Design of an Optimized Passive Balancing System with Low Power Losses

Düşük Güç Kayıplarına Sahip Optimizasyonlu Pasif Dengeleme Sistemi Tasarımı

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ABSTRACT

This study presents an approach to the design of a Battery Management System (BMS), focusing on the effective discharge processes of a battery pack consisting of lithium-ion cells. Addressing potential risks associated with the battery pack, it considers factors such as incorrect connections, unwanted short circuits resulting from external interventions, and adverse environmental conditions. Interventions are made to address issues that may arise due to these risks, including excessive temperature, overcurrent during charge-discharge cycles, and overvoltage. Additionally, emphasis is placed on using cell voltages at close levels to enhance the efficiency of the battery pack.

The proposed BMS system adopts a passive balancing method with an ARM-based STM32L433 microcontroller. The project prefers surface-mounted materials and double-layered electronic board designs, which are highly ergonomic when considering energy density and system specifications. Compared to other designs, the selection of electronic component casings and usage methods in this project provides advantages in terms of size and safety. Furthermore, the battery pack's design allows for easy adjustment of the parallel module count according to the system in use, offering a flexible structure. Consequently, the suggested BMS system enhances adaptability, particularly concerning current capacity. This article serves as a significant resource for researchers and engineers seeking to enhance the safety and performance of electric vehicle batteries while achieving size and cost advantages.

Keywords: Battery Management System, BMS Design, Passive Balanced BMS

1. INTRODUCTION

Lithium-based batteries play a crucial role in meeting today's energy needs economically and efficiently (Van Mierlo et al., 2006). These batteries exhibit superior characteristics such as high energy and power density, nearly 100% efficiency, long cycle life, and low self-discharge capacity (Ding et al., 2019). They are widely utilized as energy storage and power sources in various applications, including telecommunications, renewable energy, robotics, and electric vehicles. Despite these outstanding features, the electrochemical properties of lithium-based batteries encounter design limitations. Constraints in charge, discharge, and temperature parameters are significant factors affecting battery design (Lipu et al., 2021).

The safety of lithium-based batteries, along with the enhancement of their service life and performance, has become increasingly important (Gabbar et al., 2021). The demand for Battery Management Systems (BMS) is also rising in parallel with this trend. BMS is designed to control battery packs consisting of numerous cells during charge and discharge processes, rather than a single-cell battery. These systems continuously monitor essential parameters such as current, voltage, and temperature, intervening in case optimal limits are exceeded. Additionally, BMS is utilized to coordinate the series and parallel connections of battery packs (Steinhorst et al., 2006).

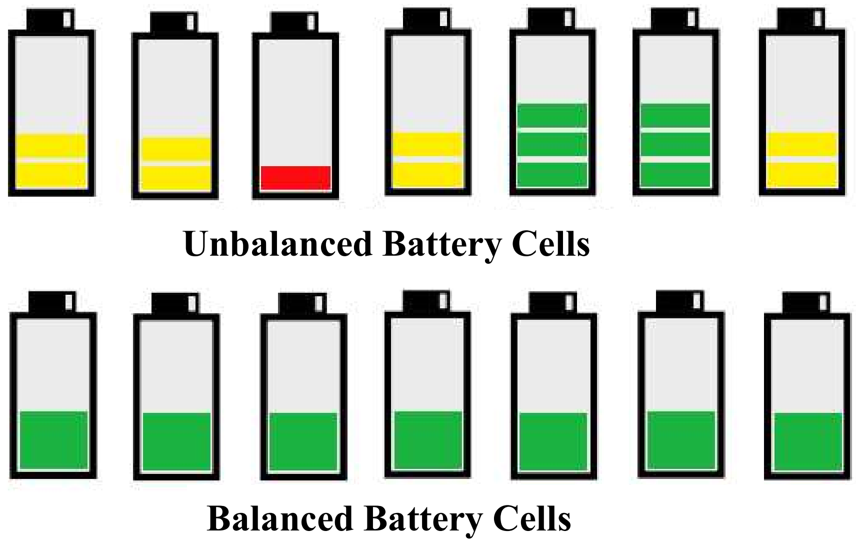

Figure 1. Battery Cells

In lithium-based battery systems, the capacities of batteries decrease during charge and discharge processes, and without proper balancing, batteries can rapidly deteriorate as a result of these procedures (Väyrynen and Salminen, 2012). Therefore, the balancing of battery packs holds significant importance. Figure 1 illustrates balanced and unbalanced battery cells. Passive balancing employs resistance to equalize the energy of cells with excess energy. On the other hand, active balancing achieves balance by charging other cells with the high-energy cell (Baronti et al., 2012). However, passive balancing is preferred due to its simpler control structure, lower cost, and ease of implementation (Saw et al., 2016).

