Integrating Centralized and Decentralized Battery Management Systems using Smart Cell Technology for Enhanced Battery Safety

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***Abstract*- Lithium-ion batteries are becoming increasingly popular due to their high efficiency, extended lifespans, and ability to contribute to clean energy sources. However, despite their benefits, these batteries can pose significant safety risks in the event of short circuits, fires, or exposure, typically due to the lack of protective circuits in battery-related applications. Therefore, battery management systems (BMS) has been designed which includes centralized and decentralized BMS. However, several flaws in BMS keeps the danger loop open. This work introduced the smart cell technique in order to achieve this goal by integrating the techniques of centralized and decentralized BMS. The suggested method makes use of the benefits of both centralized and decentralized BMS to offer more secure battery operation. In-depth discussions of the simulation, hardware implementation, and restrictions, as well as various failure types and their solutions, are included in this work.**

***Index Terms*— Lithium-ion batteries, Centralized BMS, Decentralized BMS, Smart cell, Fault handling.**

I. Introduction

The future lies in Lithium-ion (Li-ion) batteries because the world which is highly coal-reliant to meet its energy requirements is adversely affected by climate change. Of all the competitive batteries, Li-ion batteries are the best because of their higher efficiency, longer life, and higher energy density. Environment-friendly Li-ion batteries are designed in the form of cells [1]. Load requirements are beyond the power capability of one cell so the arrangement of cells in different combinations like series combinations or parallel combinations becomes inevitable to meet the load requirements of various applications. Battery cells are either connected in series or parallel combinations. The series combination can meet voltage requirements whereas current requirements are met by parallel combination [2]. Besides having a great number of advantages batteries do possess various faults which not only compromise batter performance but can also cause serious damage to the system [3].

Different types of faults appear in Li-ion batteries which not only affect the battery but can be proven dangerous. Faults in Li-ion batteries are mainly categorized into two types that is internal faults and external faults [4]. Internal faults include overcharge which can ultimately result in the decomposition of active material, an internal short circuit having the ability to make the battery explode, overheating causing the battery to swell, thermal runaway causing an external short circuit, and accelerated degradation reducing the lifespan of battery significantly. Sensor faults, cooling system faults, and cell connection faults fall under the category of external faults. Sensor fault is the erroneous behavior of temperature, voltage, or current sensor [5]. As battery management system (BMS) highly relies on data sent by these sensors so it becomes mandatory to diagnose sensor faults. Cooling system fault appears due to outdated wiring of the fan or faulty temperature sensor. Cell connection fault is because of a loose connection of cells with terminals [6].

To combat all these faults battery management systems BMS comes into play. Using different techniques of BMS not only the fault is diagnosed but also a controlling mechanism is introduced. BMS compels the battery to function within a safe operational range, hence minimizing and eliminating the risks caused by various faults need to be applied [7]. A typical BMS is shown in Fig. 1. By using different mechanisms and algorithms the BMS detects the fault in batteries. Hence the importance of BMS in battery designing is paramount as it not only detects the faults but also minimizes the risk factors. BMS provides a safe and user-friendly environment to the consumer [8].

Mainly BMS has two types centralized BMS and decentralized BMS each having its advantages and disadvantages in terms of working. The Centralized BMS deals with a series of connected battery cells to detect the faults like overcharging, over-discharge, and thermal runaway [9]. BMS has added features like state-of-health (SOH) and state-of-charge (SOC) estimation [10-13]. SOC balancing and alert system to inform the master controller regarding any fault. The disadvantage CBMS carries is its inability to detect faults in parallel connected cells. CBMS is also unable to perform energy management and energy balancing in the cells which are connected in a parallel configuration. Decentralized BMS provides management circuitry to each cell or number of cells to give gain more control over the battery system in terms of efficient energy management, fault handling, and special balancing techniques [14]. As each type of system has several advantages, it also comes up with many disadvantages [15].

