

Impact of Improper Battery Management System Design for Lithium-Iron-Phosphate Batteries

R.R. THAKOORDEEN¹, R.T. MABEO², T. HLALELE³
Council for Scientific and Industrial Research^{1,3}, Nelson Mandela University²
South Africa^{1,2,3}

SUMMARY

This paper presents an experimental investigation into the impact of Battery Management System (BMS) design on the performance and reliability of Lithium-Iron-Phosphate (LiFePO₄) batteries.

The original objective of this study was to determine the State-of-Health (SoH) of three commercially available LiFePO₄ batteries under a selected test protocol.

The experimental results showed that the integrated BMSs in all three tested brands exhibited erratic and unpredictable behaviour in their charge and discharge current limits. The initial hypothesis was that the behaviour is directly linked to the overall battery temperature due to the heating during charging and discharging however, no discernible relationship could be determined.

One observation was the premature shutdown of the batteries as depicted by the sharp current drops. The BMSs shutdown and disconnected the battery from the test equipment thereby ceasing the test. The tests were restarted and the data stitched together to be able to conduct an analysis. This highlights a flaw in the design or implementation of these “off-the-shelf” BMSs, as they limit the optimal operation of these batteries.

This study demonstrates that improperly designed and implemented Battery Management Systems can affect battery performance. While the original scope of the tests was to determine SoH, the observed BMS behaviour prevented this assessment, shifting the focus to the critical impact of these design deficiencies.

KEYWORDS

Battery Management System, Lithium-ion, performance, safety, reliability

1 ABSTRACT

Battery management systems (BMS) are an integral part of lithium-ion battery packs and modules. These electronic devices are designed to enhance battery performance, ensure longevity, increase reliability, and provide safety. Using test data, this paper highlights how improperly designed battery management systems can hamper performance and reliability by illustrating how batteries are prematurely turned off during routine operation. Three batteries sold on the South African market were purchased and tested within the specified limits as per the datasheets with the battery management system interrupting normal operation thereby depicting BMS limits erratically changing, leading to premature shutdowns. The states-of-charge and states-of-health, are hence not accurately determined leading to compromised performance and reliability.

2 INTRODUCTION

As per global sustainability goal seven, there has been a rapid adoption of Renewable Energy Sources (RES) such as wind, hydro and solar energy, along with several energy storage systems (ESS) globally.

South Africa is no exception in the adoption of Renewable Energy Sources (RES) in its energy mix. To offset the intermittency of the RES, battery technology has become an important consideration. Battery Energy Storage Systems (BESS) is mostly considered due to its declining capital expenditure, and research advancements [1]. Lithium-Iron-Phosphate or LiFePO₄ (also LFP), dominate the BESS due to the technology's maturity, low maintenance, and increasing energy density [2].

The intrinsic nature of LiFePO₄ cells and batteries prescribes that a Battery Management System (BMS) is required to monitor several key indicators and manage the battery's performance and operation [3]. Without a BMS, the battery may be exposed to overexertion during operation (Overcharging or over discharging), or its environmental conditions may cause the battery to experience thermal runaway[4], [5]. As a result, the battery's performance and safety will be compromised leading to poor performance and failure.

Hence, the BMS forms a critical component in the BESS itself by monitoring and managing the battery's performance and safety during operation [3].

The initial objective of this study was to experimentally assess the State-of-Health (SoH) of several commercially available Lithium-Iron-Phosphate batteries in the South African market under specified operating conditions.

However, as detailed in the results, the observed erratic behaviour and premature shutdowns by the integrated Battery Management Systems significantly impacted our ability to accurately determine SoH and complete routine operations. This unforeseen outcome shifted the focus of our investigation to highlight the critical impact of improper BMS design on battery performance and reliability, thereby directly addressing the central theme of this paper

The paper is structured as follows: Section 3 literature review on Battery Management Systems. Section 4 details the materials and methodology employed. Section 5 presents and discusses the results obtained from the battery tests. Section 6 concludes the paper.

