APPLICATION NOTE

Automotive BMS Validation with a Four-Channel DC Power Supply

Ensuring reliable cell balancing, overvoltage, and undervoltage protection for LiFePO4 battery packs

KEYSIGHT

Introduction

The surge in electric vehicles has increased demand for LiFePO4 batteries, in turn driving the need for battery management systems (BMS). Manufacturers must thoroughly test BMS features before installing them in vehicles. BMS testing aims to simulate real-world conditions, such as cell balancing, overvoltage protection, and undervoltage, to ensure that these features work as intended to protect the battery pack.

The BMS testing includes the following:

- **Voltage imbalance simulation** to evaluate the BMS cell balancing function.
- **Overvoltage protection simulation** to verify the BMS response to cells exceeding safe voltage thresholds.
- **Undervoltage protection simulation** to ensure that the BMS can detect and respond to low-voltage conditions.

This application note outlines the testing methodology, tools, and detailed results of the BMS condition simulations conducted with a 400 W four-channel DC power supply.

The four-channel DC power supply used is part of the Keysight Smart Bench Essentials Plus suite of instruments. This elevated set of basic instruments — power supply, waveform generator, digital multimeter, and oscilloscope — comes with proven pro-level measurement technologies that deliver precision and reliability. The instruments include large color screen displays and graphical interfaces to visualize, analyze, and share test results quickly.

Battery Management System

The BMS ensures the safety, reliability, and longevity of battery packs by monitoring and managing the State of Charge (SOC), state of health, and temperature of individual cells. It usually includes features such as cell balancing, overvoltage protection, and undervoltage protection to prevent damage and optimize performance.

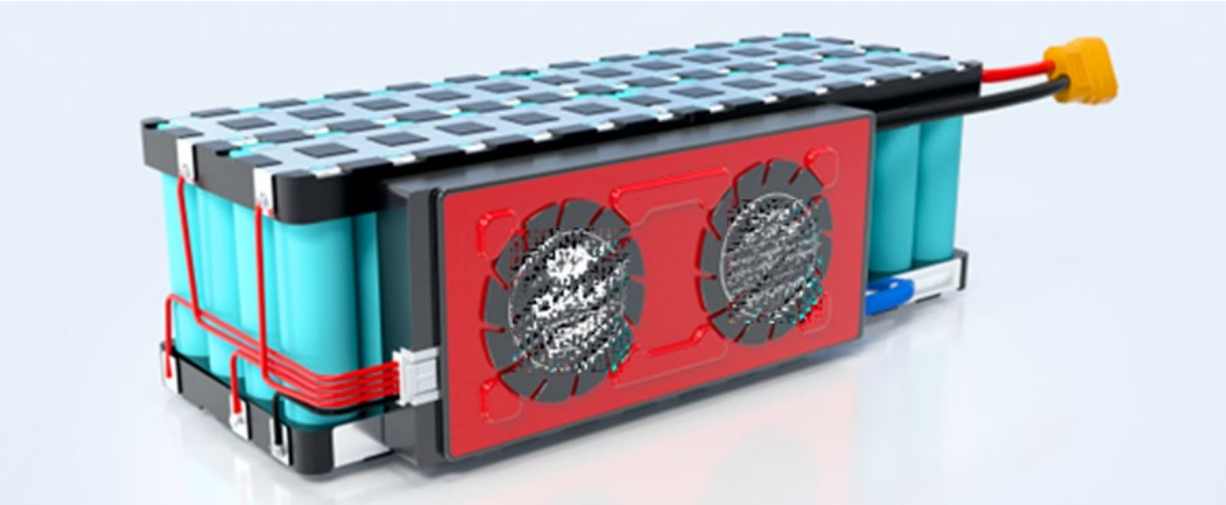


Figure 1. 4S BMS on a battery pack

The terms 3S, 4S, and 5S indicate the number of cells connected in series in a battery pack, where the “S” stands for series. Cells in series increase the total voltage of the pack while maintaining the current capacity. For example, a 3S configuration (three cells) with 3.6 V LiFePO4 produces a nominal voltage of 10.8 V. In comparison, a 4S (four cells) results in 14.4 V.

These series configurations are crucial for determining the overall pack voltage, ensuring compatibility with system requirements, and enabling proper monitoring and balancing by the BMS. Figure 1 shows that the sampling cable has five wires, although it is a 4S BMS, consisting of one black and four red wires. The black wire is the ground, while the red wires are for sampling and monitoring each cell.

Test Setup and Configuration

Prerequisites

Prepare the following:

- 4S battery management system
- BMS *Bluetooth*® dongle
- Keysight E36441A Smart Bench Essentials Plus four-channel DC bench power supply
- 5 crocodile clip wires

Caution

This application note serves as a reference for multi-rail sourcing of four channels. We do not recommend connecting multiple instruments in series.

Figure 2 illustrates a connection diagram for the instruments and the BMS.

- Connect four red sampling wires to all the positive terminals (yellow, green, blue, and red) of the DC power supply.
- Connect the black sampling wire to the negative terminal of channel 1 (yellow) on the DC power supply.
- Connect the positive terminal of each channel to the negative terminal of the adjacent channel to complete the series connection.

