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Battery Management System For Swappable Batteries In EV's

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May 28, 2025

Approval

Approval of the Department of Electronic and Telecommunication Engineering

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Declaration

We declare that the dissertation titled Battery Management System For Swappable Batteries In EV's and the work presented herein are our own. We confirm that:

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- any part of this dissertation that has previously been submitted for a degree or any other qualification at this university or any other institution has been clearly stated;
- all published work of others that we have consulted is clearly attributed;
- all quotations from the work of others are clearly indicated, with the source duly acknowledged;
- except for such quotations, this dissertation is entirely our own work;
- all main sources of help have been acknowledged;
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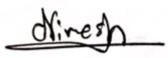

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Abstract

We introduce a Swappable Battery System for Electric vehicles to address the frequent recharging challenges faced by electric taxi vehicles. The system is structured into three main components: the Battery Management System (BMS) for individual battery packs, the central unit integrated into the vehicle, and the docking station for battery swapping. Key features of the implementation include energy-efficient cell balancing through an active balancing method, protection against over-current using an active charging technique, real-time communication using the CAN bus protocol and enhanced safety and security with authentication methods. The new system was tested on an electric tuk-tuk, and its performance and reliability were found to meet industrial standards, demonstrating its suitability for such vehicles.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In this chapter,we will explore the motivations behind initiating this project and identify the specific problems it aims to address.We will then outline the project's objectives and scope, detailing its unique aspects,potential beneficiaries, and possible applications.This chapter will conclude with a navigation guide for the subsequent chapters.

1.1 Motivation

EVs are at the forefront of the transition to sustainable transportation. According to data from Goldman Sachs Research, EVs are projected to constitute nearly half of global car sales by 2035.However,one of the primary challenges facing EV adoption is the time required for frequent recharging,which can lead to substantial downtime for drivers.For a long-distance drive, driver need to charge several times during the trip, and it will waste lot of time.An effective solution to this challenge is the implementation of a swappable battery system.By allowing drivers to exchange depleted batteries for fully charged ones, the time spent on charging can be drastically reduced.Moreover, with batteries being charged at dedicated charging stations, the costs associated with energy consumption can be optimized.

1.2 Problem Statement

The current model of single, non-swappable battery packs necessitates long charging times, contributing to "range anxiety" and limiting the practicality of EVs for users with immediate mobility needs.Existing BMSs are designed for these single, fixed battery packs, focusing on monitoring and protecting individual cells within a pack. However, they often fall short in addressing the unique challenges presented by multi-battery pack systems, particularly in vehicles designed for battery swapability. These challenges include managing the health and charge levels of multiple packs simultaneously,ensuring uniformity across different packs, and maintaining safety standards during the swapping process.

1.3 Primary Objectives

Primary objectives of our project can be listed as below.

- Designing BMS specifically for multi-pack, swappable lithium-based battery packs. This innovative BMS should address the safety, efficiency, and convenience challenges identified in current systems, making it a cornerstone technology for advancing the EV industry.
- Implementing a control unit within the BMS to ensure the batteries are exclusively used for their designated purpose in electric vehicles, maintaining system integrity and safety.

1.4 Project Scope

This project has three main scopes. The first is designing a new BMS specifically for the swapping battery packs.The second involves developing a controller unit,integrated into both the vehicle and docking station, that manages the charging and discharging of the batteries. Charging or discharging will only be possible when connected to this controller unit. The third scope involves ensuring that the new controller unit can communicate effectively with the control system of the docking station,which handles user authentication and other essential functions.

1.5 Novelty and the Uniqueness of the Project

Current BMSs typically use passive balancing, which dissipates excess energy from overcharged cells as heat, resulting in energy loss. Moreover, existing BMSs are limited in the number of parallel connections they can handle, restricting the overall current output.

Our proposed BMS offers the following key improvements:

- **Active Balancing:** By implementing active balancing, our system efficiently redistributes energy among cells, reducing energy waste during charging and discharging.
- **Increased Scalability:** AThe design supports more parallel connections, allowing for higher current output and better performance in large-scale applications.

1.6 Beneficiaries and Potential Applications

This project primarily targets future taxi drivers who may rely on EVs for their services. These drivers spend more hours on the road each day and their batteries are subject to frequent charging cycles, leading to quicker depletion. Implementing battery swapping methods can significantly benefit these drivers by minimizing downtime. Additionally, since these drivers typically operate within a limited geographic area, the need for numerous docking stations is reduced, making battery swapping a practical and efficient solution for their specific use case.

1.7 Navigation to the Chapters

The remaining chapters of this report are organized as follows: Chapter 2 provides a literature review of the project outlining the existing BMS, their charging and discharging methods and existing method in communication in vehicles. Chapter 3 details our methodology, including the proposed system architecture, analysis of alternative methods, risks and risk management plan, the estimated budget, task delegation among group members and timeline of the project; and Chapter 4 provides discussion and conclusions by summarizing the main findings of the literature review, feasibility of the project, impact of the project and further conclusions.

Chapter 2

Literature Review

EVs are gaining popularity for their eco-friendliness and efficiency, but their reliance on high-capacity lithium-ion batteries necessitates a sophisticated BMS. This chapter examines the critical aspects of BMS, including battery monitoring, cell balancing, and communication protocols, to ensure optimal battery performance and safety.

2.1 BMS Requirements

EVs are increasingly favored for their fuel efficiency and eco-friendliness, appealing to automakers, governments, and consumers alike. Unlike traditional vehicles with internal combustion engines, EVs rely on battery-stored electric energy to power electric motors. As a result, EV batteries need to have high energy capacity and long life to maximize driving range. To meet these needs, lithium-ion batteries are commonly used in EVs due to their high energy density and efficient charging capabilities. However these batteries require more careful management system due to overcharged and undercharged of batteries.This requires the adoption of a proper BMS to maintain each cell of the battery within its safe and reliable operating range [1, 2].

2.2 Battery Monitoring

Key features of BMS are battery monitoring, cell balancing, safe charging and discharging,Galvanic isolation and communication interface [3]. When it comes to battery monitoring mostly focused on cell voltages measurements, SOC(state of Charge) measurement, current and cell temperatures.ICs(Integrated circuit) usually are able to measure voltage, temperature and current and use simple methods to estimate the battery's current State of Charge (SOC).There are analog front-end ICs and digital front-end ICs. Since MCU of BMS makes decisions depending on monitored data, digital front-end ICs are more preferred. When selecting monitoring IC, there parameters to be considered according to application. They are Number of series cells (min, max), Vin (max), Features(Cell balancing, Integrated ADC, Multi-cell support, Open-wire detection, Overtemperature protection, Overvoltage protection, Separate MCU requirement..), Operating temperature range, Battery overvoltage protection (min, max) and Communication interface etc [4].

2.3 Cell Balancing

Voltage variations occur within battery cells during charging and discharging, leading to imbalances. These imbalances are unavoidable due to differences in electrical and chemical properties, aging, production tolerances, internal impedance, and temperature variations. As a result, the battery's lifespan and charge potential are reduced, significantly affecting overall performance. Additionally, factors like temperature and passivation further decrease battery capacity, worsening with cell aging.Passive cell balancing and active cell balancing are two main techniques that are used in BMS [5]. Passive cell balancing method has low cost and easy implementation while the requirement for high power resistor, energy dissipation, and low efficiency are its disadvantages. Active cell balancing is low power dissipation and smaller equalizing time while high complexity of circuit and needed large space on circuit are disadvantages [6]. Proposed BMS is used active cell balancing considering low the power dissipation.

Active cell balancing is crucial for the longevity and efficiency of high-capacity lithium-ion batteries in EVs.Among the main methods for active cell equalization capacitor-based [7], inductor-based [8], and DC-DC converter-based [9] the latter is the most suitable for high-capacity cells. Capacitor-based balancing struggles with large energy transfers, making it inadequate for our needs. Inductor-based balancing, while better, lacks the precision required for accurate voltage control in high-capacity applications. Given these limitations, we have chosen the DC-DC converter-based approach for our BMS. This method efficiently handles high currents and provides precise voltage balancing. Typically, it involves using a separate DC-DC converter for each cell [9], which can be complex and costly. To streamline this, we propose using a single DC-DC converter with a switch matrix, allowing us to sequentially balance each cell. This method, documented by Texas Instruments [10] , [11], has proven effective in large-scale applications.

Inductive active cell balancing is a widely studied technique that efficiently redistributes energy between battery cells using magnetic components such as inductors or transformers. Unlike capacitor-based balancing, which struggles with large energy transfers, inductive balancing provides higher efficiency and improved energy transfer rates. This method operates by temporarily storing excess energy from higher-charged cells in an inductor and then transferring it to lower-charged cells. The key advantages of inductive balancing include reduced energy losses, faster equalization times, and improved overall battery lifespan [12]. However, the complexity of the circuit and the need for precise control strategies present challenges in its implementation. In our study, we examined the ETA3000 [13], an inductive active balancing IC, which integrates key control functions to simplify circuit design while maintaining high efficiency [14]. By leveraging the capabilities of this IC, our BMS design optimizes energy redistribution among cells, enhancing battery performance and longevity while ensuring minimal power dissipation.