Battery Management Systems (BMS) not only perform voltage balancing but also carry out a range of tasks such as high-low voltage protection, current protection, temperature tracking, cell health monitoring, voltage balancing processes, and the use of high-efficiency cells (Habib et al., 2021). Figure 2 provides an overview of the general structure of a BMS.

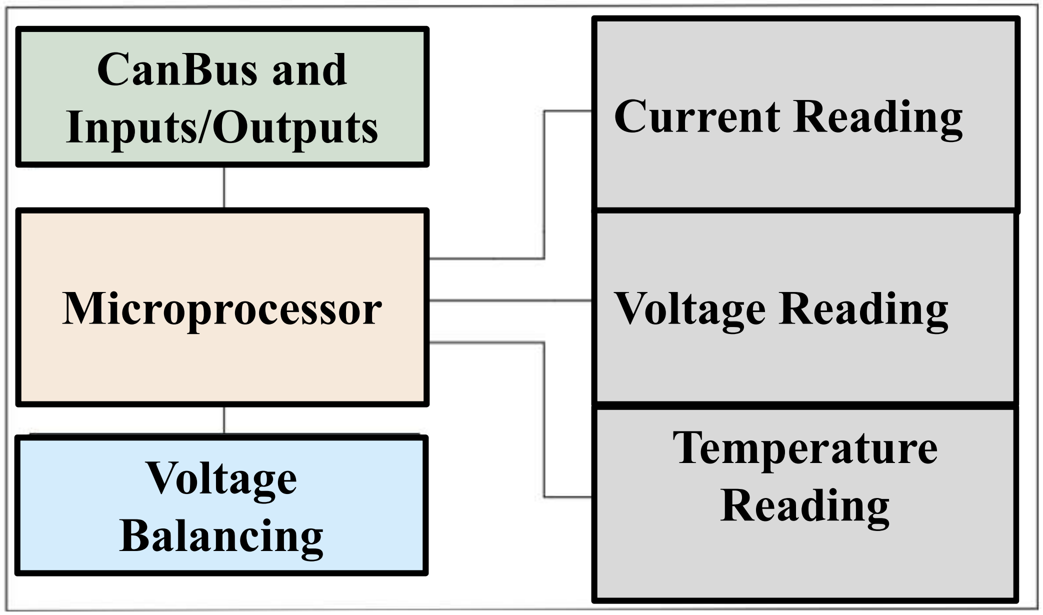

Figure 2. General Structure of BMS

Monitoring parameters such as Cell Health State (CHS) and Cell State of Charge (SOC) is crucial for the efficiency and lifespan of batteries. However, continuously monitoring these parameters increases the computational load on Battery Management Systems (BMS) and raises costs. Therefore, in commercial BMSs, these parameters are periodically checked through tests (Zou et al., 2015). In high-power capacity BMSs used in electric vehicles, continuous monitoring of cell voltages, SOC, CHS, and temperatures is necessary. This traceability is provided by BMSs that enable real-time communication through the CAN-BUS communication protocol (Xing et al., 2011).

In conclusion, the effective management of lithium-based battery systems is of critical importance for the development of energy storage technologies and the widespread adoption of electric vehicles. To achieve this goal, battery management systems and balancing methods are continuously being developed and improved.

2. BATTERY PACKS AND BATTERY MANAGEMENT SYSTEMS

Energy storage solutions for electric vehicles have diversified in tandem with the rapid changes in the automotive industry (Ribeiro et al., 2001). Lithium-Ion Batteries, the most widely used battery type in electric vehicles, are popular for their high energy density and long lifespan. However, lithium-ion batteries have both advantages and disadvantages. Nickel-Metal Hydride (Ni-MH) Batteries find applications, particularly in hybrid electric vehicles, due to their low cost and environmentally friendly features (Joshi and Deshmukh, 2006). Phosphate Lithium Iron (LiFePO4) Batteries adhere to high standards of safety and durability, making them a preferred choice for commercial vehicles like electric buses (Hubble et al., 2022). Lithium Polymer Batteries can be designed in various shapes due to their flexible form factors and may have advantages in specific usage scenarios due to their lightweight nature (Hubble et al., 2022). The design of the battery pack used in electric vehicles is crucial for the safe and effective integration of batteries into vehicles. Cell Arrangement, considering the effects of series and parallel connections, has a significant impact on the efficiency and weight of the battery pack. Voltage Balancing is essential for balancing voltage differences between battery cells, contributing to extending battery life and ensuring safety. Current Protection plays a critical role in preventing overcurrent, which is crucial to preventing battery damage (Xu et al., 2021). Temperature Monitoring ensures that batteries operate within the appropriate temperature range, increasing efficiency and ensuring safety. Cell Health State Monitoring involves continuously monitoring the condition of battery cells, with interventions made when necessary (Affanni et al., 2005). Energy Management is controlled by Battery Management Systems (BMS) to efficiently utilize energy from the battery and enhance vehicle performance.