This configuration enables the power supply to simulate four LiFePO4 battery cells connected in series. The negative terminal of channel 1 attaches to the B-terminal of the BMS. The P-terminal of the BMS remains unconnected, as no load is applied, and no charging occurs during this test.

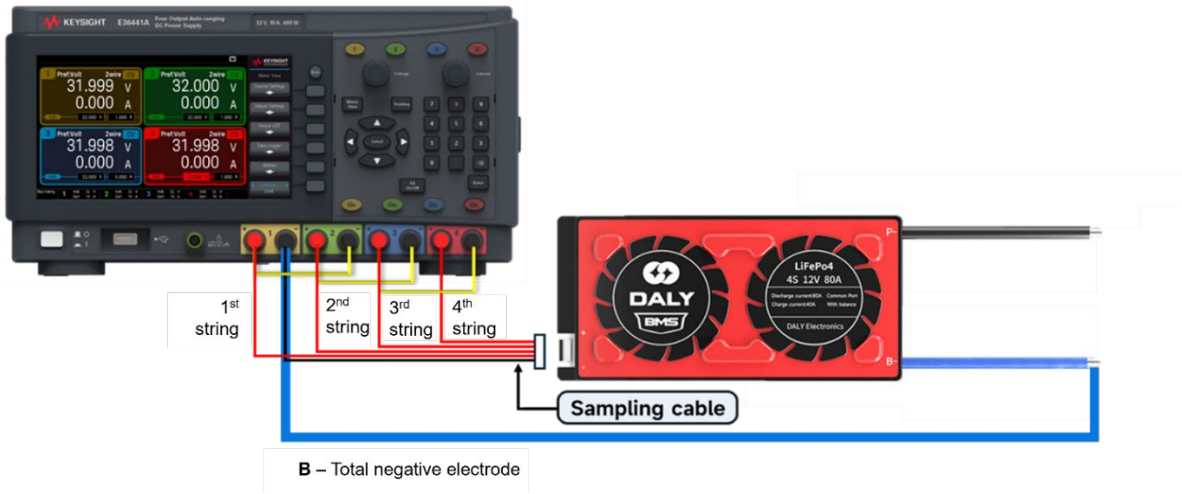


Figure 2. 4S BMS setup

To establish a connection between the smart BMS application and the hardware, plug the *Bluetooth*® dongle into the BMS. Go to the configuration menu to input the required parameters, such as the number of cells, voltage thresholds, balancing current limits, and protection settings for overvoltage, undervoltage, and overcurrent scenarios.

The screenshot in Figure 3 shows that the smart BMS application enables users to tune parameters for cell balancing. This page is designed for balancing, as it also includes SOC monitoring and temperature sensing. Ensure that all the required parameters are correctly set, then save the configuration and initiate system monitoring. Users can verify the BMS functionality under simulated conditions to ensure proper operation and response to various test scenarios.