2.4 Communication

Communication Protocol is a protocol used to transfer signals, data stream, or both between two devices in the BMS for EVs, this helps efficient exchange of Data from battery packs and main controller [15]. Modbus RS232 and Modbus RS485 protocols are well known because of their recognized reliability history, which falls in line with the implementations that need a BMS. Modbus RS232 is easy to use and cheap but with a small data transfer rate and short communication distance [16]. Modbus RS485 offers extended range and faster data rates, which makes it ideal for use-cases needing distances as well Nevertheless, the best choice between these two might be automotive often found within Controller Area Network (CAN) bus for producing tool strategies. The CAN protocol is famous for its robustness and real-time data exchange sometimes also combined advanced error-handling mechanisms making this one of the best choices in an EV environment since those vehicle system requires fast communication and very dynamic circumstances [17]. Its capacity to efficiently handle multiple nodes along with its fast communication make it ideal for modern BMS implementations.

2.5 Current Limiting

Current limiting is a critical function in power electronic systems, particularly in battery charging applications, where controlling inrush current and preventing overcurrent conditions is essential for ensuring safety, enhancing battery lifespan, and maintaining system reliability [18] [19]. Various methods have been explored in the literature, including linear regulators, resistive current limiters, and more efficient switch-mode solutions such as buck converters with feedback control [20] [21] [22]. Among these, switch-mode current limiting using feedback from a shunt resistor has proven to be both precise and energy-efficient, offering dynamic adjustment of the output based on real-time current measurements. Recent studies highlight the integration of microcontrollers or PWM controller ICs with current sense amplifiers to achieve closed-loop current regulation, especially in systems that require programmability and adaptability to varying loads [23]. Additionally, the use of common positive configurations in Battery Management Systems (BMS) simplifies circuit design by allowing ground-side current sensing and MOSFET control, reducing the need for complex high-side drivers. These advancements support the development of compact, efficient, and robust current limiting circuits suitable for modern electric vehicle (EV) charging and battery protection systems.

As summary, a well-designed Battery Management System is essential for maximizing the efficiency and longevity of EV batteries. This chapter has covered the key elements of effective battery management, including monitoring, balancing, and communication, which collectively contribute to the reliable and safe operation of electric vehicles.

Chapter 3

Methodology

3.1 Introduction to the Methodology

In this chapter, we discuss our approach, and the methods used to achieve the project objectives. The implementation is divided into three main sections: Battery Management System (BMS) for each battery pack, Central Unit for managing the charging and discharging process, and the Swapping Station, where battery exchange takes place. These three sections are developed in parallel to ensure smooth integration and functionality. In the following sections, we will examine the methods applied in each part of the system.

3.2 Project Approach

3.2.1 Battery Managment Systerm for Each Battery packs

Monitoring IC with MCU

Monitoring of 16-series cell is main objective of this IC BQ79656-Q1. The BQ79656-Q1 is a functional safety-compliant battery management system (BMS) IC (figure 3.1) designed for automotive applications, supporting 16-cell battery packs. It offers high-accuracy voltage and current measurements with ± 1.5mV ADC accuracy and integrated current sensing for improved state-of-charge (SOC) estimation. The device includes internal cell balancing with automatic thermal management, a fault diagnostic system, and an isolated differential daisy-chain communication interface for reliable multi-device communication. The battery monitoring IC continuously monitors critical parameters , including individual cell voltages, pack current, and temperature. This data is transmitted to the main microcontroller (STM32), which processes the information to manage the battery's operation.Discharging control is achieved using a contactor switch, which provides a reliable mechanism for managing power delivery to the load.

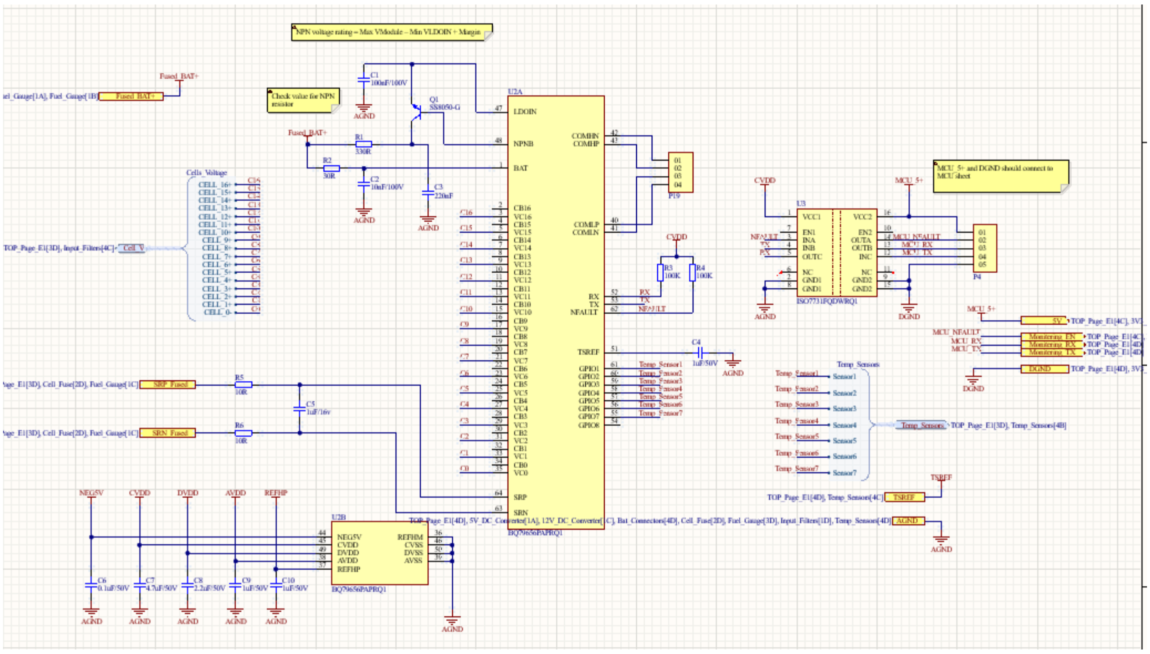

Figure 3.1: Schematic for Monitoring IC

An EEPROM module (figure 3.2) is integrated into the system to store essential operational data, including the state of charge (SOC), state of health (SOH), CAN bus address, and security and authentication parameters. This ensures secure and consistent operation across various environments. The design also features a user interface with an OLED display and a buzzer, enabling real-time feedback and alert notifications for the user. A fuel gauge is included to track charge and discharge cycles, ensuring accurate SOC calculation and improving the reliability of energy management.

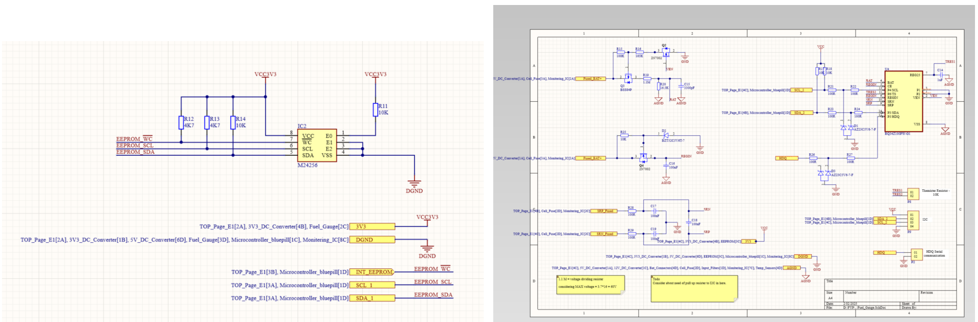

Figure 3.2: Schematic for EEPROM and Fuel Gauge

The main microcontroller (figure 3.3) processes all monitored and measured data to execute critical BMS functionalities. These include managing cell balancing, controlling charge and discharge operations, and maintaining operational safety. CAN communication is used to interface with a central unit, allowing access to all data from each connected BMS. This centralized communication system facilitates real-time monitoring and management of multiple battery packs, ensuring streamlined operations and enhanced performance.