The main idea of the research paper is to combine the benefits of centralized and decentralized Battery

Management Systems (BMS) in order to improve fault handling and detection. The implementation of a decentralized BMS involves the incorporation of "Smart Cells" for battery management purposes. These smart cells are interconnected in both series and parallel configurations to form a larger battery pack, which is subsequently linked to a centralized BMS. The smart cell contains a low-power MCU, a current sensor, a voltage sensor, a temperature sensor, and a one-wire protocol for communication purposes. The paper proposes equipping each cell in a battery pack with its own control circuitry, sensors, and microcontroller, thereby allowing each cell to operate independently while still being integrated into a larger battery pack. This approach offers several benefits, including more precise monitoring and control of each individual cell, improved safety by isolating cells with low SOC, and better detection and response to internal short circuit faults. A demonstration of the effectiveness of the proposed approach through simulations is presented, showing that it can lead to improved battery performance and safety compared to traditional centralized battery management systems.

The paper is structured into four main sections. The first section introduces the proposed architecture, which aims to integrate centralized and decentralized BMS systems. The second section provides a detailed description of the proposed architecture and how it functions to provide overcharge and over-discharge protection to the battery cells. The third section presents the simulations that were performed to test the proposed architecture, including simulations on sensor fault detection and internal short circuit protection. Finally, the fourth section summarizes the key findings of the paper and draws conclusions about the feasibility and effectiveness of the proposed architecture for BMS. Overall, the paper presents a comprehensive analysis of the proposed architecture and demonstrates its potential to improve the performance and safety of BMS systems.

II. Proposed Architecture

The article proposes a novel concept of a "Smart Cell" designed for use in battery packs. The smart cell includes a low-power microcontroller unit (MCU), a charge-discharge MOSFET, a temperature sensor, a voltage sensor, and a current sensor. Fig. 2 displays the functions and simplified diagram of the smart cell. The low-power MCU is responsible for executing various algorithms designed for fault protection and SOC estimation. The charge-discharge MOSFETs serve to isolate the cell in the event of short circuit detection, over-charge, or over-discharge. The current sensor aids in SOC estimation and short circuit detection, while temperature sensors are implemented to prevent thermal run-away.

In addition to these features, a fuse circuit is included to automatically isolate the cell in the case of a severe short circuit. Furthermore, the smart cell utilizes a one-wire communication protocol, which allows multiple cells to be connected through a single wire. Each cell is assigned a specific address, as displayed in Fig. 3, enabling the master MCU to communicate with and verify the status of each cell individually. When connected in parallel, these cells are designed for self-protection. The cells are then combined to form a battery pack, which is connected to a centralized BMS as shown in Fig. 4. This architecture combines the advantages of both centralized and decentralized BMS techniques, enabling effective fault handling and better energy management.

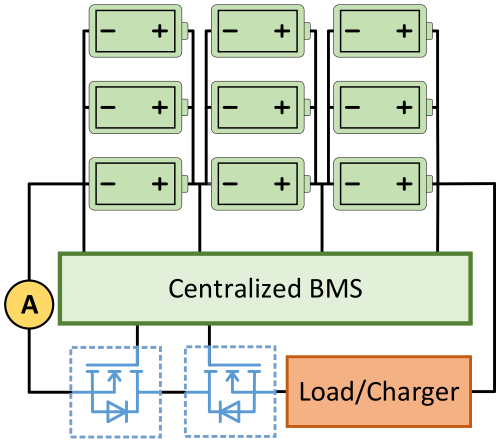

Fig. 1 Conventional BMS system simplified diagram.

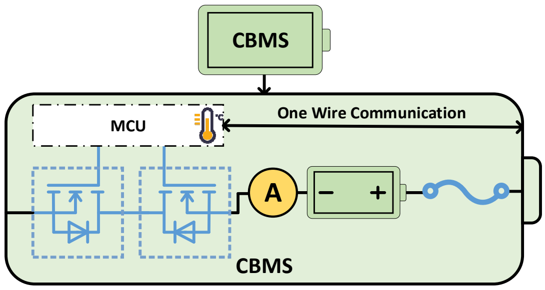

Fig. 2 Smart cell components illustration.