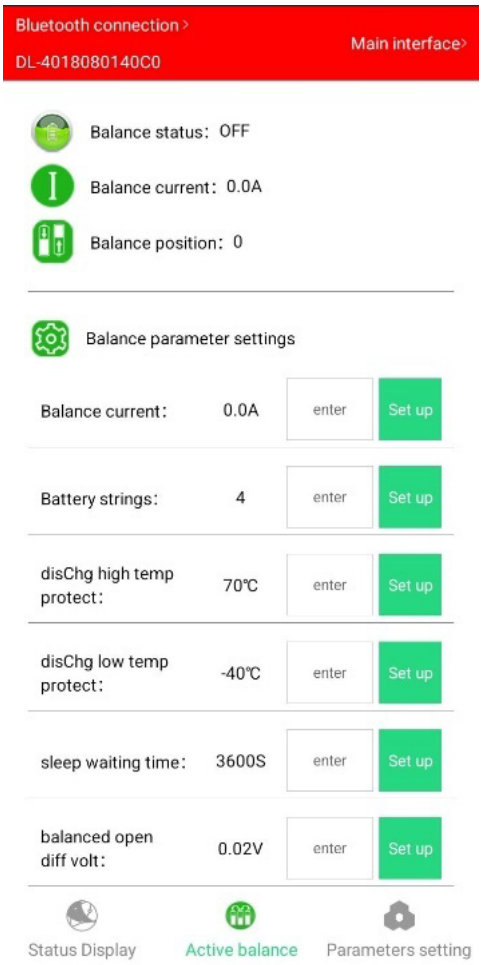


Figure 3. Smart BMS application interface

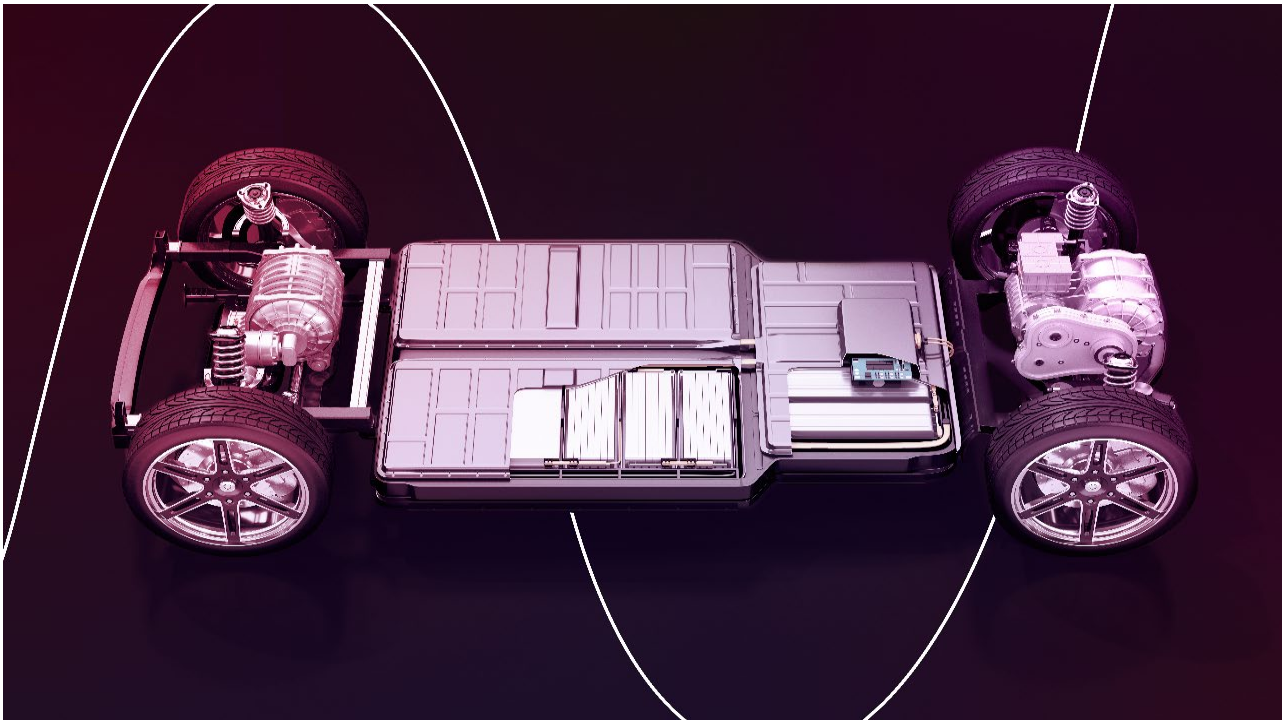
The Importance of Validating BMS Auto Balancing

The BMS auto-balancing functionality is critical in maintaining the health, efficiency, and longevity of multicell battery packs, such as those used in electric vehicles, energy storage systems, and portable electronics. Over time, individual cells in a battery pack can develop slight variations in capacity, internal resistance, and SOC caused by manufacturing tolerances, temperature variations, and aging effects. These discrepancies result in cell imbalance, where some cells charge or discharge faster than others.

A well-functioning auto-balancing algorithm addresses this issue by redistributing charge across cells, ensuring all cells remain at similar voltage and SOC levels. Validating the auto-balancing functionality ensures that the BMS can detect imbalances accurately and mitigate them effectively through passive or active balancing. Without proper validation, imbalanced cells can lead to premature aging, reduced usable capacity, and, in extreme cases, safety risks such as thermal runaway caused by overcharging or over-discharging weaker cells.

Additionally, validating BMS auto-balancing guarantees consistent pack performance under real-world operating conditions. An imbalanced battery pack cannot be fully used, as the weakest cell dictates the overall pack's limits, resulting in reduced runtime, decreased efficiency, and wasted capacity.

Manufacturers can ensure that the system maximizes energy use while safeguarding the battery pack by verifying that the BMS auto-balancing mechanism operates across varying cell voltages, current loads, and environmental conditions. Testing and validating this function under simulated scenarios using a controlled environment, such as a multichannel DC power supply, enables engineers to fine-tune the balancing algorithm, ensuring it reacts promptly to deviations. This validation process enables manufacturers to deliver robust, high-performance battery systems that meet stringent safety and reliability standards, which are essential for applications where downtime, inefficiency, or failure are unacceptable.



Active vs. passive cell balancing

Understanding the differences between active and passive cell balancing is key to managing battery packs. Both methods aim to equalize cell charges but operate differently. Let's delve into how passive and active cell balancing work and their effects on battery performance.

Passive cell balancing

Passive cell balancing is relatively straightforward as it balances the voltages of the four cells by discharging the cell with the highest voltage. The BMS draws more current from the cell with the highest voltage. The excess energy stored in the higher-voltage cell dissipates as heat through the balancing resistors. This method ensures that all cells reach a similar state of charge, preventing any single cell from becoming overcharged or undercharged, which could lead to reduced battery life or safety issues. However, this method results in the battery pack having a lower overall voltage.

Active cell balancing

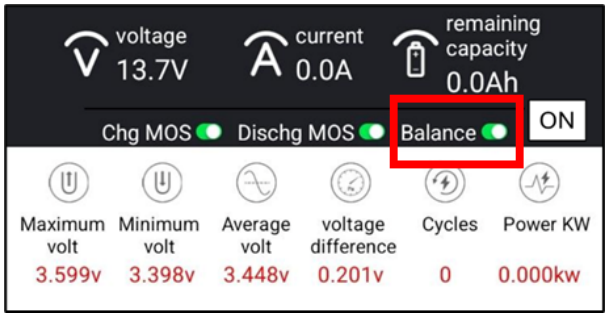
In contrast, a BMS uses active balancing to charge the cell with the lowest voltage. Instead of charging it with an external source, active balancing transfers energy from the cell with the highest voltage to the one with the lowest, using components such as capacitors and inductors. In capacitor-based active balancing, a capacitor alternately charges and discharges between cells.