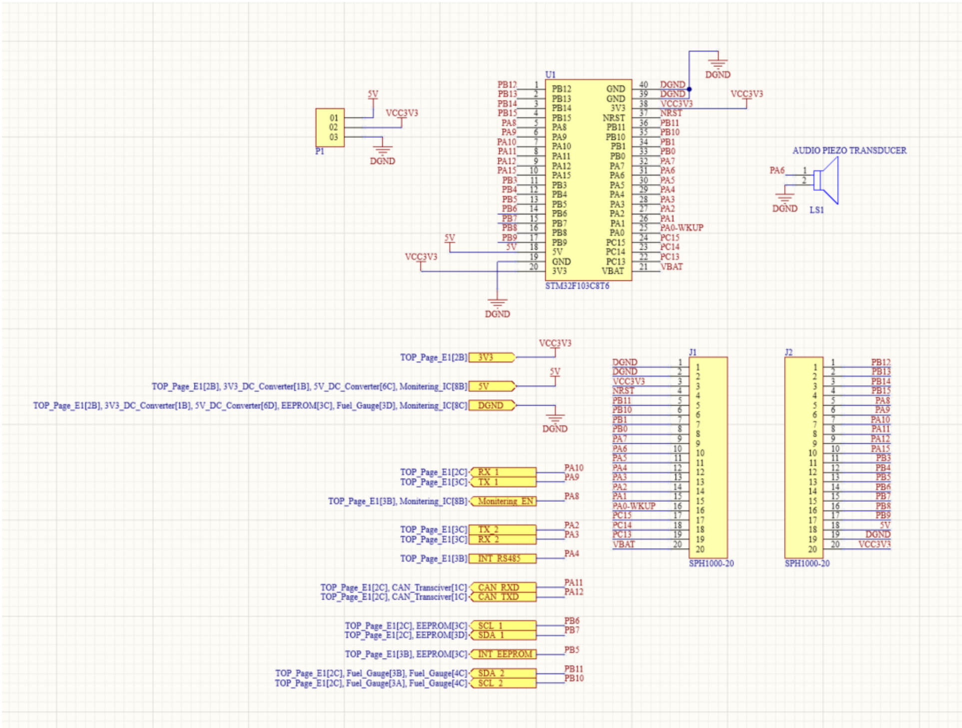

Figure 3.3: Schematic for STM32 MCU

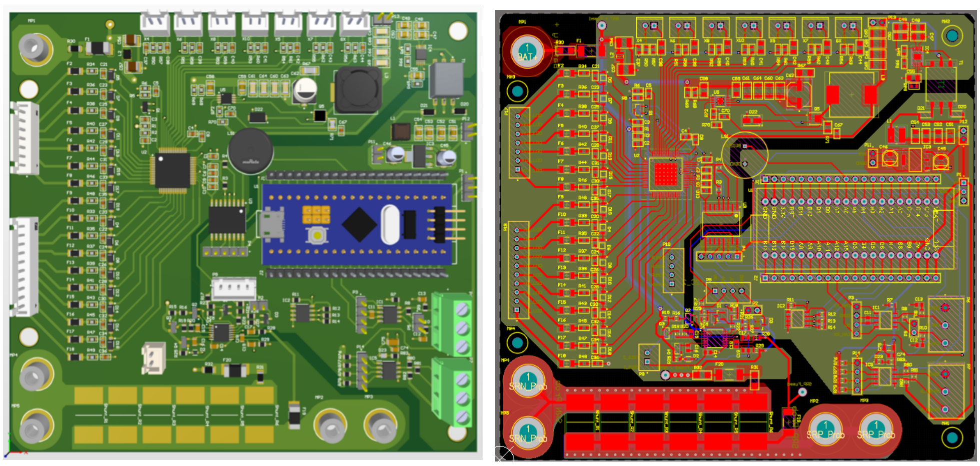

Figure 3.4: PCB layout of monitoring IC with MCU

Cell Balancing

Cell balancing is a technique used in battery management systems (BMS) to equalize the charge among individual cells in a series-connected battery pack. Since no two cells are perfectly identical, they exhibit variations in capacity, internal resistance, and self-discharge rates. Over time, these differences cause some cells to become overcharged while others remain undercharged, leading to performance degradation and potential safety risks. Cell balancing ensures that all cells in a series configuration maintain the same state of charge (SoC), preventing imbalances that could reduce the overall efficiency, lifespan, and safety of the battery pack.

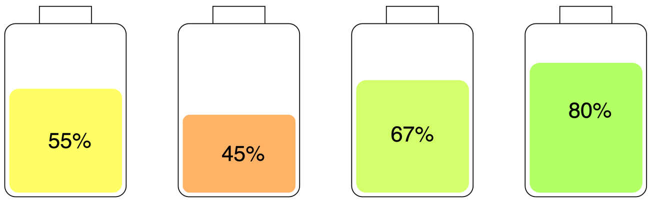

Figure 3.5: battery cells in a series connected battery pack

In a series-connected battery pack, the weakest cell dictates the performance of the entire pack. Without cell balancing, several problems can arise. One of the most significant issues is capacity loss and reduced runtime. In an unbalanced pack, weaker cells reach full charge or discharge earlier than others, reducing the usable capacity of the entire pack. The total pack capacity is limited by the weakest cell, leading to reduced energy availability.

Another critical problem is overcharging and overdischarging risks. Cells with lower capacity may overcharge when the rest of the pack reaches full charge, which can lead to thermal runaway and severe safety hazards. Similarly, during discharge, weaker cells may drop below their minimum safe voltage, leading to irreversible degradation or permanent damage.

The lifespan of the battery pack is also significantly affected by imbalance. Continuous overcharging and deep discharging of weaker cells accelerate their degradation, increasing capacity fade and shortening the overall lifespan of the pack. Additionally, unbalanced cells with varying internal resistances can generate thermal issues, leading to uneven heating. These hotspots can trigger thermal runaway, increasing the risk of catastrophic battery failure.

Finally, inefficient charging becomes a problem when the charging process is halted as soon as the first cell reaches full charge, leaving other cells underutilized. This reduces the overall charge efficiency and limits the energy storage capability of the battery pack.

Cell balancing techniques can be broadly classified into two categories: passive balancing and active balancing. Passive cell balancing dissipates excess energy from higher-capacity cells as heat through resistors until all cells reach the same voltage level. While this method is simple and low-cost, it is inefficient because the excess energy is wasted as heat rather than being used elsewhere.

On the other hand, active cell balancing transfers excess charge from higher-voltage cells to lower-voltage cells using inductors, capacitors, or transformers. This method

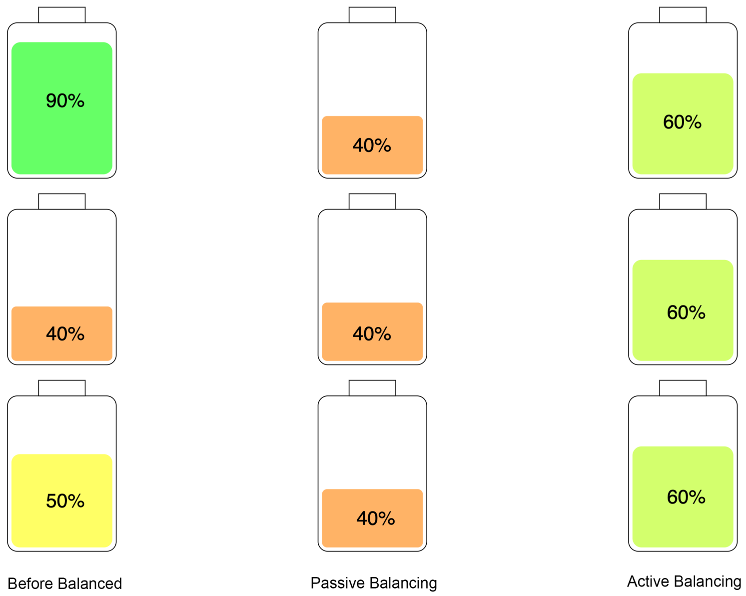

Figure 3.6: Active cell balancing vs passive cell balancing

is more efficient since it redistributes energy within the pack rather than dissipating it. However, active balancing systems are more complex and costly due to additional circuitry and control mechanisms.

Since we are dealing with high-capacity (50Ah) $LiFePO_4$ cells, passive balancing methods are not suitable due to significant power loss in the form of heat. Therefore, we have decided to use an active balancing method. Several active balancing techniques exist, such as capacitor-based balancing, inductor-based balancing, and DC-DC converter-based balancing. Among these, we have chosen the DC-DC converter-based active cell balancing method, as it offers the highest power transfer rate compared to other active balancing techniques.

Inductive Cell balancing

Our supervisor suggested using the ETA3000, an inductive active cell balancing IC. After evaluating its features and benefits, we decided to implement our active balancing system using this IC.

The ETA3000 employs an inductive charge transfer mechanism to balance two series-connected cells efficiently. Unlike passive balancing, which dissipates excess energy as heat, inductive balancing transfers charge from a higher-voltage cell to a lower-voltage cell using an inductor. The IC detects voltage differences between the two cells and, when an imbalance is detected, it activates a controlled switching operation that allows energy to be temporarily stored in an inductor before being transferred to the lower-voltage cell. This process repeats until the voltage difference is minimized, ensuring that both cells remain at nearly the same state of charge (SoC). The IC features an intelligent state machine that operates in three main states: Sleep State, Check State, and Balance State to optimize power usage and prevent unnecessary balancing cycles.

A typical ETA3000 application circuit consists of two series-connected Li-ion or $LiFePO_4$ cells, an external inductor (typically around 2.2µH to 10µH depending on current requirements), a few capacitors, and resistors for stability and tuning. The SW pin of the

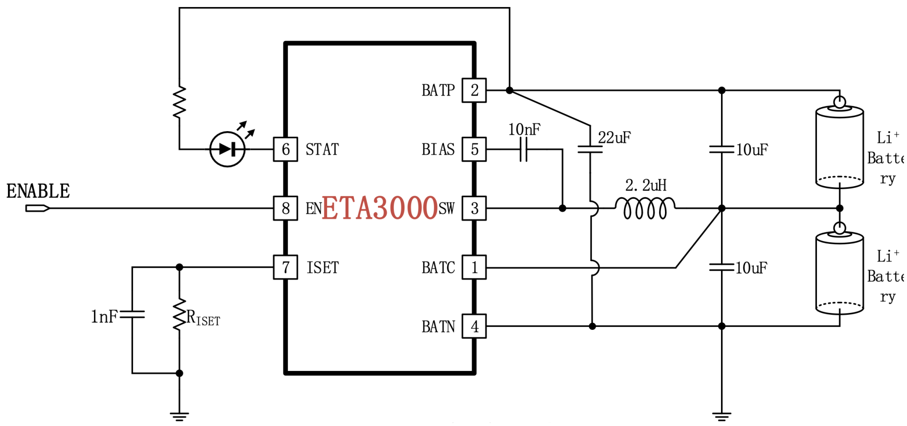

Figure 3.7: Example circuit for balancing two series connected cells - Datasheet

ETA3000 controls the energy transfer, while the BATP, BATC, and BATN pins connect to the respective battery terminals. An enable (EN) pin allows the IC to be turned on or off, and an ISET pin is used to configure the balancing current. The circuit operates autonomously, making it ideal for integration into battery management systems (BMS) of electric vehicles (EVs), energy storage systems, power tools, and consumer electronics where efficient balancing is required.