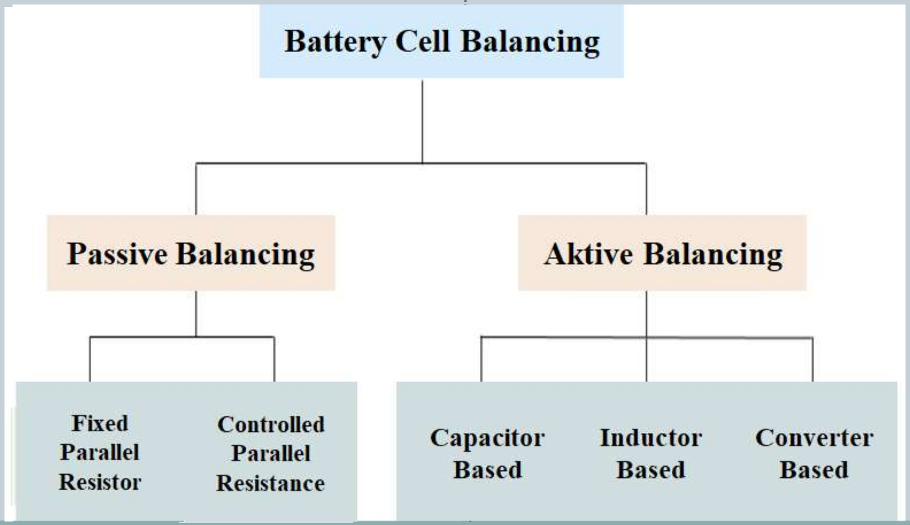

Figure 3. Types of BMS

Battery Management Systems (BMS) are divided into passive and active balancing methods. The balancing methods in this field are illustrated in Figure 3. The BMS algorithm is initiated through microcontrollers, which set the initial parameters. While temperature and voltage measurements are carried out by the microcontroller, the BMS evaluates the total current of the battery pack measured through resistance. During the charging process, maximum charge and temperature limits are monitored, and if necessary, the balancing process is initiated. During the discharge process, the lower voltage limits of the cells are monitored, and protective measures are taken. The relevant structure is provided in Figure 4.

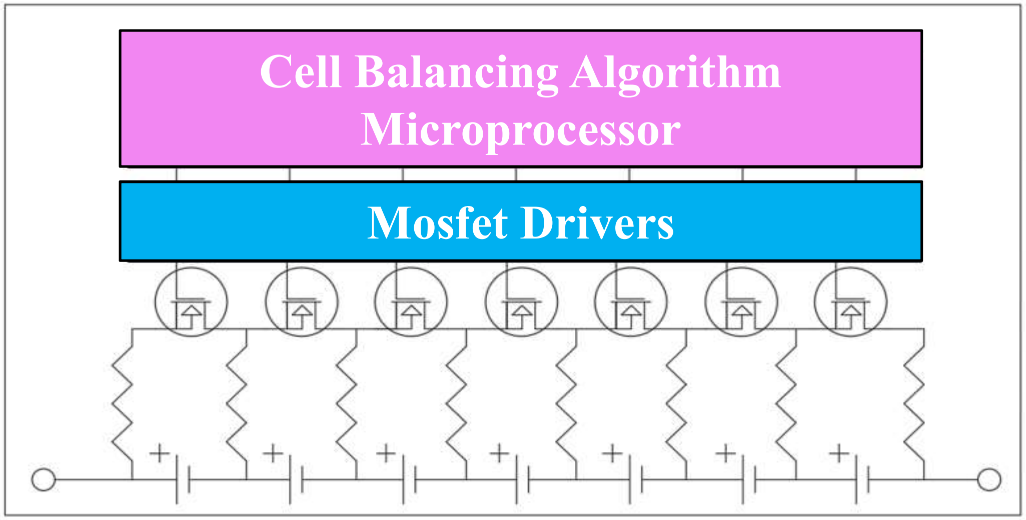

Figure 4. Passive Balancing BMS Cell Measurement and Balancing

Battery pack's total current is measured through the voltage drop across the resistor and evaluated by the Battery Management System (BMS). During the charging process, the maximum charge and temperature limits of battery units (4.2 V and 60°C) are monitored. Passive balancing, applied in two ways in the design, is employed. The first method initiates the balancing process when the batteries reach their upper limit. In this method, the current flowing to cells reaching the upper limit is dissipated through high-power resistors to balance the energy. The second method utilizes a differential balancing algorithm. A battery with a lower voltage compared to others is identified and compared with the rest. When the voltage difference exceeds a certain value, energy is again dissipated through resistors to achieve balance.