The capacitor connects to a higher-voltage cell, charges up to its voltage, and then switches to a lower-voltage cell to discharge its stored energy. This cycle repeats, gradually equalizing the cell voltages. In inductor-based active balancing, inductors use magnetic energy to transfer charge between cells. An inductor connects to a higher-voltage cell and stores energy by generating a magnetic field when current flows through it. When the connection switches to a lower-voltage cell, the magnetic field collapses, releasing the stored energy into the lower-voltage cell. This method is highly efficient, as inductors can handle larger currents with minimal energy loss, making it suitable for high-capacity battery packs. Both methods allow energy to be moved rather than dissipated as heat, unlike passive balancing, improving energy efficiency and extending the runtime and lifespan of the battery pack.

Passive Balancing Simulation

Since the 4S BMS uses passive balancing, you can simulate cell balancing by creating a voltage imbalance between the cells. Begin by setting one cell to 3.6 V and the remaining three cells to 3.4 V. The BMS should detect this voltage difference and activate its balancing function to restore equilibrium. You can then observe from the smart BMS application that when the voltage difference exceeds the preset threshold, it will switch to balance mode and attempt to balance the cells, as shown in Figure 4. The balancing mode switches off when the 3.6 V cell reduces to 3.4 V.

Passive balancing on



Passive balancing off

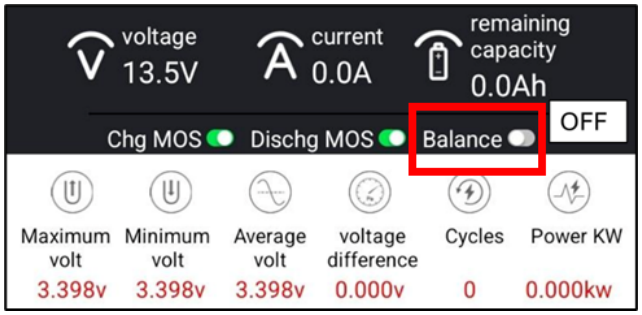


Figure 4. Passive balancing is switched on when the BMS detects the voltage imbalance

While this method is straightforward, it does not provide visibility into the behavior of the BMS after balancing. The BMS will continuously attempt to balance the voltages, but equilibrium will never be achieved as an external source cannot influence the 3.6 V power supply value. However, you can simulate this using the power supply's LIST mode. In Figure 5, an output LIST is configured to gradually increase the voltage to 3.6 V and then return to 3.4 V, simulating the equilibrium point.



Figure 5. Simulation of BMS voltage balancing using the power supply's LIST mode, where the voltage gradually increases to 3.6 V and then drops to 3.4 V, representing the achieved equilibrium

You can observe that, when running in LIST mode, the voltage increased from 3.4 V to 3.45 V, and the BMS immediately increased the current draw. The current draw did not stop until the voltage dropped back to 3.4 V.



Figure 6. Power supply data logger view showing the BMS response in LIST mode

To see the response time, change the data logger settings to track only the voltage and current of channel 1. In the vertical settings, set the Per Division of V1 to a small number to make the change in voltage more apparent in the data logger. When running the LIST mode, you can see that the response time is rapid as the BMS reacts to the sudden change in voltage by increasing the current draw.