This IC can be cascaded to balance more than two series-connected cells. We can use multiple such ICs as needed to achieve balancing across the entire battery pack. The following picture shows an example circuit from the datasheet that can be used to balance multiple series-connected cells.

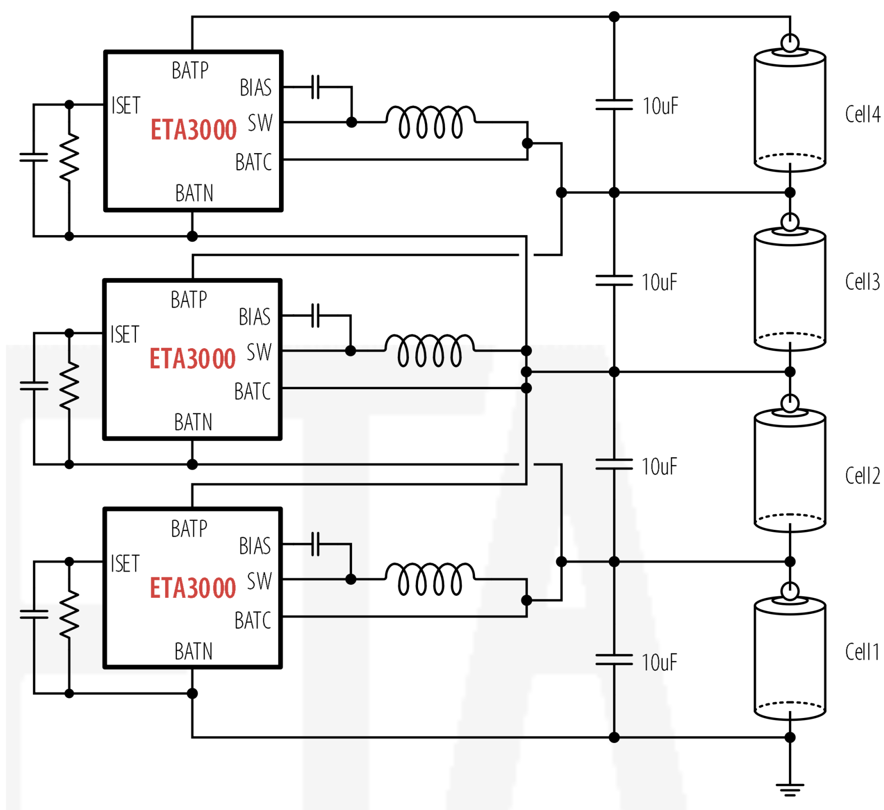

Figure 3.8: Example circuit for balancing series connected cells - Datasheet

16-Cell inductive active cell balancing circuit

According to the datasheet, we set the current-selecting resistor to correspond to 1.7A. We then designed the schematic for the balancing circuit to balance two series-connected cells. Additionally, we incorporated an enable pin, which is connected through an optocoupler to isolate the MCU control signal from the battery pack, ensuring safe operation.

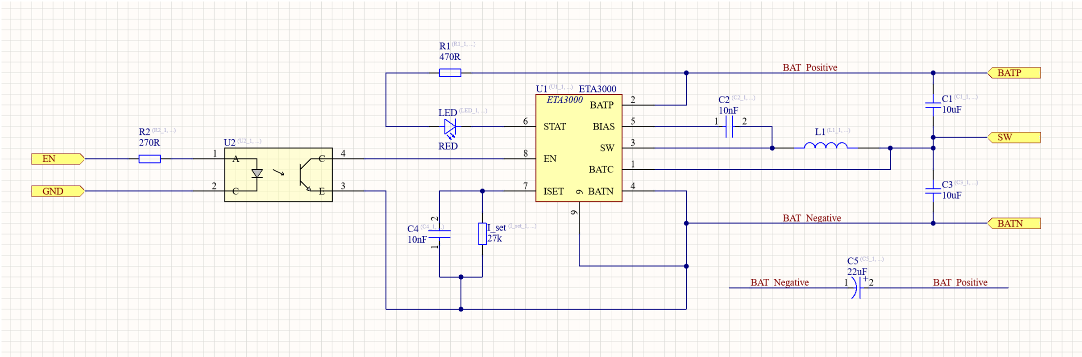

Figure 3.9: Schematic of balancing two series connected cells circuit

Since we are connecting 16 series-connected cells, we used 15 instances of the above circuit to ensure proper balancing across all cells.

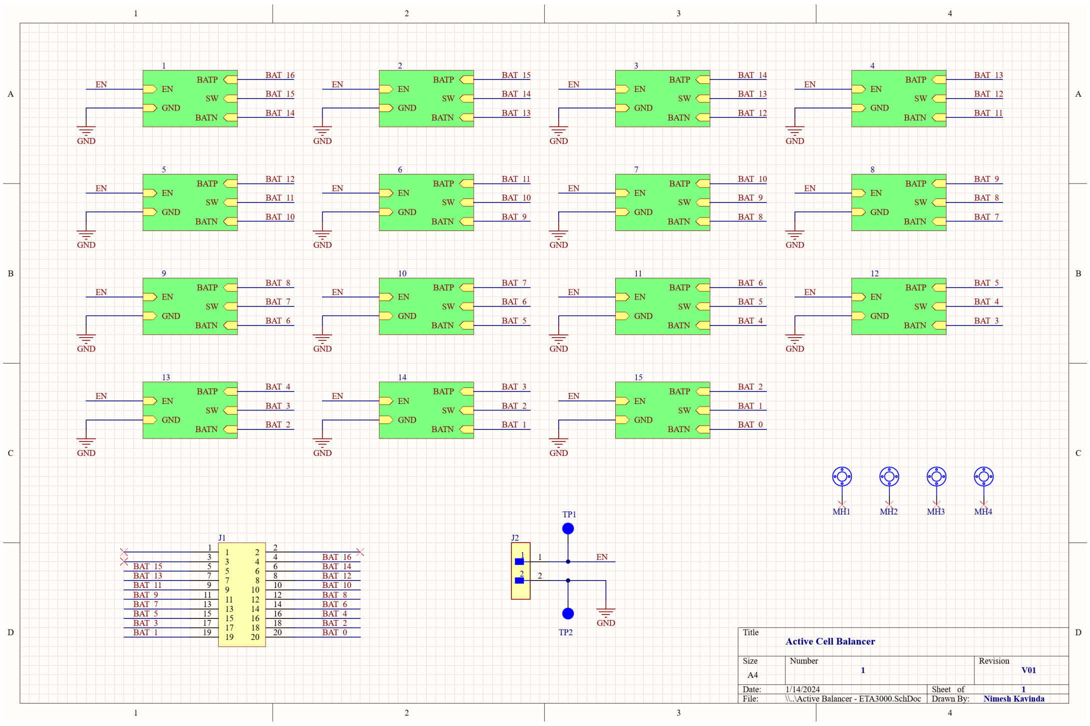

Figure 3.10: Schematic of balancing 16 series connected cells circuit

After that, we designed the PCB layout for the schematic and went through several iterations, incorporating our supervisor's advice on both the schematic and layout. Once the final design was completed, we sent it for fabrication.

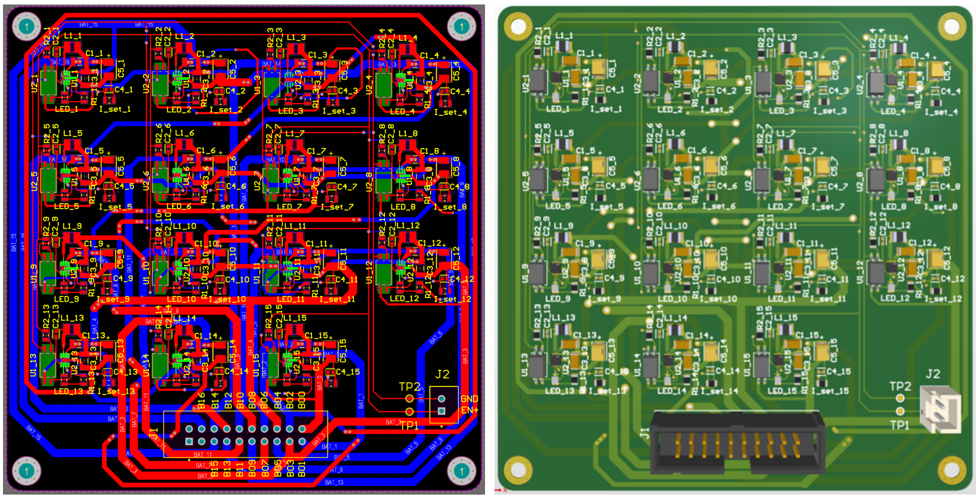

Figure 3.11: 16-Cell inductive cell balancer - layout and 3D view

Charging Current limiting circuit

We designed the current limiting circuit with the ability to limit the charging current at the charging station and the vehicle value of 20A, which can be according to the requirement. The charging station a is equipped with a charger capable of delivering a maximum current of 100A. However, batteries connected to the charger in parallel have a critical limitation. Also, a fully charged battery pack which is capable of providing 50A discharged current is connected with discharged battery packs in parallel when the battery is replaced by a fully charged battery. If the charging current exceeds 20A, it can negatively impact battery lifespan and compromise safety.To ensure optimal battery performance, longevity, and safety, the charging current has been deliberately limited to a maximum of 20A. This limitation takes into account factors such as charging time, battery lifespan, and safety considerations. Regardless of the charger's maximum current capacity, the charging current is restricted to 20A or less to maintain safe and efficient operation.