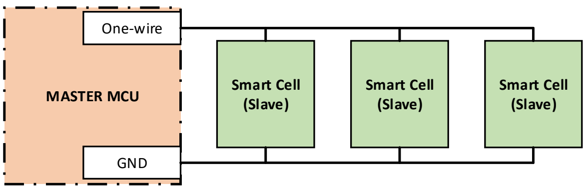

Fig. 3 One-wire protocol to connect multiple smarts cells with master MCU.

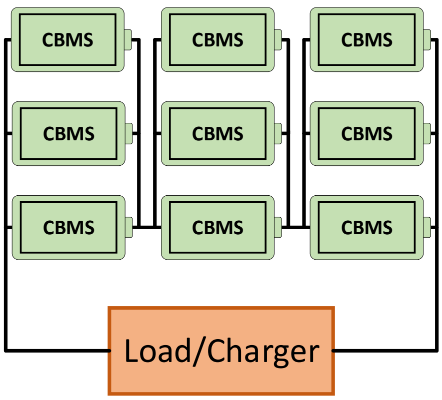

Fig. 4 Integrated Centralized-Decentralized BMS.

A. State of health SOH Improvement

Cell-balancing, which is the sharing of the charge from fully charged battery cells to less charged battery cells, is automatically carried out in parallel connected cells. This current flow is not necessary if proper energy management is performed and also this current flow for balancing causes the degradation of the SOH of the cell because of charge-discharge cycles which are directly related to the SOH of the battery. Eq. (1) shows the SOH of the battery reduced because of current flow for cell balancing.

$$SOH_b(t) = \frac{1}{Capacity_{rated}} \int_0^t I_b(t)dt \qquad (1)$$

Where $SOH_b(t)$ represents the SOH degraded because of I_b flows for balancing purposes. To avoid this SOH degradation because of balancing current, the cell with less SOC is isolated and it is activated again when the other cells' SOC reached close to it. To isolate the cell, charge-discharge MOSFETs are utilized and the decision of turning on-off MOSFETs is taken by getting neighbor cells' SOC information through the master MCU via the one-wire protocol.

B. Over-charge and over-discharge protection

The protection of battery cells against over-charge and over-discharge is a critical aspect of battery management. In this regard, the MCU plays a central role. The MCU is designed to detect instances of over-charge and over-discharge of the cell through the use of shunt resistance. This resistance is used to monitor and regulate the flow of current into and out of the cell. Moreover, there are various methods employed to estimate the SOC of the battery cell. These include Coulomb-counting, SOC-OCV lookup table, and several modeling techniques. These methods are crucial for monitoring the battery performance and ensuring the longevity of the cell. In addition, temperature sensors are also employed to detect excessive current flow from the battery cell. These sensors generate alerts to the MCU, which subsequently takes appropriate measures to isolate the cell and prevent further damage. By employing these measures, the battery management system can protect the battery cells against over-charge, over-discharge, and other potential sources of damage, ultimately improving the overall performance and reliability of the battery.

C. Internal short circuit protection

In the context of battery management systems, short circuits can pose a significant risk to the performance and safety of the battery cells. To mitigate this risk, there are two primary methods employed to prevent short circuit protection. The first method involves the use of a fuse to isolate a cell in case of a severe short circuit. In such cases, when there is an excessive flow of current from neighboring cells, the fuse is designed to break the circuit and prevent the current from flowing further. This approach is particularly useful when the MCU may cause a delay in taking a decision, allowing the fuse to provide an immediate response. The second method involves the use of a shunt resistor, which enables the MCU to sense excessive current flow in the battery cell. The MCU can then take appropriate measures to control the charge-discharge MOSFETs and isolate the cells to protect the other parallel connected cells. This approach is particularly useful when a short circuit is less severe and can be addressed by regulating the flow of current to prevent further damage. By utilizing both methods, the battery management system can effectively prevent short circuits and protect the battery cells from potential circuits ultimately improving the performance and longevity of the battery.