3 LITERATURE REVIEW: BATTERY MANAGEMENT SYSTEMS

The complexity of a BMS is strongly linked to the application of the battery [6]. The BMS found inside a stationary use battery possesses fewer features than that of one found in an electric vehicle (EV) [6]. A single battery, battery module or battery pack (henceforth referred to simply as 'battery' in this paper) consists of several individual cells.

3.1 Balancing

A battery voltage is obtained by the configuration of cells within the battery itself. Typically, a 51.2V, 100Ah battery will possess 16 cells, each with a nominal voltage of 3.2V wired in series. It is imperative that these cells maintain the same voltage and states-of-charge (SoC) [7]. Should a cell voltage differ from the other cell voltages, an imbalance occurs which can lead to thermal runaway [5]. To counteract this, balancing or equalization is employed.

There currently exists several balancing strategies with three overarching schemes namely: battery selection; dissipative (Passive Balancing) and non-dissipative equalization (Active Balancing). Figure 1 shows the hierarchy and relationship between methods. Under battery selection two further methods exist. The first is a screening process whereby [8]:

Balancing circuits are found more often in EVs than general domestic or stationary applications. A high-level overview of balancing topologies, along with the required electrical components is presented in Figure 1.

Under battery selection, methods include grading cells based on similar characteristics or grouping them to form balanced packs. Dissipative equalization involves bleeding excess energy from higher voltage cells, often as heat, to match lower voltage cells. Non-dissipative equalization, in contrast, transfers energy between cells more efficiently without significant loss.

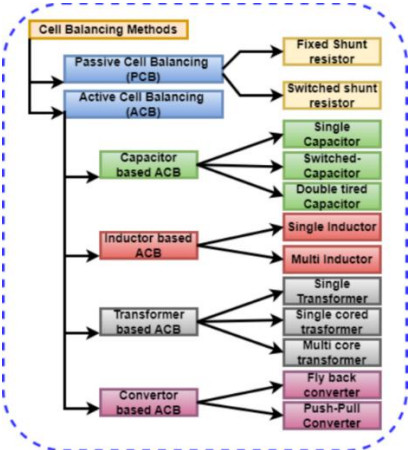


Figure 1 Classification of cell balancing topologies [9]

3.2 Voltage Monitoring

The BMS will monitor the maximum and minimum voltage of each cell and that of the entire battery [10]. This is to prevent overcharge and over-discharge. Voltage monitoring is also used in balancing. Should a cell fall out of balance, the BMS will either shut down the entire battery or activate a balancing a process [5]. While a relationship does exist between SoC and voltage, this relationship is non-linear[6]. Instead, the relationship in a LiFePO4 battery will resemble Figure 2. SoC monitoring are also imperative in balancing [6].

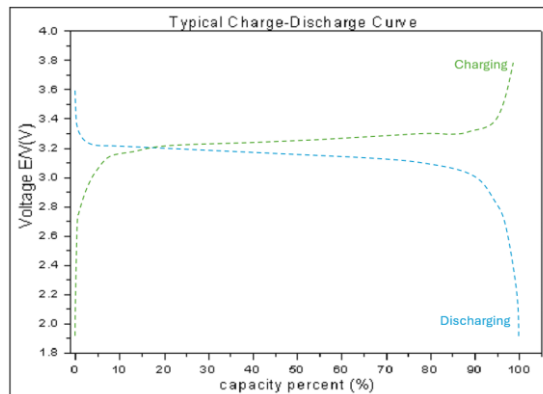


Figure 2 Typical Charge/Discharge Curve of Voltage vs Capacity Percentage (State-of-Charge)

The typical charge/discharge curve for LiFePO4 batteries (Figure 2) illustrates a relatively flat voltage plateau (with ~0.2V change between 5-90% SoC) across a wide range of State-of-Charge (SoC), making accurate SoC estimation particularly challenging compared to other lithium-ion chemistries. This non-linear relationship necessitates sophisticated algorithms for precise monitoring.