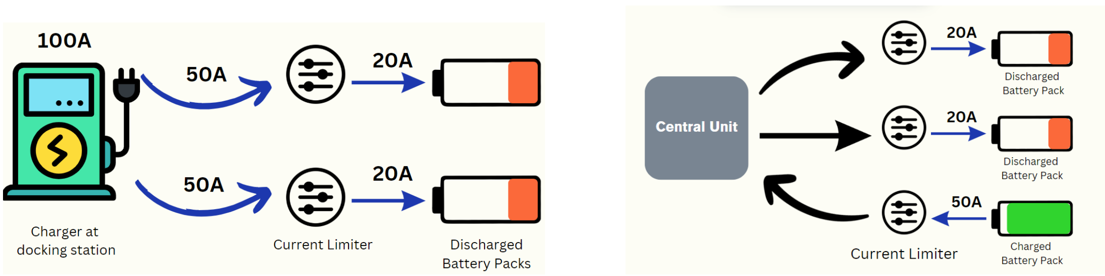

Figure 3.12: Concept of current limiter

To achieve efficient current limiting with minimal power loss, a switch-mode power supply (SMPS) based on a buck converter topology has been implemented. In this design, the duty cycle of the Pulse Width Modulation (PWM) signal is dynamically adjusted based on feedback from the output. Typically, in a buck converter, the feedback is derived from the output voltage to regulate the desired voltage level. However, in our solution, the feedback is taken from the voltage across a shunt resistor. This approach provides direct information about the current flowing to the load, enabling precise control over the charging current.

The controller IC adjusts the duty cycle of the PWM signal based on the feedback voltage obtained from the shunt resistor. By monitoring the current flow in real-time, the system ensures that the charging current does not exceed the predefined limit of 20A, even if the charger is capable of delivering higher currents. This method not only optimizes power efficiency, but also ensures the safety and longevity of the batteries by maintaining the charging current within the specified limits. The use of a buck converter topology further minimizes power losses, making the solution both effective and energy-efficient.

Common positive configuration

In a typical buck converter, the ground is common, and the positive path is interrupted to regulate the output voltage. However, in the context of a Battery Management System (BMS), a common positive configuration is used, where the positive path remains continuous, and the ground (negative) path is interrupted. This design is chosen because, in many BMS architectures, the positive terminal of the battery is directly connected to the load or charger, while the negative terminal is managed by the BMS. Breaking the ground path simplifies the system design, as the positive line does not need to pass through the BMS, reducing complexity in the overall circuitry. Additionally, placing MOSFETs in the ground path simplifies their driving circuitry, as the gate drive signals can be referenced to the ground, eliminating the need for high-side gate drivers. Figure 3.13 shows voltage levels of both configurations.

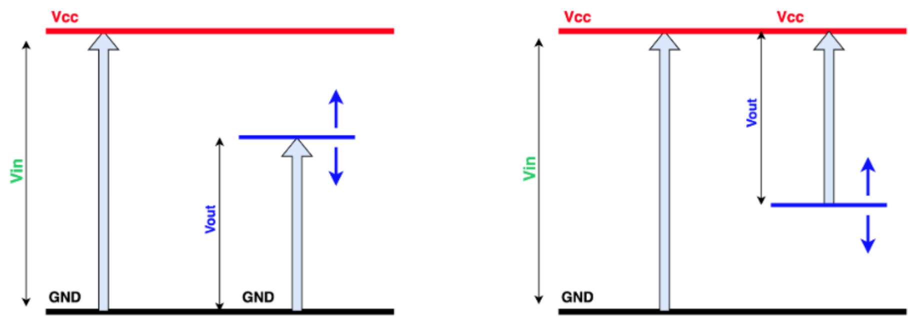

Figure 3.13: Voltage levels of both configurations

The common positive configuration enables the same MOSFETs to control both charging and discharging, reducing components and simplifying control logic. A shunt resistor in the ground path measures current, providing feedback to the controller IC. This adjusts the PWM duty cycle to maintain the desired current limit (e.g., 20A), ensuring accurate regulation. Combining the buck converter topology with this configuration achieves efficient power conversion with minimal losses, aligning with BMS design practices and improving reliability.

Current limiting circuit version 1

When designing current limiting circuit, three main ICs have been used; PWM controller IC, Gate driver and current sensing IC. Figure 3.14 shows high level schematic design.

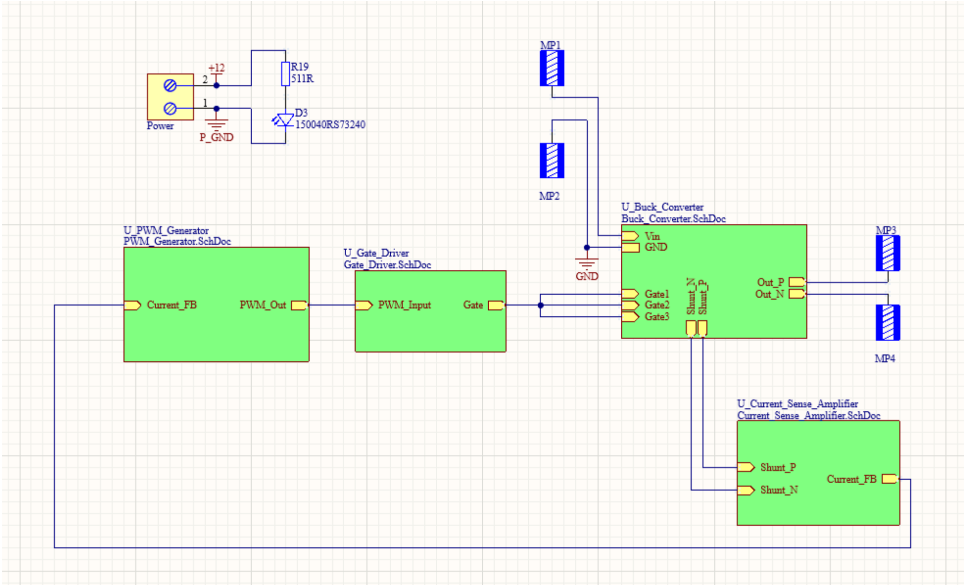

Figure 3.14: High Level Schematic

The TL494 IC is a PWM controller IC that adjusts the duty cycle of the PWM signal proportionally based on the error voltage input to the IC. In the designed asynchronous buck converter circuit, which operates in a common positive configuration, the voltage across the shunt resistor is measured and amplified by a shunt amplifier. This amplified signal is fed back to the TL494 IC as an error voltage. The TL494 IC then modulates the duty cycle of the gate drive PWM signal, which is delivered to the MOSFETs via MOSFET drivers, to regulate the current flow.

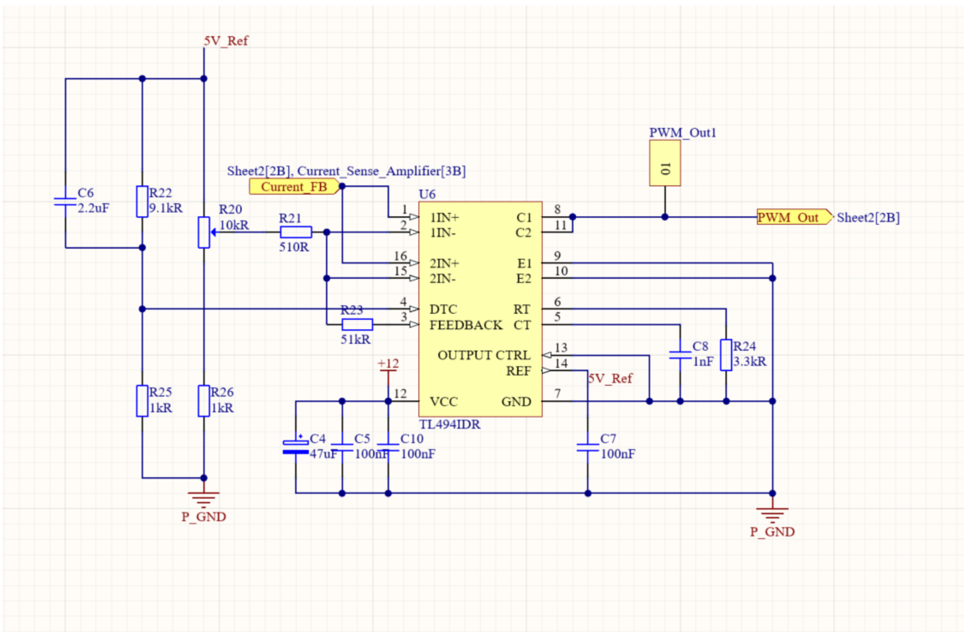

Figure 3.15: PWM Controller Schematic

Figure 3.16 schematic represents a gate driver circuit using the UCC27511DBVR IC to amplify a PWM signal for driving a MOSFET. It operates on a +12V supply, with decoupling capacitors (10µF and 100nF) ensuring power stability and noise filtering.