D. Sensors fault detection

The importance of sensor fault detection in BMS cannot be overstated. Faulty sensors can lead to inaccurate data, which can result in incorrect decisions being made by the BMS. This can lead to inefficiencies in energy usage, increased operating costs, and potentially even safety hazards for building occupants. Integrating centralized and decentralized BMS can make it easier to detect faults in sensors. By comparing the readings from the two systems, it is possible to identify discrepancies and pinpoint the location of the faulty sensor. This can help reduce the time and effort required for troubleshooting and repairs. In addition, integrating centralized and decentralized BMS can provide redundancy, which can improve the reliability of the system as a whole. If one system is experiencing a fault, the other can continue to operate and provide critical data to maintain the building's operations. Overall, sensor fault detection is essential for ensuring the proper functioning of the BMS and optimizing building performance. Integrating centralized and decentralized BMS can make this process easier and more effective, improving the efficiency and safety of the building.

III. SIMULATIONS

In BMS, the detection of faults in cells is crucial for the safe and efficient operation of the battery pack. Over-charging and over-discharging can cause damage to the battery cells and reduce their overall lifespan. To prevent such faults, BMS typically employ protection circuits that isolate the affected cells from the rest of the pack. To demonstrate the effectiveness of such protection circuits, a simulation was performed using MATLAB Simulink. Three cells were connected in parallel, each with a different SOC level. Charge and discharge currents were applied to these cells, and the simulation tracked their SOC levels. In the event of over-charging, where the SOC level exceeds 100%, the protection circuit triggers and isolates the affected cell from the rest of the pack. Similarly, in the event of over-discharging, where the SOC level falls below 30%, the protection circuit also triggers and isolates the affected cell.

The simulation results, presented in Fig. 5 and Fig. 6, show the control signals that trigger the charge-discharge MOSFETs to isolate the cell. These figures demonstrate the effectiveness of the protection circuit in preventing over-charging and over-discharging of the battery cells. Overall, the simulation results demonstrate the importance of fault detection and protection circuits in BMS for ensuring the safe and efficient operation of battery packs. By detecting and isolating faulty cells, BMS can prevent damage to the battery pack and extend its overall lifespan.

The proposed BMS scheme includes a robust sensor fault detection mechanism that can effectively detect faults in various types of sensors used in the system. In particular, a voltage sensor fault algorithm has been developed and implemented in MATLAB Simulink to showcase the sensor fault detection capability. Moreover, this approach can be extended to detect faults in other sensors such as current and temperature sensors.

The proposed BMS topology includes a centralized BMS and smart cells connected to it. The centralized BMS can sense the voltage of each series cell, while the smart cells can sense the voltage of each individual cell. To detect sensor faults, a comparison is performed between the voltage sensing of the smart cells and the centralized BMS. The smart cells do not include a separate voltage sensor to reduce hardware complexity and cost. Instead, voltage sensing is performed by the internal analog to digital converter (ADC) of the MCU. However, powering the MCU from the smart cell can generate complexity in generating the ADC reference for accurate calculations, as the smart cell voltage varies and changes the ADC reference.