3.3 Temperature Monitoring

While temperature monitoring for the entire battery is commonplace, cell temperature monitoring is seldom seen. Certain applications such as electric vehicles (EVs) may employ cellular temperature monitoring as an added safety and performance feature [6].

Cell and battery temperatures have massive implications on performance and safety [11]. While many manufacturers generally state an acceptable operating temperature range of 0°C – 50°C ($\pm 5^\circ\text{C}$), it is widely accepted that room temperature (20°C - 25°C) is the prime range with deviations outside this range negatively affecting performance in terms of cycle life, state-of-health (SoH), energy efficiency and Columbic efficiency [12]. However, operating the battery beyond the manufacturers ratings may lead to thermal runaway while operation at subzero temperature may result in irrevocable damage [6].

The BMS may be programmed differently for charge and discharge however, it may simply shut down all operation until the battery or cell temperatures are once again within range.

3.4 Current Monitoring

Current monitoring is one of the crucial monitoring mechanisms of ensuring the safety, efficiency, and longevity of the battery [10]. In particular applications such as EVs, RES, and portable electronic equipment this BMS feature is central [13].

The BMS continuously measures and analyses the charge/discharge current of the battery and the cells [10]. This prevents overcurrent conditions, which can lead to overheating, fire hazards, and quicker degradation of the cells. Typically, the allowable charge/discharge current is determined by the chemistry and design of the battery. For this particular study, the limits are identified in Table 1.

SoC and SoH estimations, which are critical in maximizing performance and reliability, are also obtained through current monitoring.

3.5 State-of-Health

SoH, while a crucial metric in BMSs, is often not a feature included in many systems [14]. It reflects the overall condition (or health) and available useful life of a battery. SoH provides an approximation of the battery's capability to store and distribute energy. It is compared in relation to its rated capacity [15]. As a rule of thumb, in EVs end-of-life is considered to be at 80% [16].

Many factors affect SoH, including internal resistance, cycles, operating temperatures/conditions, operating currents. Hence, an accurate SoH estimation is crucial for battery longevity, safety and reliability. Using other metrics obtained via the BMS, advanced algorithms along with historical performance data is used in the SoH estimation [6].

3.6 State-of-Charge (SoC) and Depth of Discharge (DoD)

State-of-Charge (SoC) is the actual capacity of a battery as a percentage of its total rated capacity. Analogous to a fuel gauge within an internal combustion engine (ICE) vehicle, SoC indicates the usable capacity remaining within the battery [6]. Closely related to SoC is Depth of Discharge (DoD), which indicates the percentage of battery capacity that has been discharged relative to its total capacity. Essentially, DoD is calculated as $100\% - \text{SoC}$. Both parameters are crucial for optimal battery operation.

The most common method in determining SoC is Coulomb Counting.

4 MATERIALS AND METHODOLOGY

In this study three separate brands commercially sold in the South African market were tested. Henceforth, these batteries will be referred to as Brand A, Brand B and Brand C. Selected data, shown in Table 1, were extracted from the relevant datasheets.

Table 1 Selected Data Extracted from Datasheets¹

	Brand A	Brand B	Brand C
Chemistry	LiFePO4	LiFePO4	LiFePO4
Nominal Capacity	104 Ah	100 Ah	100 Ah
Nominal Voltage	51.2 V	51.2 V	48 V
Operating Voltage (DC)	45.6 V – 56.16 V	43.2 V -57.6 V	44.5 V – 53.5 V
Nominal Charge/Discharge Current	50 A	50 A	50 A
Maximum Charge/Discharge Current	100 A	100 A	74 A
Operating Temperature	-20°C – 60°C	-20°C –55°C	-10°C –60°C

The tests were carried out using a Chroma 17020, 32 Channel battery tester in ambient and uncontrolled temperature conditions. Each channel has the capability of delivering 30A, 200V with a 2.5kW limit, hence four channels were paralleled for this study.

Each test for each battery was conducted under similar conditions. The same test protocol (Table 2) was also applied to each battery.