The PWM input is fed into the gate driver, which outputs a strong signal to control the MOSFET gate through 10 ohm resistors, regulating switching speed and minimizing ringing.

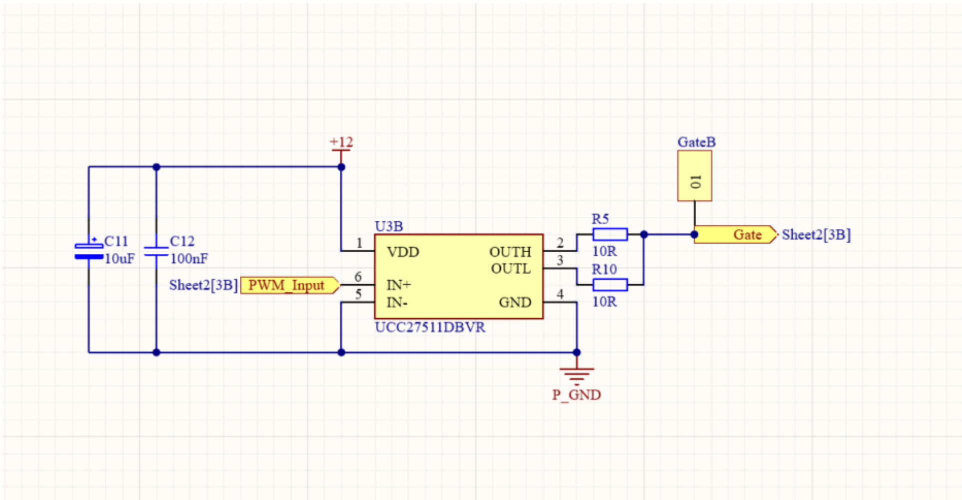

Figure 3.16: Gate driver Schematic

Current sensing amplifier circuit using the INA310A3IDGKR IC, which measures the voltage across a shunt resistor to determine current flow. The shunt inputs are connected to a resistor in the buck converter circuit, where the voltage drop is proportional to the current. The INA310 amplifies this differential voltage and provides an output voltage corresponding to the sensed current. A 5.1k resistor sets the gain, while 10µF and 100nF capacitors filter noise for stable operation. The comparator output can be used for overcurrent detection. The processed current feedback signal is sent to the PWM generator, enabling closed-loop current regulation.

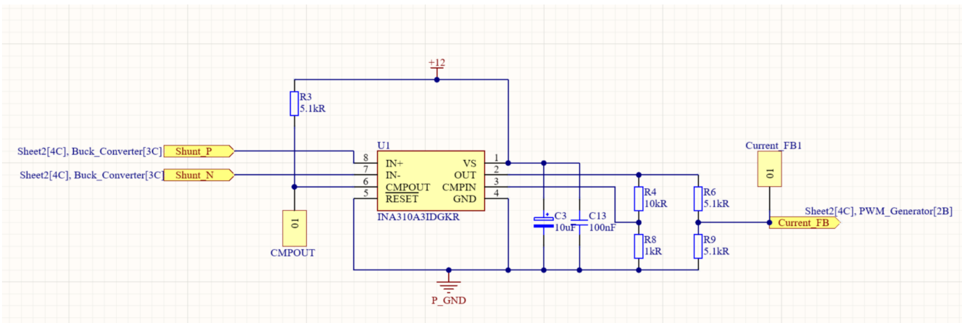

Figure 3.17: Current Sensing Amplifier Schematic

Component sizing was critical step at schematic and PCB designing step with working methodology where all components are selected considering design requirements. Asynchronous buck converter uses MOSFETs (PSMN019-100YLX) for switching, Schottky diodes (RB298NS100FHTL) for freewheeling, and inductors (SHBC24N-2R1B0039V) to smooth the output current. Capacitors (33µF) filter voltage fluctuations, while shunt resistors (5 miliohom) enable current sensing for feedback and protection. The MOSFETs are chosen for low conduction losses, inductors for controlled ripple, and capacitors for stable output. Proper component sizing ensures efficient power conversion, reduced losses, and reliable operation in varying load conditions.

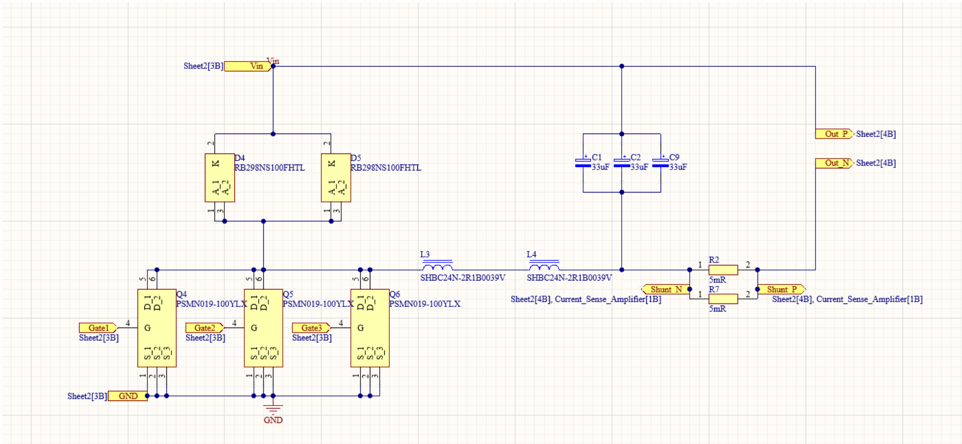

Figure 3.18: Buck Converter Schematic

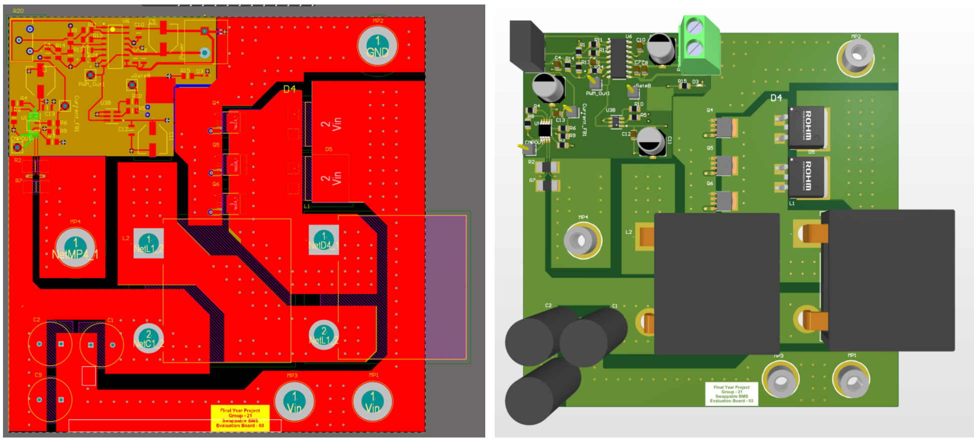

Figure 3.19: Current Limiting PCB version 1

PCB design accommodates a 20A current by utilizing wide copper polygon pours, thick copper 4 layers, and strategic trace routing to minimize resistance and heat buildup. Large copper areas effectively distribute current, reducing voltage drop and improving efficiency. Thermal management is addressed through wide traces, heat dissipation via copper pours, and proper spacing to prevent overheating. High-current paths are reinforced with large through-hole pads and multiple vias for inter-layer connectivity. Additionally, careful component placement and clearance ensure safety and reliability, preventing arcing or unintended shorts in high-power regions.

After fabricating the Version 1 PCB, we tested the circuit; however, it did not achieve the expected level of accuracy. The results are discussed in the Results section. After debugging the Version 1 circuit, we proceeded to develop Version 2 of the current limiting circuit, incorporating several changes, including modifications to the PWM generator IC, current sensing amplifier IC, and capacitors. Before finalizing the component selection, we tested the new components sourced from the local market by integrating them with the buck converter section from Version 1.

Current limiting circuit version 2

In the Version 2 design, an ATtiny85 microcontroller was used as the PWM generator, allowing for programmable control. The design also focused on monitoring the current drawn by each IC, and buffers were added between ICs to improve signal integrity. Additionally, a contactor was included on the PCB to function as a switch for discharging the battery that powers the circuit. Figure 3.20 shows the high-level schematic of the Version 2 design.