3. IMPLEMENTATION OF THE PROPOSED BATTERY MANAGEMENT SYSTEM IN MATLAB-SIMULINK SIMULATION ENVIRONMENT

Successful simulations of the passive balancing of the Battery Management System (BMS) in electric vehicles have been conducted, yielding positive results. These simulations were performed using the Matlab-Simulink platform, and the design of the BMS was modeled based on these simulations. The simulation results were utilized to assess the effectiveness of the algorithm. The Matlab interface is presented in Figure 5.

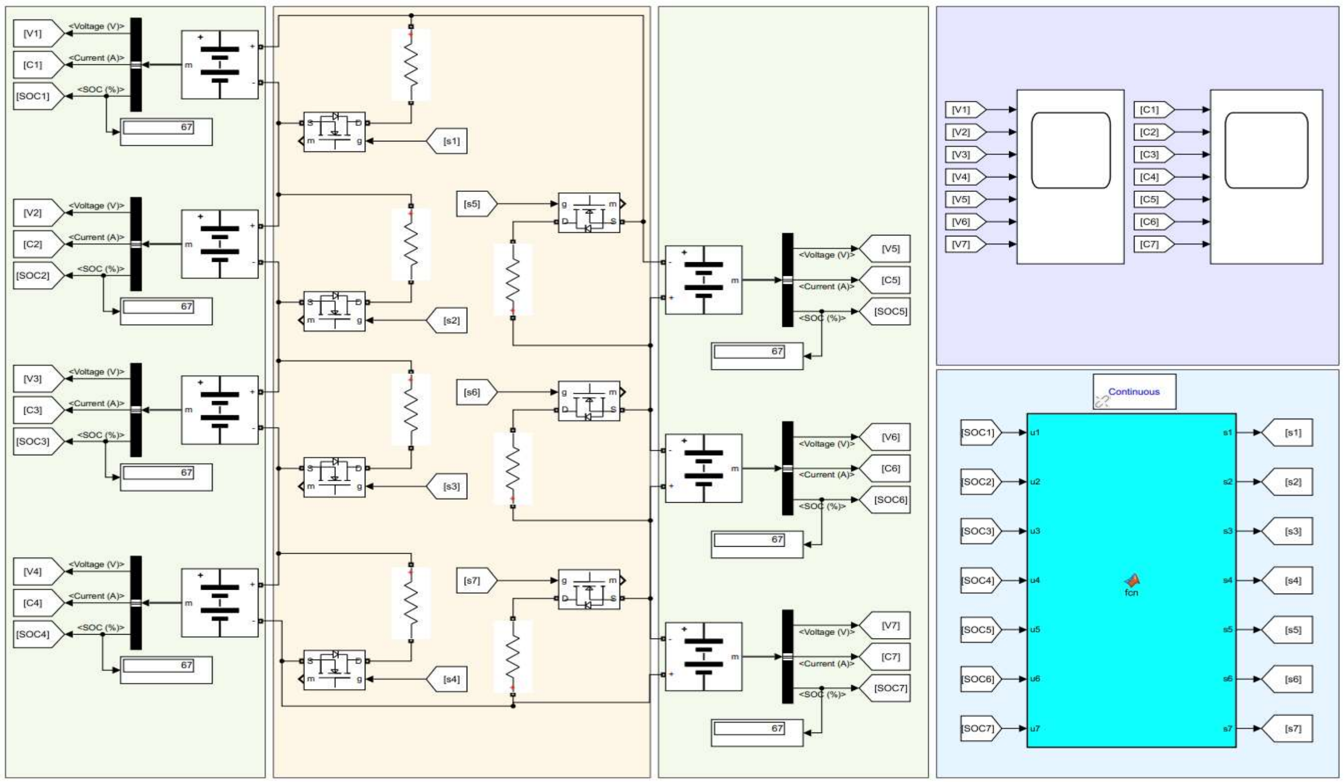

Figure 5. Matlab Simulink Passive Balancing BMS Simulation

Changes were made to various State of Charge (SoC), voltage, and load values to optimize the design of the Battery Management System (BMS) passive balancing algorithm. Additionally, discharge resistance was considered as part of this optimization process. These modifications and adjustments were made to adapt the performance of the BMS to different operating conditions and achieve maximum efficiency. This process was carried out by simulating various scenarios necessary to enhance the effectiveness of the algorithm over a broad operating range. As a result, the Battery Management System has been made capable of reliably operating under different charge states and working conditions. The analysis results demonstrate how the BMS control structure charges the battery at different charge current levels and the voltage variation of each cell during charging. The initial conditions of the cells were diversified to create different simulation scenarios.