Table 2 Test Protocol Applied to the Batteries

Step	Operation
1	Charge at 50 A or 0.5 C (2 hours)
2	Rest for 30 minutes
3	Discharge at 50 A or 0.5 C (2 hours)
4	Rest for 30 minutes
5	Charge at 50 A or 0.5 C (2 hours)
6	Rest for 30 minutes
7	Discharge at 50 A or 0.5 C (2 hours)
8	Rest for 30 minutes
9	Charge at 50 A or 0.5 C (2 hours)

Each battery underwent a testing protocol, detailed in Table 2, to ensure consistency and comparability of the results. This protocol was designed to determine the SoH. The chosen charge and discharge rates (0.5C) represent moderate operational loads, reflecting a balance between daily cycling and ensuring sufficient testing within a reasonable timeframe. The 30-minute rest periods between steps allow for battery relaxation.

Full charge preparation is the first step of the methodology. This begins by fully charging each battery to its maximum capacity. A consistent starting point for capacity testing is thus established.

Steps 3 to 7 is where the actual Capacity Testing occurs. All three brands were subjected to similar charge and discharge currents and voltages as dictated by the datasheets to evaluate their capacity and performance metrics.

Step 8 prepares the battery for storage. After completing SoH protocols, each battery was charged to a 30% SoC. This is in accordance with industry best practices and

¹ Selected performance data, obtained from the proprietary datasheets provided by the respective manufacturers, were extracted and are presented in Table 1. Due to their proprietary nature, the full datasheets cannot be directly cited or provided in this publication

international standard UL1974 [20], which suggests that storing batteries at 30% SoC can reduce the rate of natural degradation [21].

5 RESULTS AND DISCUSSION

Figures 3, 5, 7 and 9 show how the BMS limits changed throughout the testing. Figures 4 and 6 show the actual charge and discharge currents of Brand A and Brand B respectively, with arrows indicating where the BMS initiated a shutdown procedure. Figure 8 for Brand C shows the charge/discharge current, but a BMS shutdown was not observed in this specific discharge cycle shown.

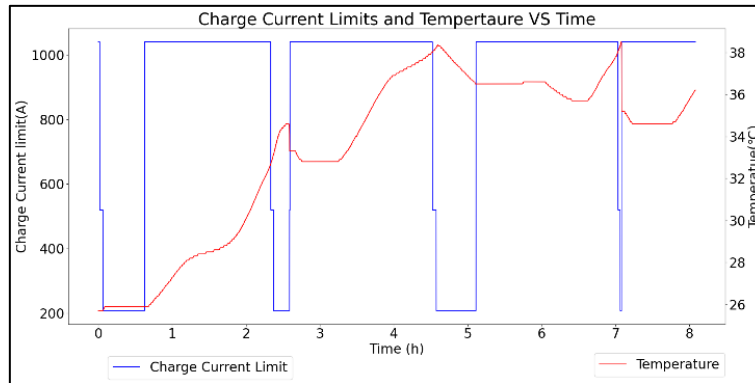


Figure 3 Brand A Charge Current Limits and Temperature vs Time

Figure 3 shows how the Charge Current Limits inconsistently changed throughout the test.

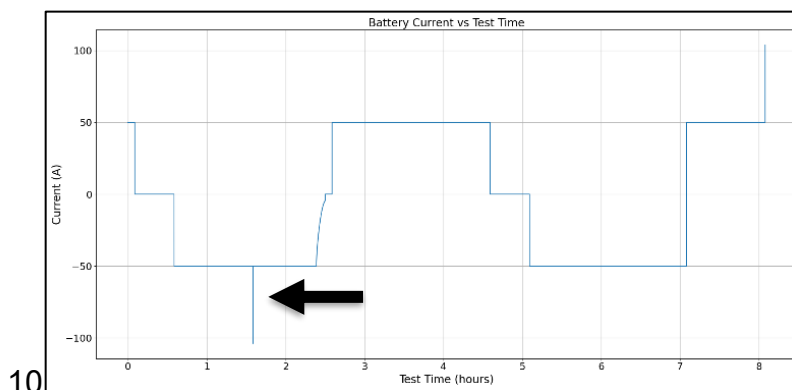


Figure 4 Brand A: Charge/Discharge Current vs Time

Figure 4, by way of the arrow, shows where the BMS initiated a shutdown process, deactivating the battery upon reaching a predefined limit or condition.