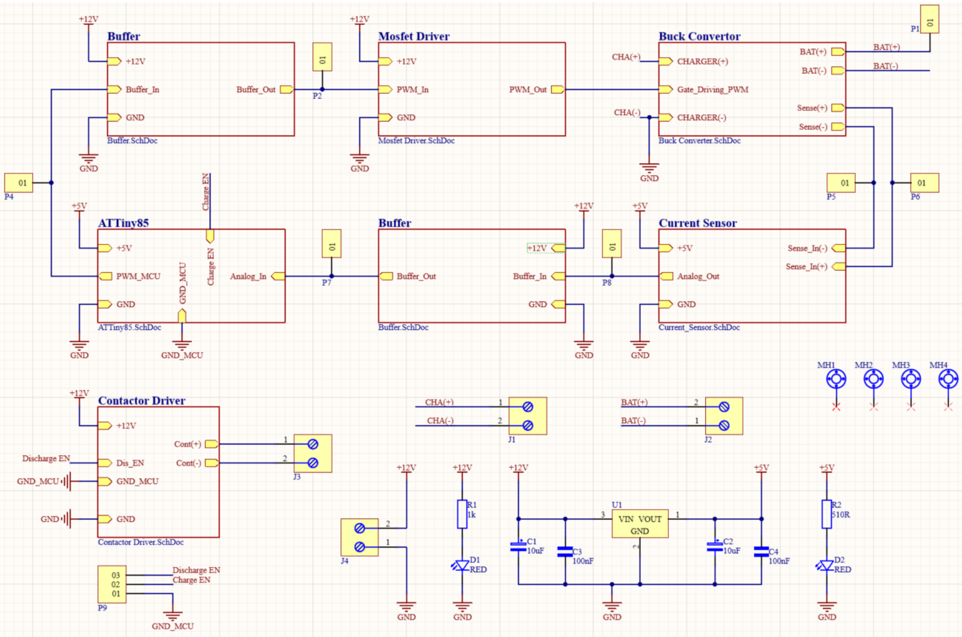

Figure 3.20: High level schematic of version 2

The ATtiny85 microcontroller is used in this design to generate a PWM signal with a variable duty cycle based on the current sensor input received through its analog pin. Despite having limited peripherals, the microcontroller is well-suited for this application, providing sufficient functionality for current control. A dedicated charging enable signal is used to turn the current limiting circuit on or off, and this signal is received from the battery management system through an opto-isolator to ensure electrical isolation and protect the microcontroller from high-voltage transients. The design also incorporates filtering and decoupling to ensure stable operation and accurate signal processing.

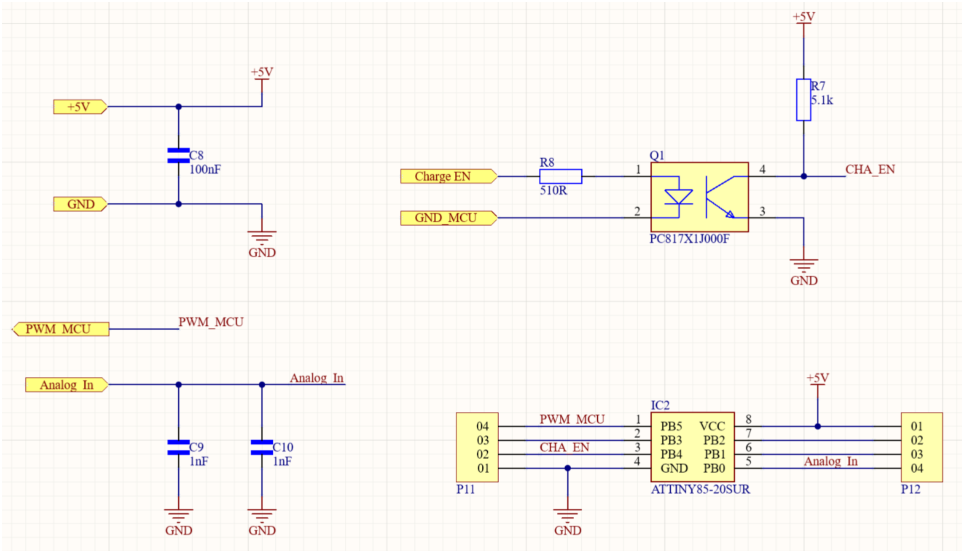

Figure 3.21: ATTiny85 schematic

For current sensing, we use INA240 which is capable of reading bidirectional current through the shunt resistor. In the version2 design we use INA240 module to plug into pcb as in figure 3.22.

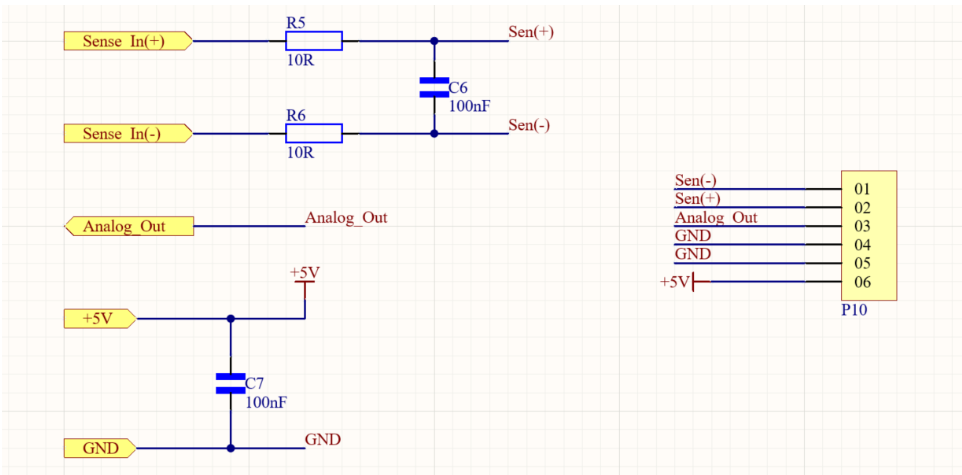

Figure 3.22: Current sensor schematic

In this design, the UCC27511DBVR MOSFET driver is used to drive the gate of the power MOSFET, as in Version 1; however, two drivers are used in parallel to ensure reliable gate driving and improved current handling capability. This dual-driver configuration enhances safety and reduces the risk of overloading a single driver when switching high gate charge MOSFETs. The input PWM signal is fed to both drivers simultaneously, and the outputs are combined through series resistors to provide controlled and balanced gate drive strength.

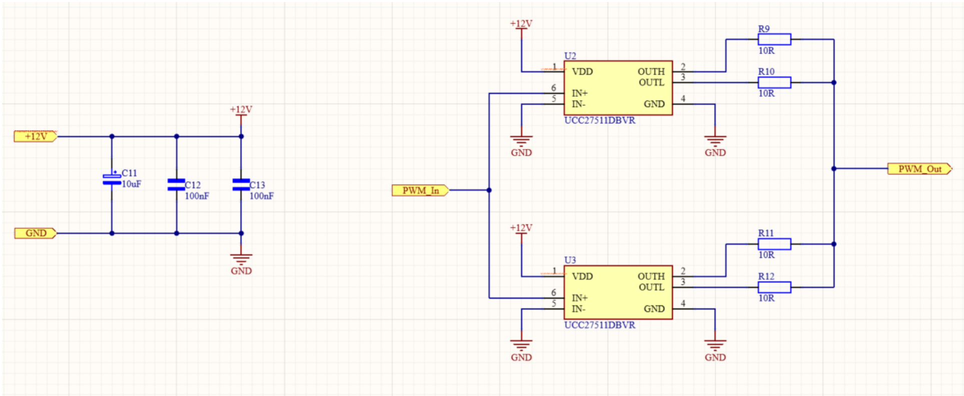

Figure 3.23: Gate driver schematic

To ensure accurate current sensing, a voltage buffer using a TL071 op-amp is placed between the current sensor, MCU, and MOSFET driver. This prevents high current draw from the sensing line, which can cause voltage drops and inaccurate readings. The buffer, configured as a voltage follower, offers high input impedance and low output impedance, effectively isolating the sensing circuit and preserving signal integrity.

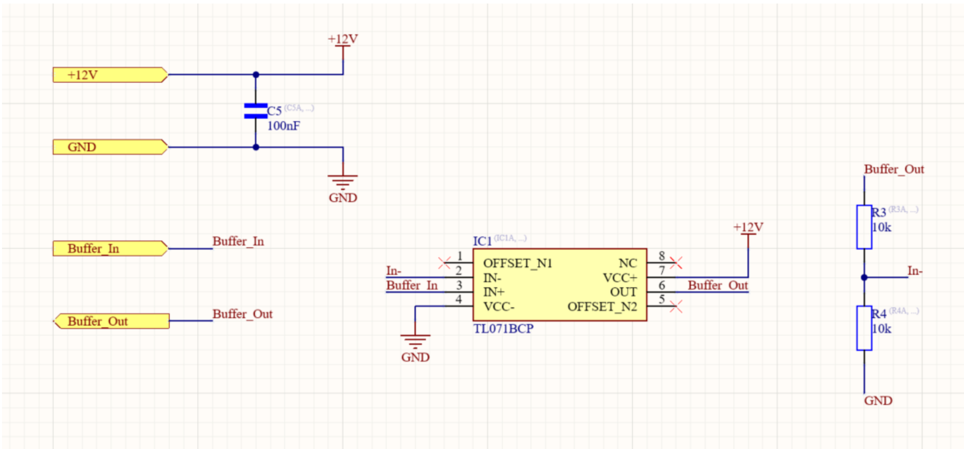

Figure 3.24: Buffer schematic

In this updated buck converter circuit, the input and output decoupling capacitance has been increased to improve voltage stability and reduce ripple under high load conditions. Additionally, the power MOSFETs have been upgraded to support higher current handling, enhancing the overall efficiency and thermal performance of the system. Diodes D5 and D6 are added to prevent reverse current flow, protecting the limiting circuitry from potential discharge paths during power-down or fault conditions.