4. IMPLEMENTATION OF THE PROPOSED BATTERY MANAGEMENT SYSTEM

The recommended Battery Management System (BYS) utilizes two different processing units: a central microcontroller and a secondary microcontroller. The chosen microcontroller is the STM32L433, a 32-bit ARM Cortex-M4 series from STMicroelectronics. This selection was made considering crucial features such as low power consumption, high performance, and signal processing capabilities. It operates with a consumption of 8.56mA during active operation and 1.06uA in sleep mode. The accurate and stable detection of voltage differences between cells during charge and discharge processes is of critical importance. The STM32L433 microcontroller is equipped with three internal channels of 12-bit ADC, providing a sensitivity of 0.809 mV in cell voltage readings. The microcontroller can operate at frequencies up to 80 MHz, ensuring fast data processing and response times. Its low power consumption during sleep mode contributes to extending battery life. The STM32L433 microcontroller is also employed as the secondary microcontroller in the recommended BYS due to its wide availability and high-performance values in the market.

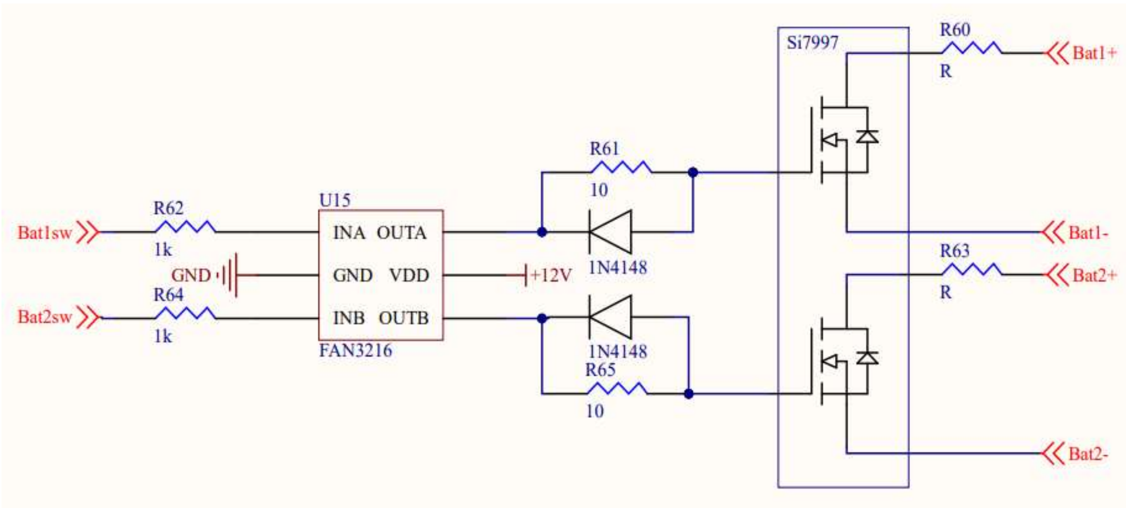

Figure 6. Schematic Used for Cell Balancing

FAN3216 is a low-side driver integrated circuit (IC) commonly used to control MOSFET or IGBT switches. This IC operates effectively in high-speed switching applications, providing fast switching processes with low delay times. FAN3216 is employed as a reliable driver in various applications such as industrial control systems, power supplies, and motor drivers. SI7997, on the other hand, is a switching device solution in power electronics applications, offering high performance with low RDS(on) values. This component is used for switching operations in electrical circuits and contains two N-channel MOSFETs. It is particularly preferred in applications requiring power switching. The usage of MOSFET and MOSFET driver is illustrated in Figure 6. Figure 7 provides a visual representation of the package with two MOSFETs, highlighting its size and material advantages.