In Figures 4 and 6, the arrow shows where the BMS shuts down operation. However, it can be seen that the current returns to -50A where operations continue. This is due to the test operators resuming the test at the point of failure in order to complete the test.

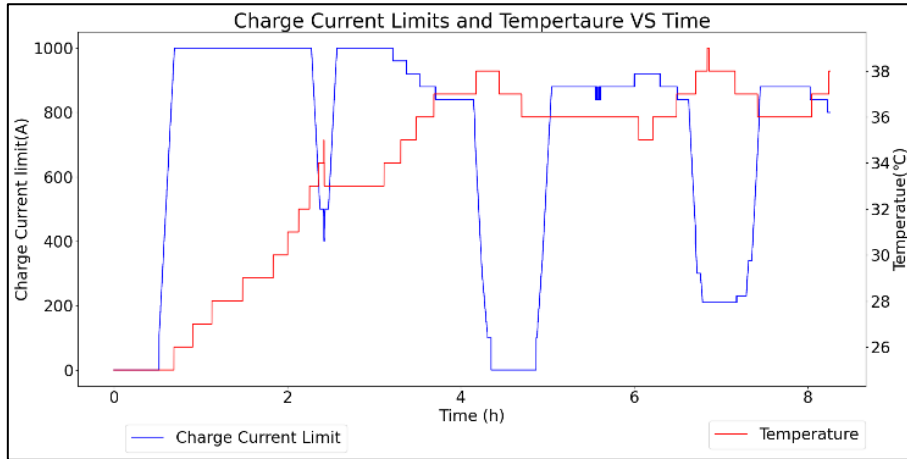


Figure 5 Brand B: Charge Current Limits and Temperature vs Time

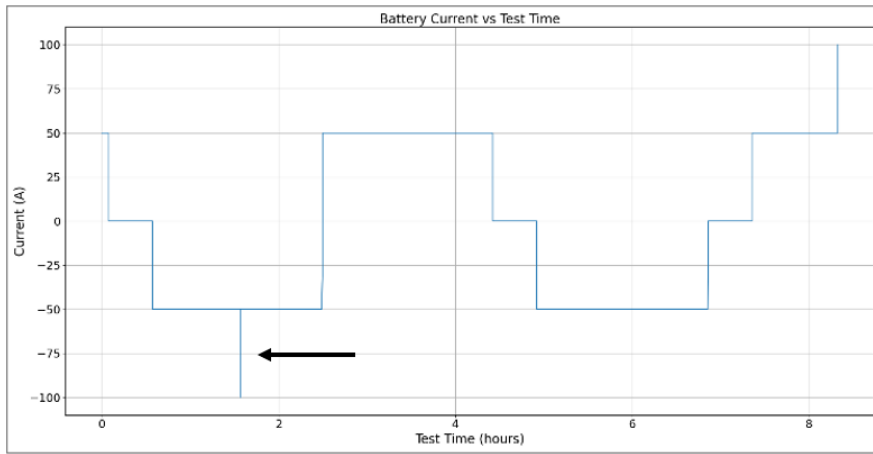


Figure 6 Brand B: Charge/Discharge Current vs Time

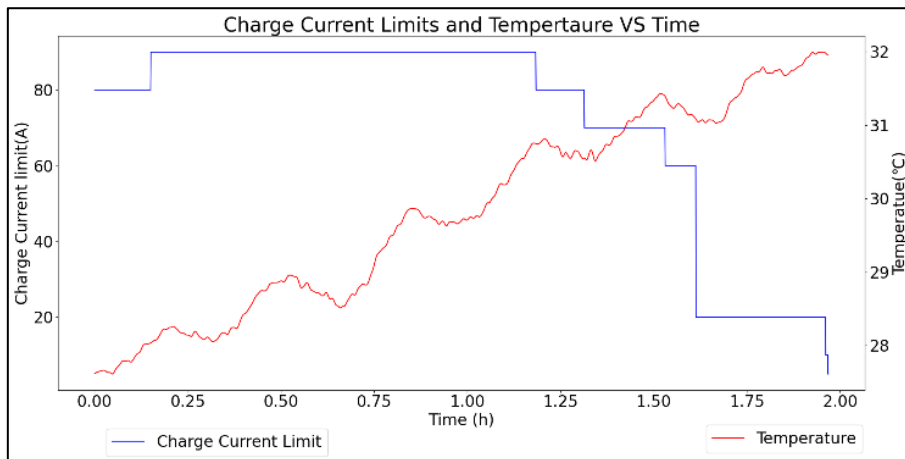


Figure 7 Brand C: Charge Current Limits and Temperature vs Time

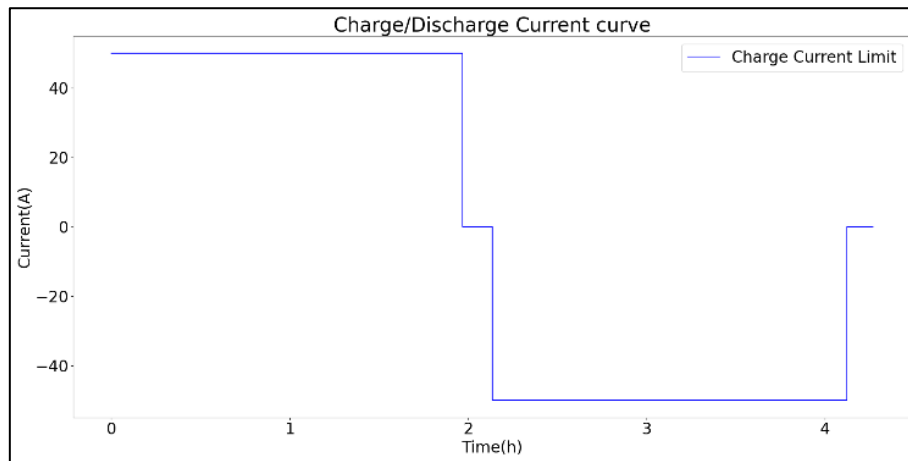


Figure 8 Brand C: Charge/Discharge Current vs Time

The charge Current Limits (Figures 3 to 5) for each brand change erratically over time. The erratic and unpredictable changes observed in the charge current limits (Figures 3, 5, 7) for each brand, and similarly for discharge current limits (Figures 9, 10, 11), suggest complex underlying BMS algorithms. While an initial hypothesis linked these fluctuations to the overall battery temperature, no discernible direct correlation could be established. These variations are likely a result of the BMS dynamically adjusting its operational limits based on a multitude of internal parameters, such as individual cell voltage deviations, internal resistance fluctuations, or proprietary protection strategies designed by the manufacturers. Inner workings of Battery Management Systems are, and in this case, proprietary and hence inaccessible. Although, hypotheses can be derived. In certain occurrences, the BMS shutdowns coincided with delicate cell voltage imbalances which may suggest that subtle abnormalities may have fallen out the limits. Current surges were also detected prior to shutdowns, which could plausibly lead to overcurrent protection however, Chroma's system would've likely detected this. In one battery, a cell imbalance was confirmed post testing. Since the BMS lacked the active or passive balancing capabilities, it's possible that the battery was shut down to prevent damage to the battery pack. These points suggest that the BMS protection schemes (conceivably to cell voltage deviation, increases in internal resistance or hotspots) could be responsible for unpredictable limit changes and premature shutdowns. Future work involving cell-level voltage and temperature monitoring will help verify these triggers.

It appears the BMS prioritizes battery protection, even if it leads to premature cessation of operation, without providing clear external indicators for these internal adjustments. This behaviour highlights a lack of transparency or sub-optimal programming in the BMS designs, leading to inconsistent performance during routine testing. Temperature is plotted on the same graphs in order to determine a possible relationship between temperature and the limits.