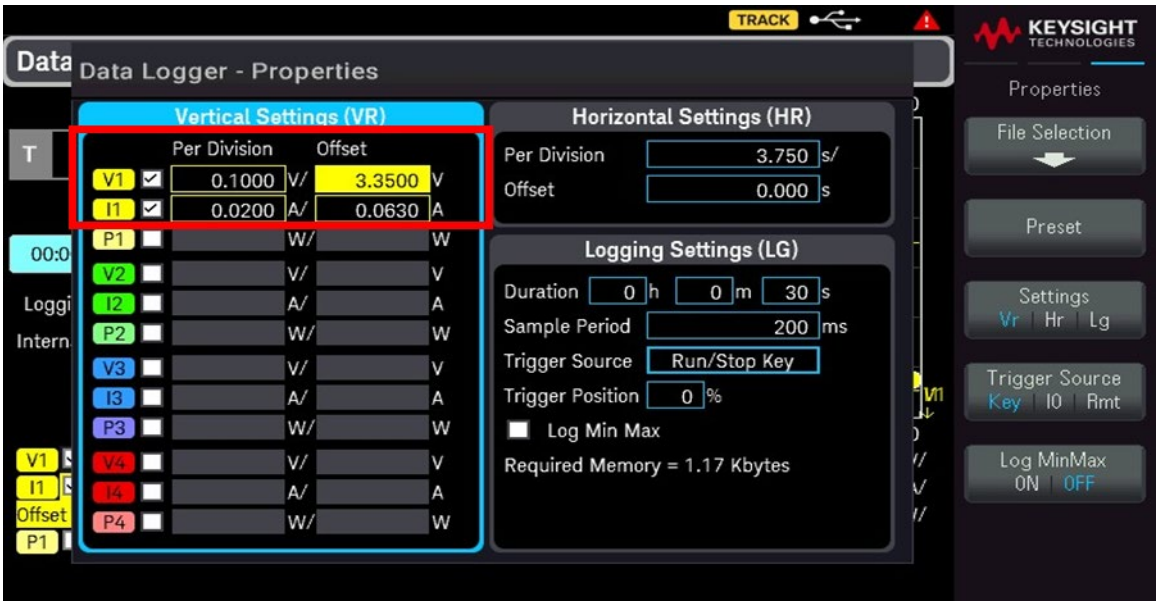


Figure 7. Power supply data logger view showing the vertical settings

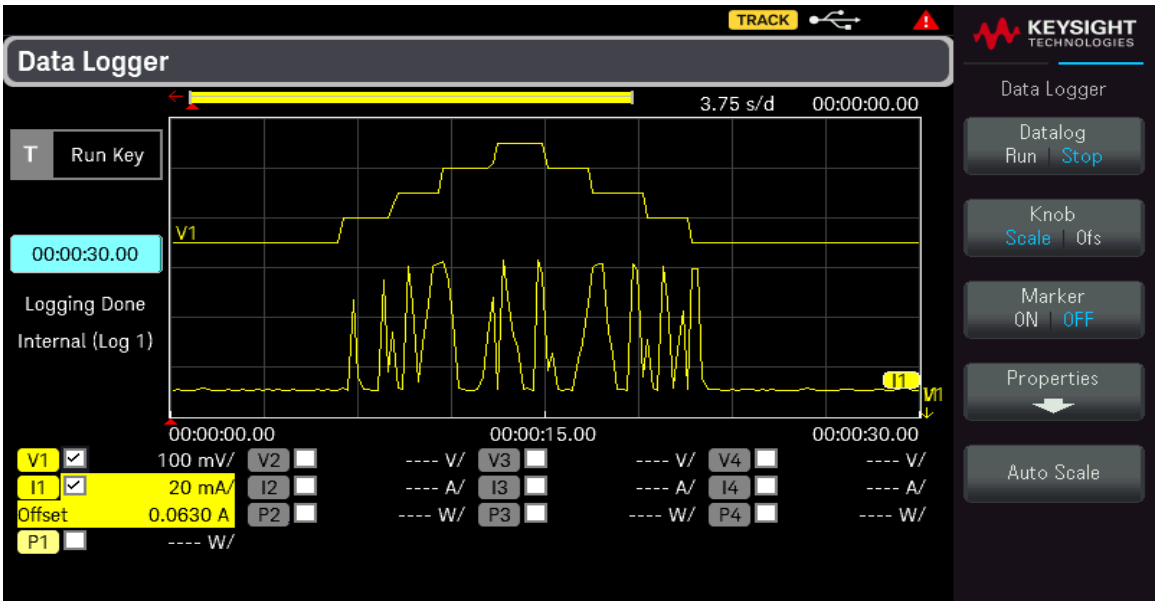


Figure 8. Power supply data logger view showing the BMS response in LIST mode, with a rapid increase in current draw