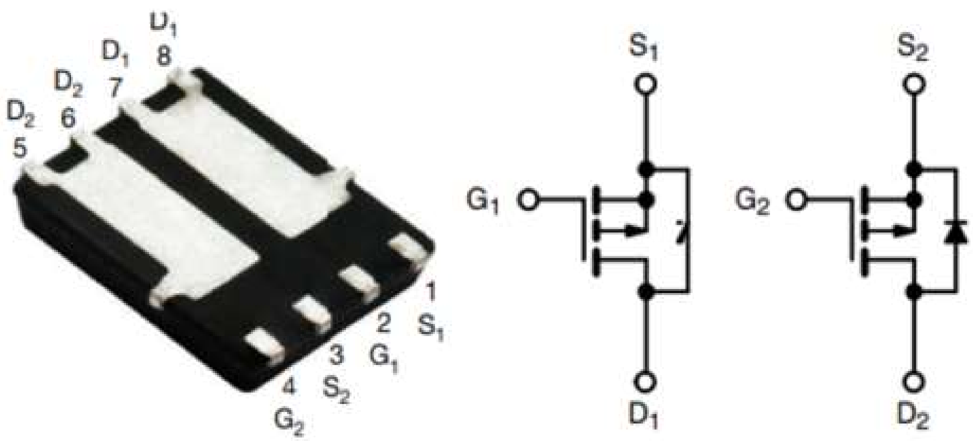

Figure 7. Cell Balancing Switching Element

The article addresses the voltage divider circuit, a commonly used method for measuring and balancing battery voltages. In Figure 7, the relevant schematic for measurement is provided. During the reading process, voltage values are continuously monitored. When approaching the predefined limit values, voltage balancing processes are carried out at ideal time intervals. The passive balancing method, operating on the principle of converting excess energy to heat during the charging phase, ensures the balancing of voltage values in battery cells due to the varying internal resistance of each cell. Voltage measurement, monitoring, and reliable balancing operations can be performed using the low-power and high analog-to-digital resolution STM32L433 microcontroller.

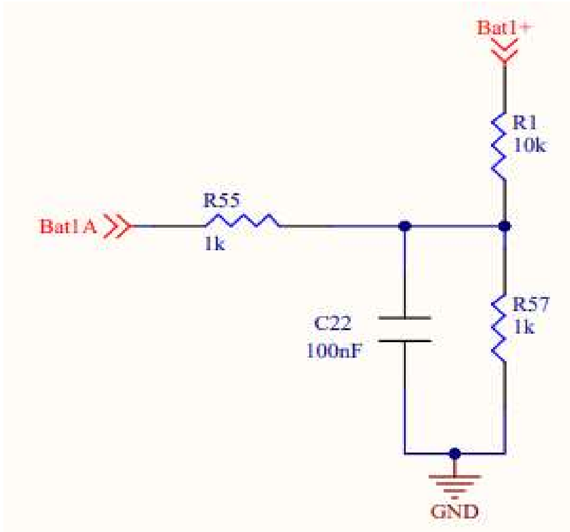

Figure 8. Schematic Used for Cell Measurement

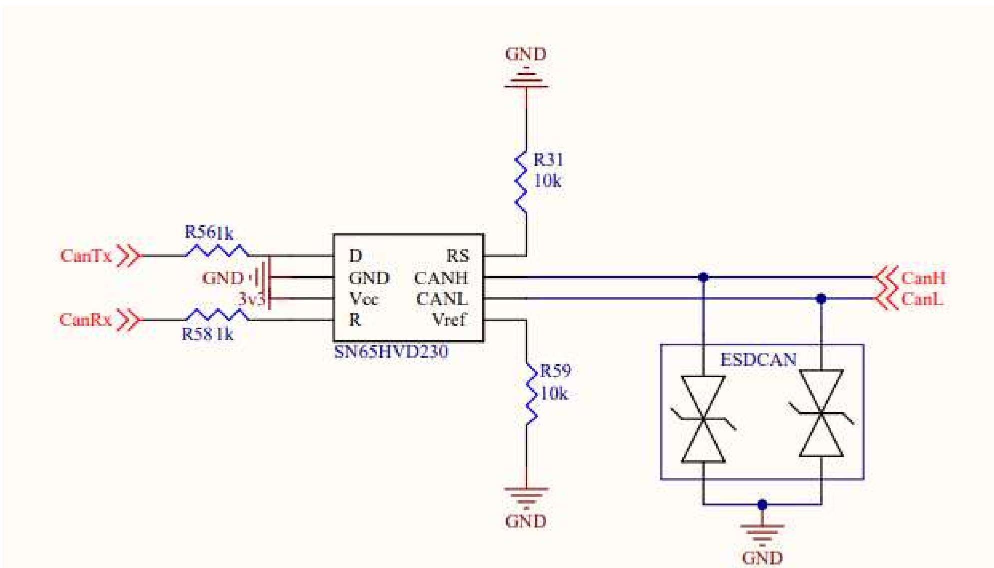

Figure 9. CAN Communication Hardware Structure

Electronic communication through the Controller Area Network (CAN-BUS) protocol is implemented, especially in high-power Battery Management Systems (BYS), particularly those used in electric vehicles, to ensure high levels of system security. To achieve this high level of security, continuous monitoring of battery cell values is necessary. This monitoring capability is facilitated by the CAN-BUS, which has serial communication capabilities (Stuart et al., 2002). The CAN communication protocol has been used for data transmission and control. This communication protocol is protected through integrated circuits, preventing faults in the Battery Management System (BMS) from affecting other cells (Er and Bingöl, 2022). The hardware structure of the CAN communication protocol is illustrated in Figure 9. The ESDCAN24 TVS diode, which has a 30kV IEC contact rating and AEC Q101 certification, enhances the system's reliability (Lepkowski et al., 2005).