The algorithm for detecting voltage sensor faults is demonstrated in Fig. 7, where *Vsc1* represents the voltage of cell 1 measured by the MCU of the smart cell, and *Vcc1* represents the voltage of cell 1 measured by the centralized BMS. Herein α can be adjusted based on the sensitivity of the sensor. Similarly, the pack voltage is measured by the sum of voltages measured by MCUs of smart cells connected in series and compared with the pack voltage sensed by the centralized BMS. It should be noted that this algorithm assumes the voltage sensor of the smart cell is functioning correctly, as voltage sensing is performed by the MCU of the smart cell internally. If there is a failure in the MCU, voltage measurements can be inaccurate. MCU failure detection can be done through a scanning process during cell connection faults. The simulation is performed for the detection of voltage sensor fault and the results are shown in Fig. 8 and Fig .9. Once a sensor fault is detected, the main MCU of the BMS can use the voltages sensed by the smart cells for future decisions. It should also be noted that similar algorithms can be applied to measure faults in current and temperature sensors.

The following equation is used to detect the sensor fault.

$$V_{sc1} + \alpha < V_{cc1} \;||\; V_{sc1} - \alpha > V_{cc1} \qquad (2)$$

Where represents voltage sensed by smart cell, represents voltage sensed by centralized BMS, and is the factor required to add or subtract. As the values of both the sensors cannot be 100% the same because of the type of sensor and different factors, the values can be a little bit different while both sensors work correctly. For this purpose, there is some formulation required which is described below.

$$\alpha = E_{sc1} + E_{cc1} \qquad (3)$$

Where represents the maximum error in the voltage sensor of decentralized BMS while represents the maximum error in voltage sensing sensed by centralized BMS.

Internal short circuit protection is a critical aspect of BMS that is implemented to prevent excessive current flow from a parallel connected cell, which can potentially damage the cell and pose a safety risk. In order to achieve this, a protection mechanism is developed using MATLAB Simulink, which includes a fuse that is blown in case of an internal short circuit in a cell. This action helps protect the remaining parallel connected cells from being short circuited, as well as preventing the centralized BMS from isolating the entire parallel cell string.

The implementation of internal short circuit protection in MATLAB Simulink involves simulating the charging and discharging of the battery cells and introducing an internal short circuit in one of the parallel cells. The protection mechanism is designed to detect the short circuit and trigger the fuse to blow, which breaks the electrical connection between the shorted cell and the other parallel cells. As a result, the remaining parallel cells are protected from any potential damage caused by the short circuit.

Overall, the implementation of internal short circuit protection using MATLAB Simulink provides a reliable and effective means of protecting the battery cells from damage caused by excessive current flow due to internal short circuits and enhances the safety and reliability of the battery management system. The results for internal short circuit simulation are shown in Fig. 10.

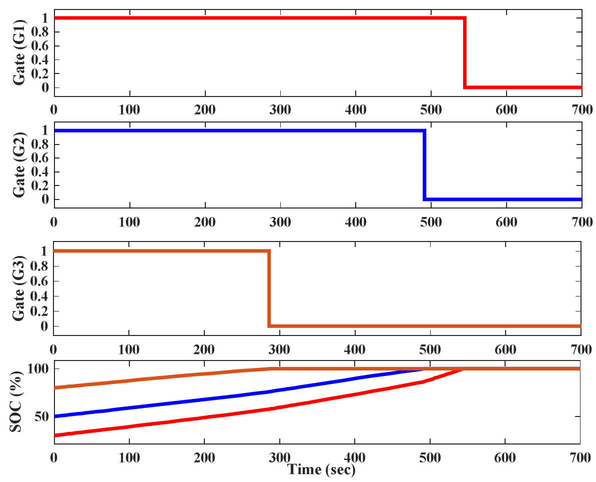

Fig. 5 Over-charge protection test.

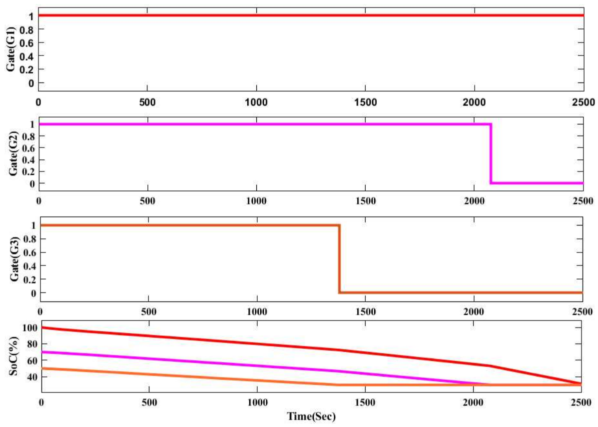

Fig. 6 Over-discharge protection test.