4S BMS behavior during voltage balancing

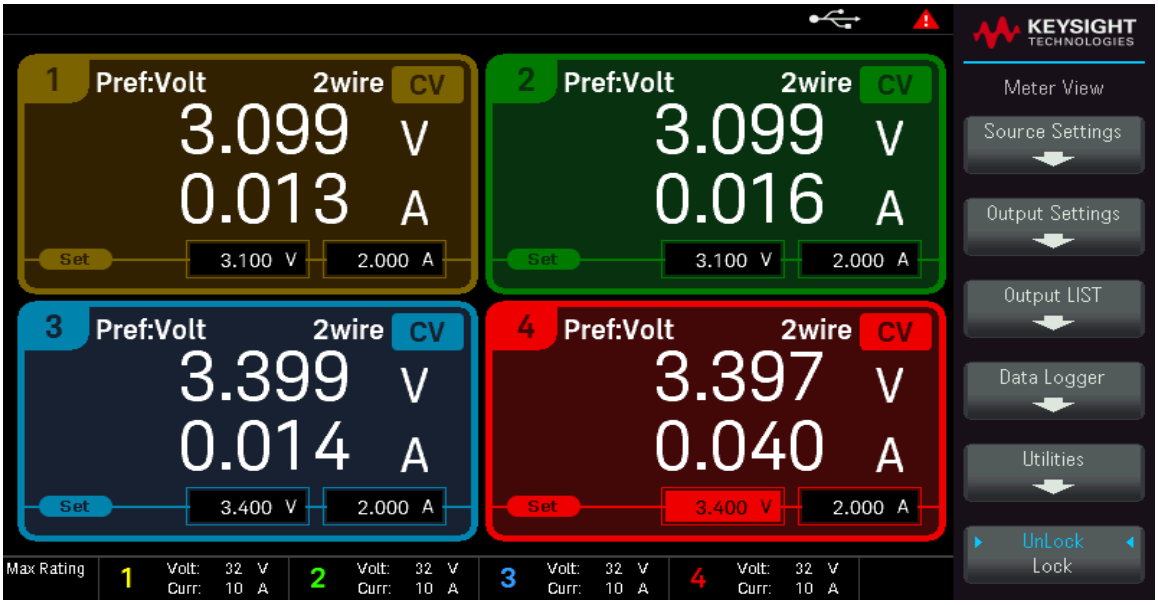


Figure 9. Power supply voltage settings

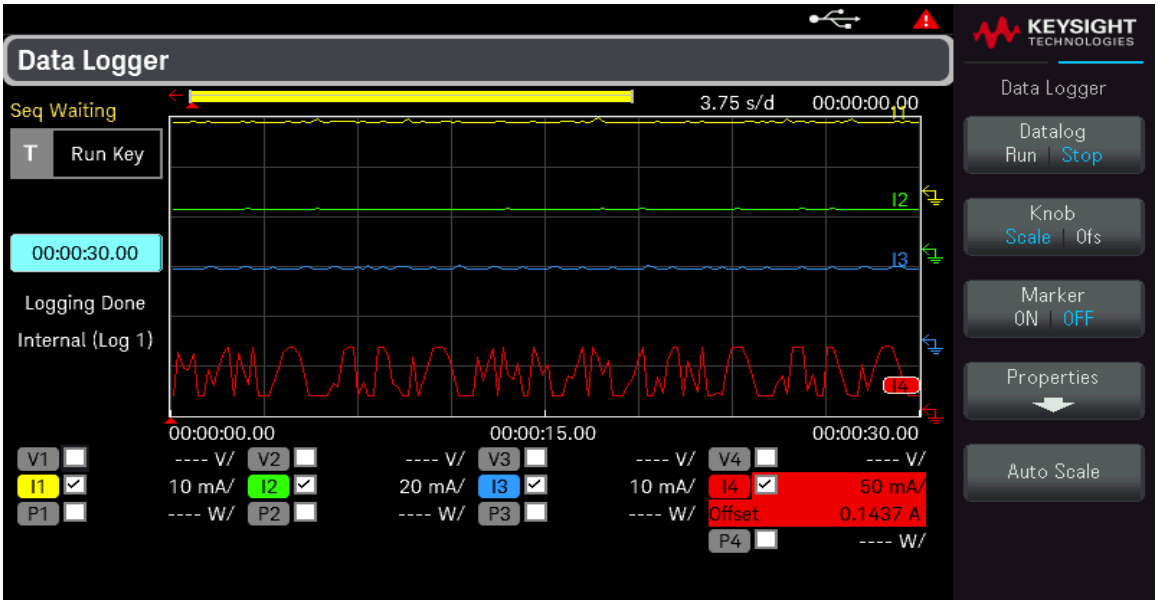


Figure 10. Power supply data logger view

In this test setup, configure the fourth and third string cells to 3.4 V and the second and first string cells to 3.1 V. Using the built-in data logger, notice that the fourth string will discharge first. Although the fourth and third strings have the same voltage, the BMS balanced the cell closest to the battery pack's overall positive.