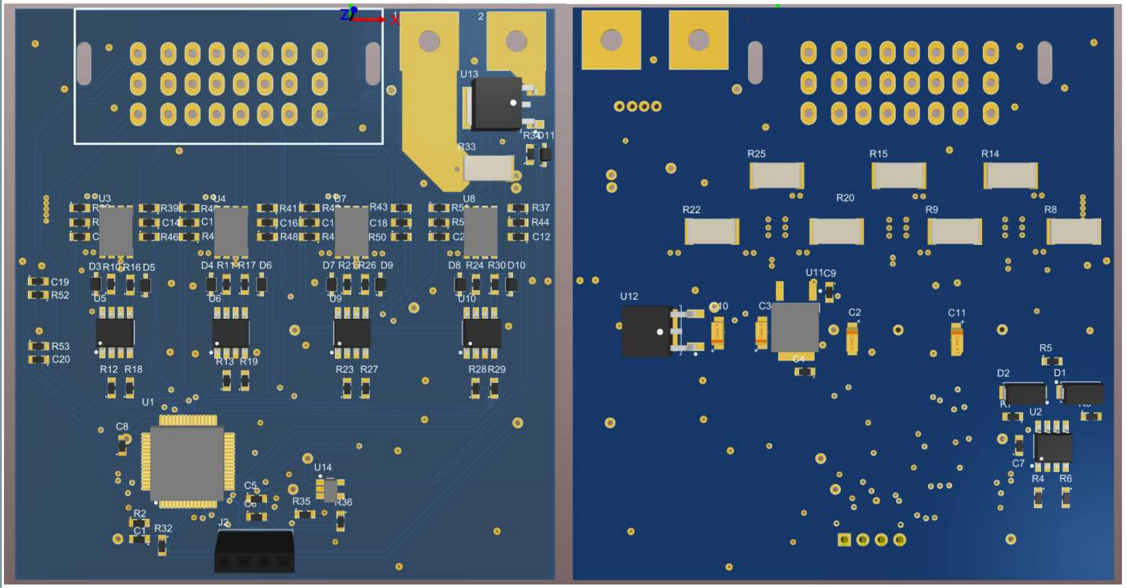

Figure 10. Altium Designer 3D View

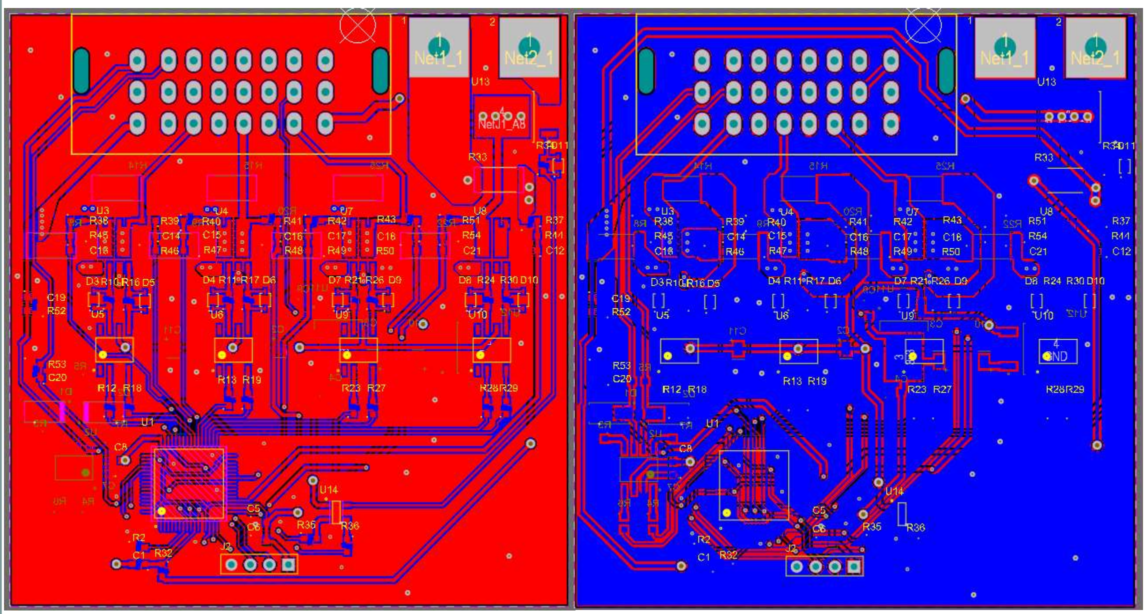

Figure 11. Altium Designer 2D View

Schematic designs have been implemented in the Altium Designer program and placed on the board to create a double-sided Battery Management System (BYS) design. Along with this board, the effectiveness and practical applicability of the BYS will be demonstrated. Figure 10 presents the 3D view of the design, while Figure 11 displays the 2D design.

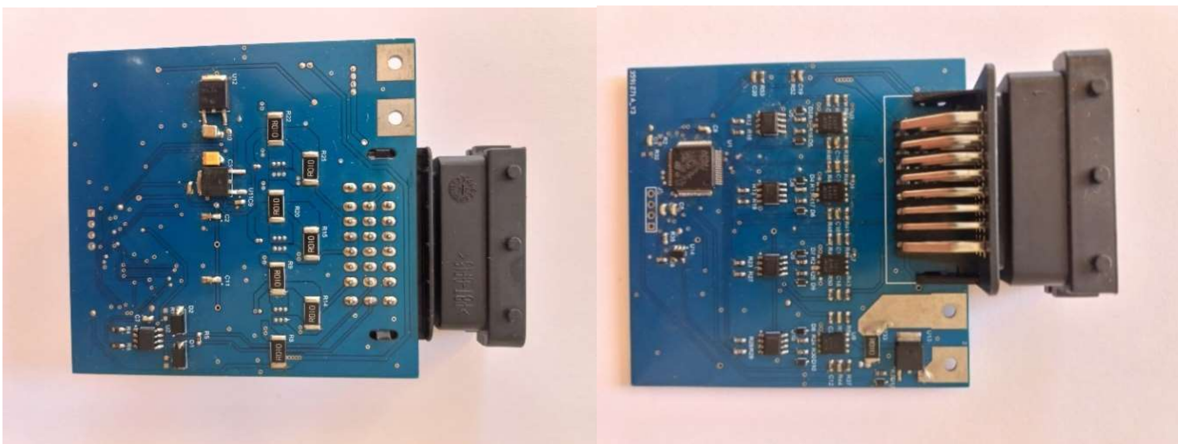

Figure 12. Circuit Board of the Implemented System

The designed BYS board is presented in Figure 12, and its operation has been confirmed by connecting and testing 7 Li-ion battery cells. Data from the battery unit is transmitted through the plug-and-play connections on the BYS board. Printed circuit boards prepared with Altium Designer were used for data transmission and all connections. The PCB process for both the BYS and other boards was carried out as double-sided.

5. CONCLUSION AND EVALUATION

In this study, battery balancing systems for electric vehicles have been examined, focusing on the problems that may arise when modules in series electrical connections do not have equal voltage. To overcome these issues, battery management systems with passive balancing capabilities are utilized. While passive balancing systems offer a cost advantage, they can lead to energy waste and long balancing times, making active balancing systems an alternative. However, active balancing systems are characterized by high costs and complexity. Therefore, the selection of balancing methods depends on design requirements, and determining when and under what conditions the balancing process will take place is crucial.

Furthermore, a new Battery Management System (BYS) has been developed and tested using passive balancing methods for Li-ion cells with a rated voltage of 3.6V and a rated current of 2.85Ah. The BYS makes all measurement data traceable through the ARM-based STM32L433 microcontroller, enabling the early detection of issues. Successful simulations for passive balancing of the battery management system have been conducted as part of this study using Matlab-Simulink, with positive results presented as part of the research. These simulations, performed using the Matlab-Simulink platform, were utilized to model the BYS design. The simulation results were used to evaluate the effectiveness of the algorithm, and these outcomes are presented as part of the study.

Lastly, a low-cost BYS has been designed and prototyped to control the energy flow. This design incorporates Surface Mount Device (SMD) components to reduce costs and size by utilizing a central BYS system. The BYS card includes features that protect battery cells from high and low voltages and temperatures. Additionally, a passive balancing system is used during cell charging to achieve maximum efficiency. The BYS can perform State of Charge (SoC) calculations for each cell and predict State of Health (SoH). Given the advantageous design and cost factors of passive balancing systems, the designed BYS is considered suitable for current applications.

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