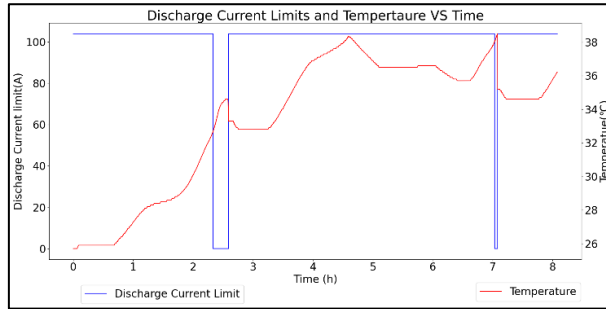


Figure 9 Brand A: Discharge Current Limits and Temperature vs Time

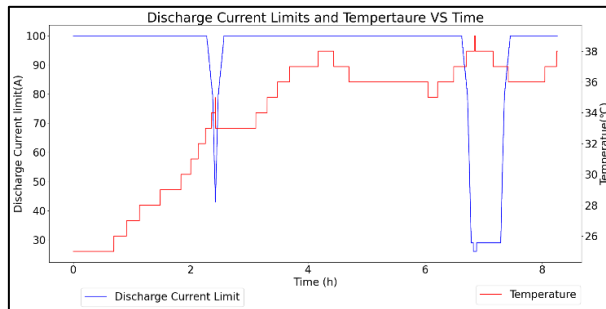


Figure 10 Brand B: Discharge Current Limits and Temperature vs Time

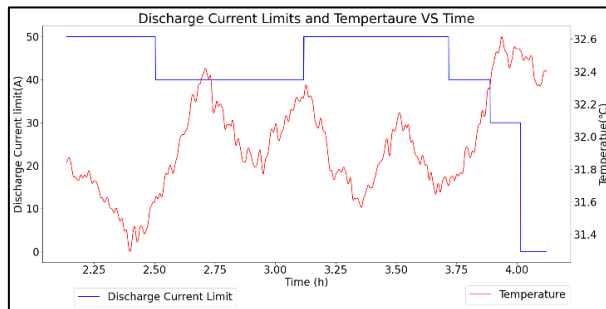


Figure 11 Brand C: Discharge Current Limits and Temperature vs Time

Similarly, the discharge Current Limits (Figures 9 to 11) were also plotted against temperature and similar erratic and unpredictable changes were noticed.

From Figures 3 to 8, during the tests, the BMS limits tend to unpredictably change. While the overall battery temperature was monitored and plotted alongside the current limits, no discernible relationship could be determined. This suggests that either the BMS's current limit adjustments are not primarily driven by the measured external battery temperature, or they are reacting to more localized internal cell temperatures or other unmonitored parameters, such as individual cell voltages or internal resistance, which were not accessible during these tests. Further investigation into internal cell conditions might shed light on these behaviours.

The unpredictable variation in charge and discharge current limits and the premature shutdowns initiated by the BMS severely hampered the ability to conduct complete charge and discharge cycles as required for accurate State-of-Health (SoH) determination. Standard SoH estimation relies on measuring the full usable capacity of the battery; however, since the BMS unexpectedly interrupted normal operation, the true capacity could not be fully discharged or charged, making a reliable SoH

calculation impossible. This directly illustrates how improperly designed BMSs can prevent even fundamental performance assessments.

6 CONCLUSION

The original intention of these tests was to determine each of the batteries' SoH. Due to the erratic behaviour of the BMS, this could not be achieved. Of the three batteries were to be tested one battery experienced a defect, later discovered to be a cell out of balance. The BMS employed in this battery, hence did not possess any balancing capabilities.

More attention needs to be given to BMS integration in LiFePO₄ batteries. While smart and adaptable BMSs will tend to protect batteries, improperly designed and implemented systems will hamper battery performance, reliability and longevity. In certain applications such as EVs, this may cause catastrophic incidents.