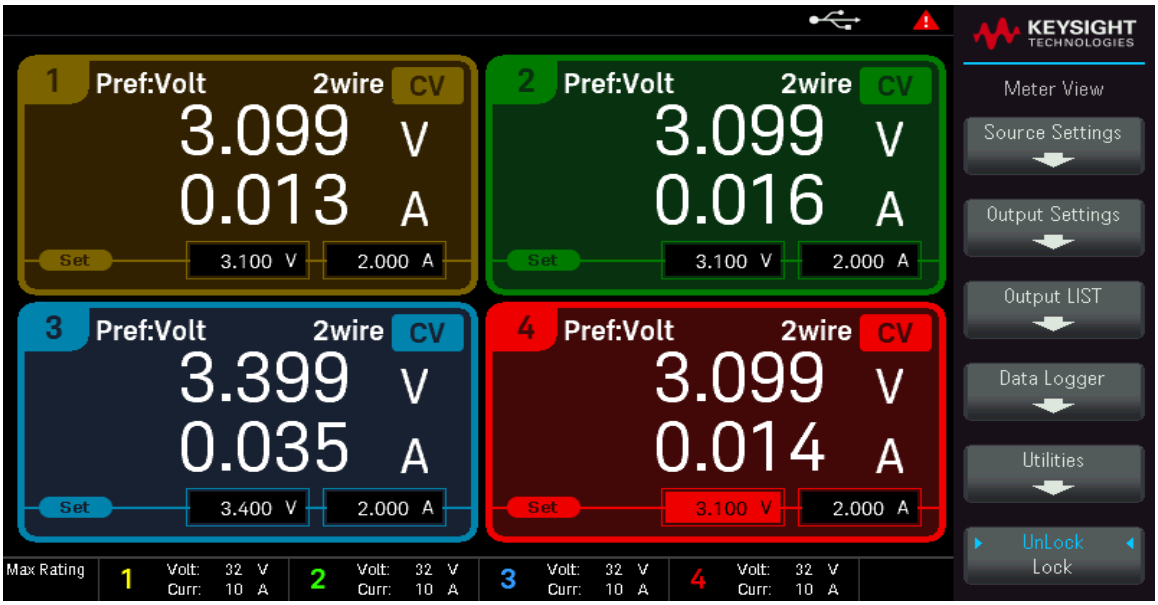


Figure 11. Power supply voltage settings

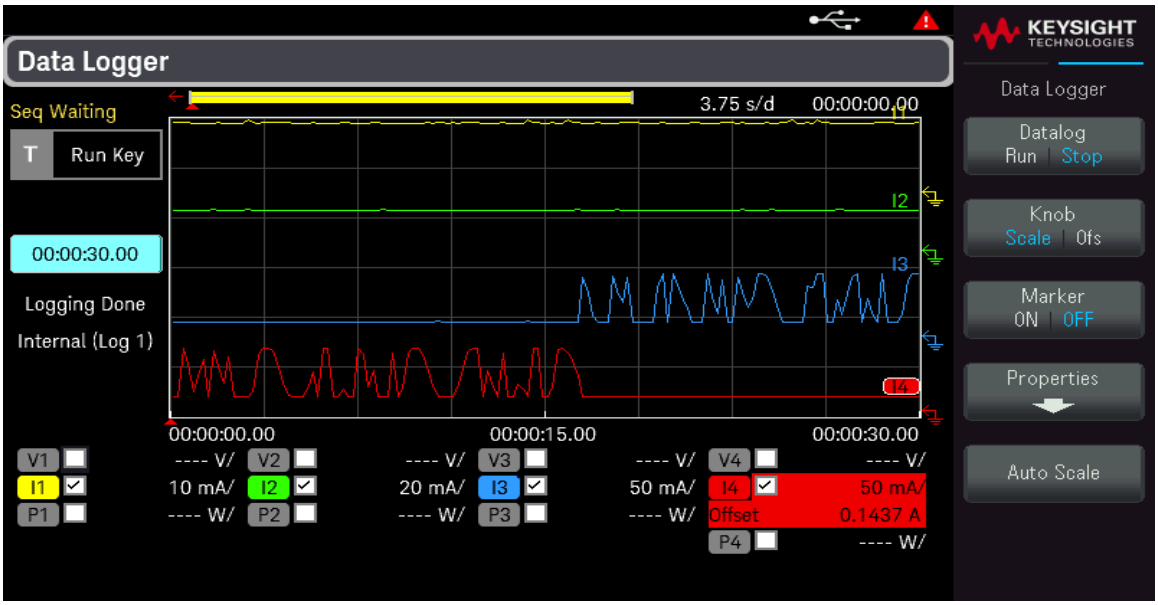


Figure 12. Power supply data logger view

Next, change the fourth string voltage from 3.4 V to 3.1 V while the data logger is still running to simulate the fourth string being discharged and balanced. The BMS does not draw current from the third string until the voltage of the fourth string is balanced. The BMS is limited to balancing the cells in sequence from the string nearest to B+ to the string nearest to B-, so it cannot simultaneously balance multiple cells.

Overvoltage and Undervoltage Protection

BMS overvoltage and undervoltage protections ensure the safety and longevity of battery packs. Overvoltage protection prevents the voltage of any cell from exceeding its maximum safe limit, which can cause overheating, swelling, or even catastrophic failure, such as fire or explosion.

In the case of LiFePO4 batteries, the nominal voltage is around 3.2 V with a maximum voltage of 3.65 V. However, the capacity within the margin of 3.65 V and 3.6 V is minimal, which is why it is best to set the single-cell max voltage at 3.6 V to preserve battery health.

Undervoltage protection, on the other hand, ensures that the voltage of any cell does not drop below its minimum safe limit. While LiFePO4 cells can technically discharge to voltages as low as 2.8 V, doing so can cause significant stress and potential damage to the cell's chemistry. This deep discharge can lead to a reduction in the battery's capacity and overall lifespan. Setting the undervoltage protection to around 3 V ensures that the battery does not enter a deep discharge state, preserving its performance and longevity. By maintaining the voltage of each cell within a safe operating range, the BMS protects the battery pack from potential hazards and ensures reliable performance.

The importance of overvoltage and undervoltage protection cannot be overstated, especially in applications where battery reliability and safety are paramount, such as electric vehicles, renewable energy storage systems, and portable electronics. These protections help prevent conditions that could lead to battery failure, thus enhancing the device's or system's overall safety. Additionally, by preventing overcharging and deep discharging, the BMS helps maximize the battery pack's usable capacity and lifespan. This not only improves the user experience but also contributes to the sustainability and cost-effectiveness of battery-powered systems.

Overvoltage and undervoltage simulation can occur only if all cells have equal voltages. Suppose only one cell is above or below the threshold voltage. In that case, the balancing will trigger rather than overvoltage protection as the combined voltage does not exceed or drop below the threshold.

Overvoltage Simulation and Protection

For overvoltage, start the simulation by setting all cells to 3.4 V initially and then simultaneously raising the voltages to over 3.6 V. As shown in Figure 13, the charging process switches off once this condition is detected. However, the total cell voltage has yet to exceed the overvoltage threshold. While the BMS correctly displays a “cell volt high” status, the “sum volt high” status remains inactive.

