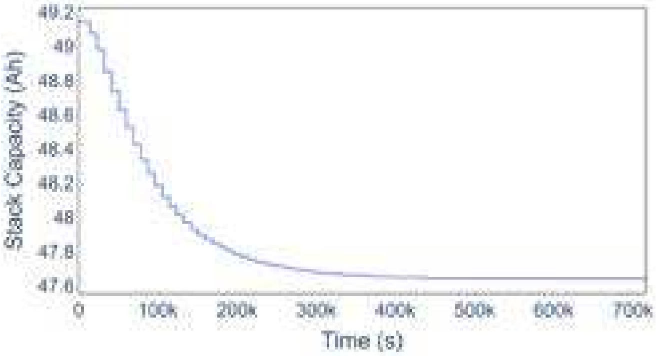


***Figure 10 –** The capacity of the battery stack during the entire simulation, with balancing enabled.*

The final steady state value of the stack capacity is dependent on a number of balancing algorithm parameters, most important of which is the voltage delta. The value of this parameter can be configured using the BMS register *stack_cell_balancer.voltage_delta*. This parameter represents the maximum deviation in terminal voltage between cells that is allowable before balancing is triggered.

Figure 11 shows the decay of stack capacity for different voltage delta values.

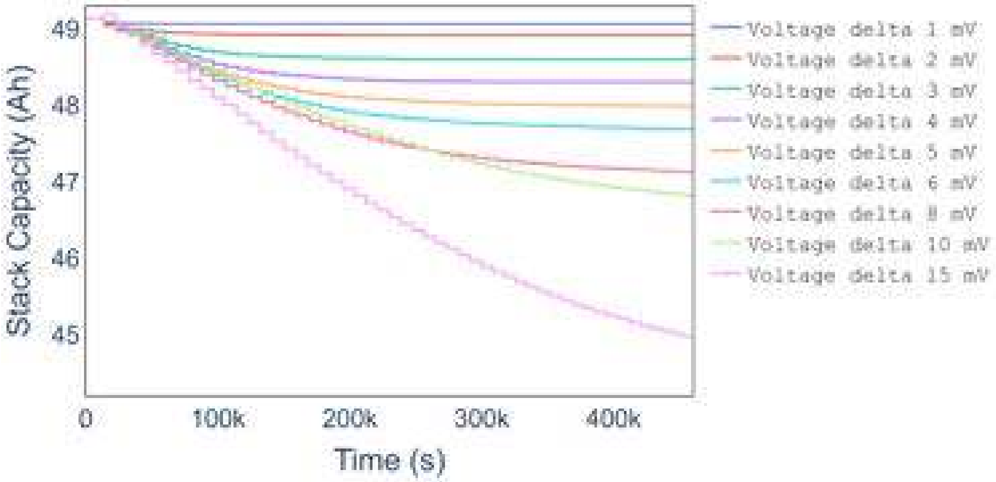


***Figure 11 –** The capacity of the battery stack for different values of voltage delta in the BMS balancing algorithm.*

Figure 11 illustrates the importance of accurately selecting a reasonable value for voltage delta in the BMS. Failure to do so will result in a large portion of the total capacity remaining unused during operation. By using this simulation framework, the balancing operation of the BMS can be accurately predicted and the algorithm parameters fine-tuned for optimal performance.

Conclusions

We hope that this paper provided a deeper understanding of the cell balancing solution implemented in Nuvation Energy's battery management system, and how it can be simulated in software for testing, integration, and optimization prior to deployment.

Some of the key takeaways are:

- Without a robust cell balancing algorithm, the amount of energy available from the stack will gradually decrease over time.
- It is variability in the cell's coulombic efficiency and self-discharge that leads to stack imbalance.
- Nuvation Energy offers a highly configurable balancing solution that can be tailored for any lithium-ion battery.
- Nuvation Energy has the capability of running closed-loop cell balancing simulations using proprietary models and algorithms. Not only do these simulations provide new insights into stack imbalance for different battery chemistries, but they also allow Nuvation Energy's BMS engineers to tune the balancing algorithm for a wide range of different battery profiles.

We are confident our cell balancing solution will allow you to maximize the usable energy in your ESS and operate your system in a safe and efficient manner. Contact Nuvation Energy or call (855)-261-0507 to discuss your battery management requirements.

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