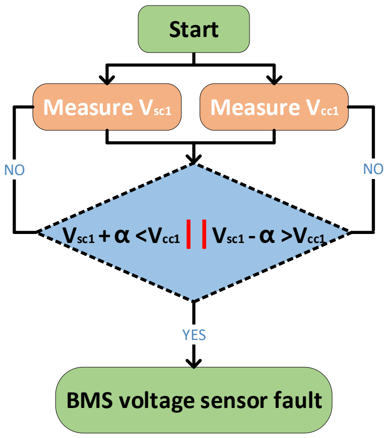

Fig. 7 Algorithm for voltage sensor fault detection.

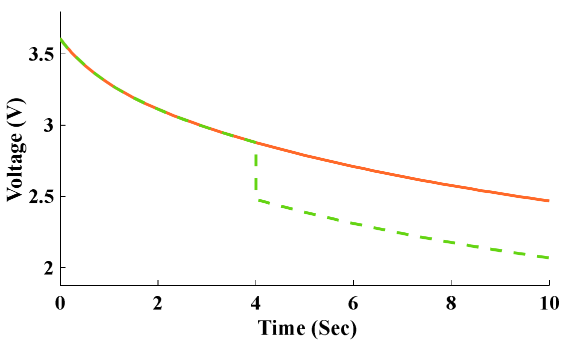

Fig. 8 Fault is introduced in voltage sensor.

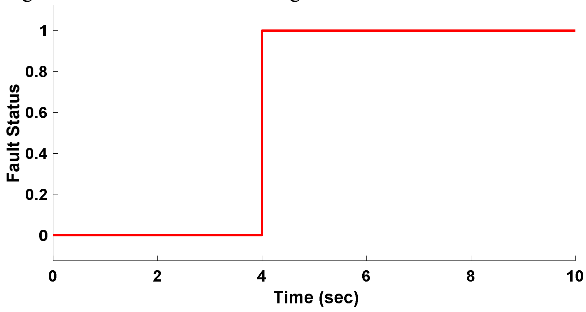

Fig. 9 Voltage sensor fault detection.

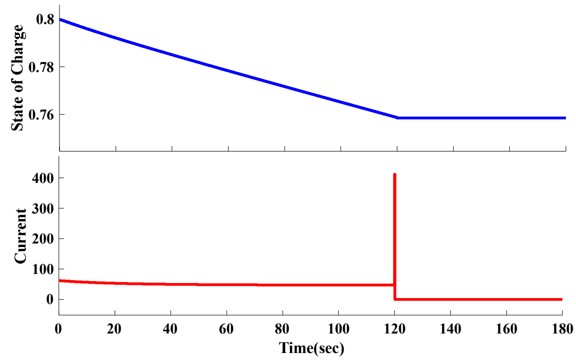

Fig. 10 Results for fuse blown at excessive current flow.

IV. CONCLUSIONS

The proposed architecture provides a comprehensive solution for battery management that addresses the critical issue of fault handling in parallel connected cells. By integrating centralized and decentralized BMS, this approach overcomes the limitations of conventional BMS systems and enhances the performance and efficiency of battery management. The use of smart cell architecture with charge-discharge MOSFETs ensures that SOH reduction is avoided, which is a significant advantage over conventional cell balancing techniques. Additionally, the presented simulations for over-charge and over-discharge protection, sensor fault detection, and internal short circuit demonstrate the effectiveness and reliability of the proposed architecture. Overall, this paper provides a valuable contribution to the field of battery management and lays the foundation for future research and development in this area.

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