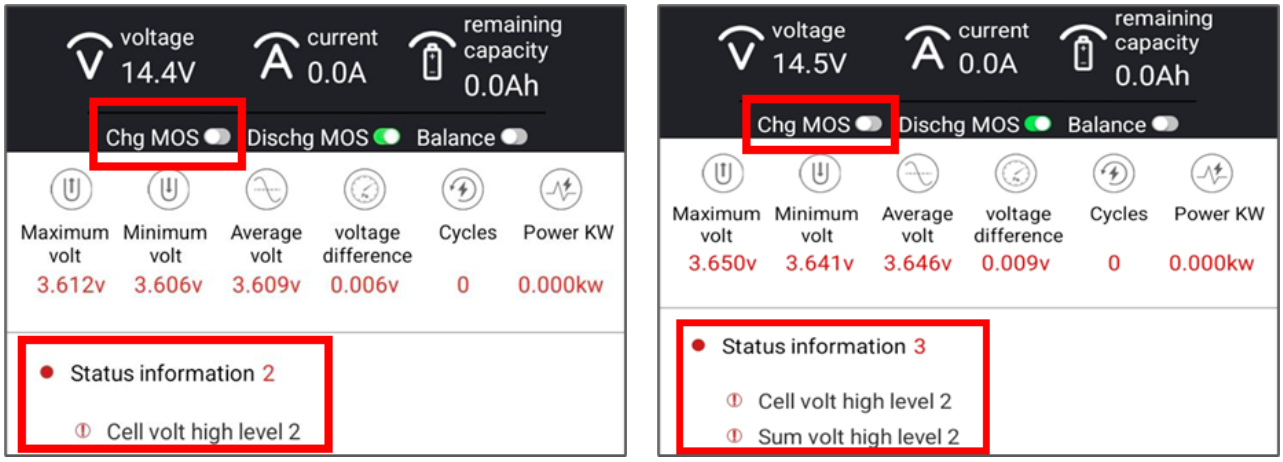


Figure 13. BMS response to overvoltage, showing charging deactivation with “cell volt high” active and “sum volt high” inactive

When the cell voltages rise to 3.65 V, the maximum voltage increases to 14.5 V. The sum volt high status is now displayed while the charging continues to be switched off.

Undervoltage Simulation and Protection

For undervoltage, start the simulation by setting all cells to 3.4 V and then simultaneously dropping all the voltages to below 3 V. When the voltage drops to below 3 V, the discharge switches off. At 2.95 V, the BMS displays a status of cell volt low and sum volt low, indicating that the battery pack is below its optimal voltage. This result proves that the BMS indeed stopped the discharging to protect the battery from going below the optimal voltage and maintaining battery health.

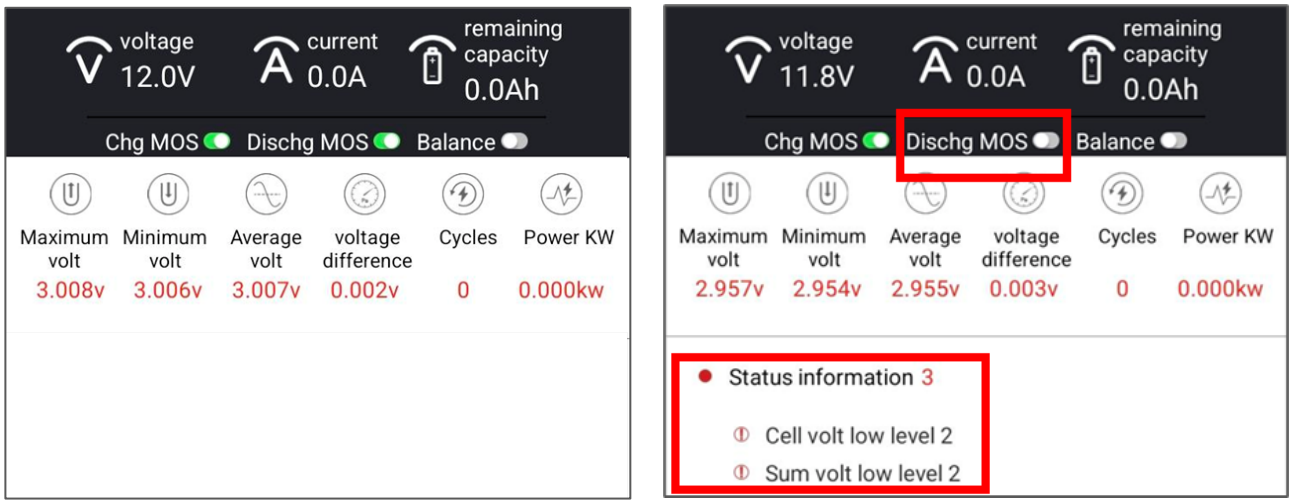


Figure 14. BMS response to undervoltage, showing charging with cell volt low active and sum volt low active

Conclusion

With the Keysight E36441A Smart Bench Essentials Plus four-channel DC bench power supply, engineers can simulate a LiFePO4 battery pack to test the balancing, overvoltage protection, and undervoltage protection features of a battery management system. Validating the performance of the BMS before integrating it into battery packs helps mitigate the risks of overcharging and cell imbalance. This step is particularly important in electric vehicles to ensure the safe functioning of other systems and protect consumer safety.

For more information

Learn more about the Keysight E36441A Smart Bench Essentials Plus four-channel DC bench power supply.

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