These results suggest a larger issue for stakeholders. Unexpected and erratic BMS shutdowns could compromise power delivery and jeopardize reliability in both residential and commercial grid-connected (and off-grid) systems. When integrating commercially available batteries with off-the-shelf products, designers should exercise caution due to inadequately transparent BMS algorithms concealed limitations.

Future research should focus on developing more robust and transparent BMS algorithms that provide clearer indications of protection triggers. Advanced thermal management strategies at a cell level, are also critical.

BIBLIOGRAPHY

- [1] W. Huang, Q. Zhang and F. You, "Impacts of battery energy storage technologies and renewable integration on the energy transition in the New York State," *Advances in Applied Energy*, vol. 9, pp. 100126, 2023.
- [2] M. J. Rasul and J. Kim, "Comprehensive review and comparison on battery technologies as electric-powered source in marine applications," *Journal of Energy Storage*, vol. 88, pp. 111509, 2024.
- [3] S. Nyamathulla and C. Dhanamjayulu, "A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations," *Journal of Energy Storage*, vol. 86, pp. 111179, 2024.
- [4] M. Waseem *et al*, "Battery technologies and functionality of battery management system for EVs: Current status, key challenges, and future prospectives," *J. Power Sources*, vol. 580, pp. 233349, 2023.
- [5] J. Zhao *et al*, "Battery safety: Fault diagnosis from laboratory to real world," *J. Power Sources*, vol. 598, pp. 234111, 2024.
- [6] R. R. Kumar *et al*, "Advances in Batteries, Battery Modeling, Battery Management System, Battery Thermal Management, SOC, SOH, and Charge/Discharge Characteristics in EV Applications," *IEEE Access*, vol. 11, pp. 105761–105809, 2023. . DOI: 10.1109/ACCESS.2023.3318121.

- [7] M. Parker and R. McMahon, "Investigations into the Charge Times of Lead–Acid Cells under Different Partial-State-of-Charge Regimes," *Batteries*, vol. 10, (6), pp. 201, 2024.
- [8] Y. Shang *et al*, "A cell-to-cell battery equalizer with zero-current switching and zero-voltage gap based on quasi-resonant LC converter and boost converter," *IEEE Transactions on Power Electronics*, vol. 30, (7), pp. 3731–3747, 2014.
- [9] R. Venkatasatish and C. Dhanamjayulu, "Design and implementation of an inductor based cell balancing circuit with reduced switches for Lithium-ion batteries," *Scientific Reports*, vol. 14, (1), pp. 28691, 2024.
- [10] G. V. Rao *et al*, "Modular battery management system architecture for commercial vehicle applications," *Materials Today: Proceedings*, vol. 92, pp. 1538–1543, 2023.
- [11] J. Jaguemont and F. Bardé, "A critical review of lithium-ion battery safety testing and standards," *Appl. Therm. Eng.*, vol. 231, pp. 121014, 2023.
- [12] T. Ouaneche *et al*, "Room temperature efficient regeneration of spent LiFePO₄ by direct chemical lithiation," *J. Power Sources*, vol. 579, pp. 233248, 2023.
- [13] S. K. Pradhan and B. Chakraborty, "Battery management strategies: An essential review for battery state of health monitoring techniques," *Journal of Energy Storage*, vol. 51, pp. 104427, 2022. .
- [14] M. Chen *et al*, "An overview of data-driven battery health estimation technology for battery management system," *Neurocomputing*, vol. 532, pp. 152–169, 2023. .
- [15] M. H. Lipu *et al*, "Deep learning enabled state of charge, state of health and remaining useful life estimation for smart battery management system: Methods, implementations, issues and prospects," *Journal of Energy Storage*, vol. 55, pp. 105752, 2022. .
- [16] M. Etxandi-Santolaya *et al*, "Quantifying the Impact of Battery Degradation in Electric Vehicle Driving through Key Performance Indicators," *Batteries*, vol. 10, (3), pp. 103, 2024. .