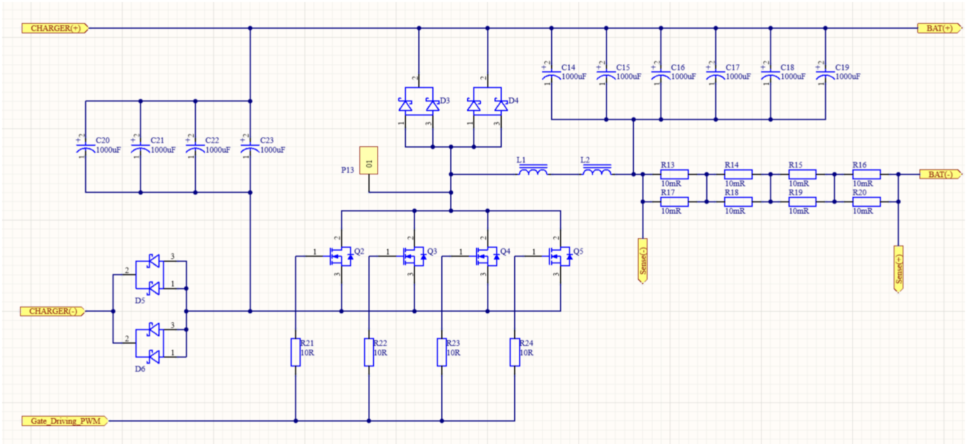

Figure 3.25: Buck convector schematic version 2

This contact driver circuit uses an optocoupler to isolate the MCU from the power stage. When the enable signal is active, the MOSFET is turned on, allowing current to energize the contactor coil. A flyback diode protects against voltage spikes, and an LED indicates contactor status.

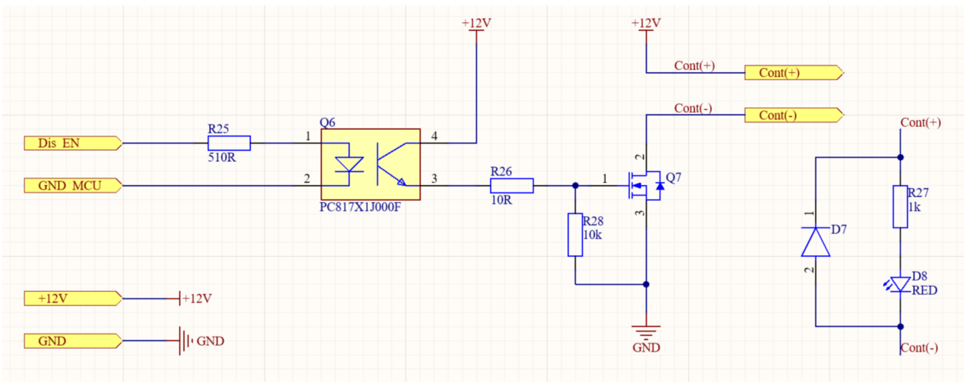

Figure 3.26: Contact driver schematic

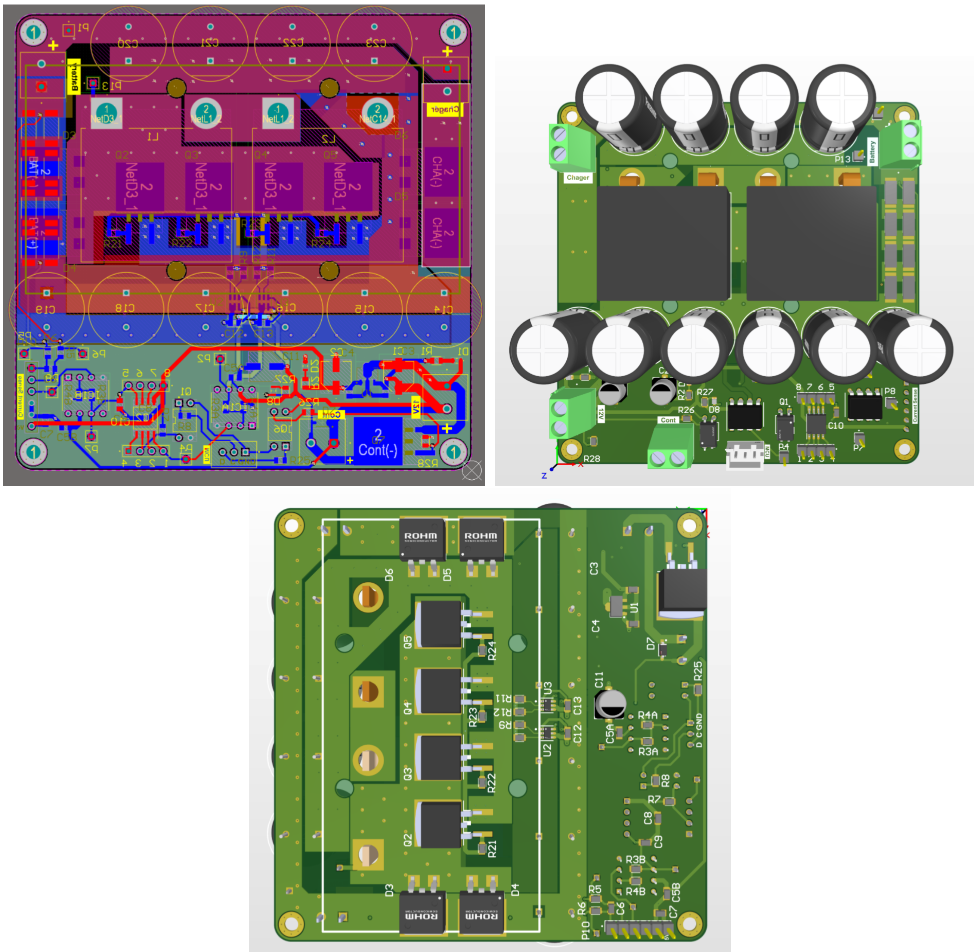

Figure 3.27: Current Limiting PCB version 2

3.2.2 Central Unit

The Central Unit is responsible for managing the charging and discharging of battery packs through the Battery Management System (BMS). It is connected to both the tuk-tuk and the docking station, with each BMS communicating with the Central Unit via CAN bus. To ensure secure communication, the authentication process of the BMSs is controlled using an AES128-bit encrypted method. In the tuk-tuk, the Central Unit also interacts with the tuk-tuk's CAN bus to transmit data, including temperatures, State of Charge (SOC), and State of Health (SOH) of each battery pack, to the tuk-tuk's dashboard. For version 1.0, we used the STM32F446 Nucleo development board as the core microcontroller for the Central Unit.

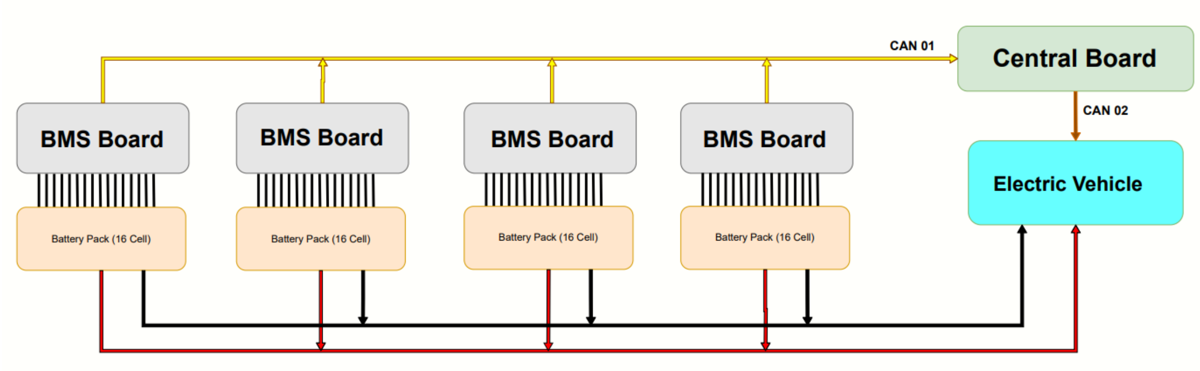

Figure 3.28: Block Diagram in vehical

In version 2, we designed the PCB using the STM32F446 IC as the microcontroller in the Central Unit, replacing the development board used in version 1.0 to create a more compact and application-specific hardware solution. Figure 3.29 shows the designed PCB.

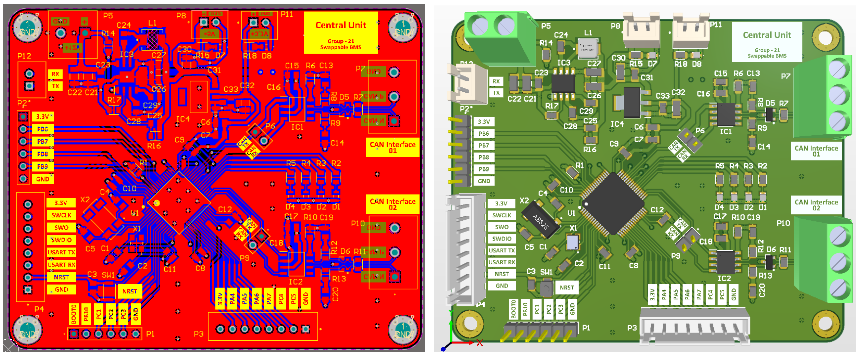

Figure 3.29: Central Unit PCB

3.2.3 Battery Swapping Station (Docking Station)

Figure 3.30: Designed Swapping Station

The swapping station allows users to exchange their depleted battery packs for fully charged ones within minutes. The process is RFID-based, beginning with the customer verifying their identity using an RFID tag. The station then communicates with a central database to check customer details, including subscription status and available credits. If the user has sufficient credit, he can place the discharged battery in an empty slot and take a fully charged one. However, if he doesn't have enough credits, the exchange will not be possible. In version 1.0, the station has 10 slots, with one slot always empty.

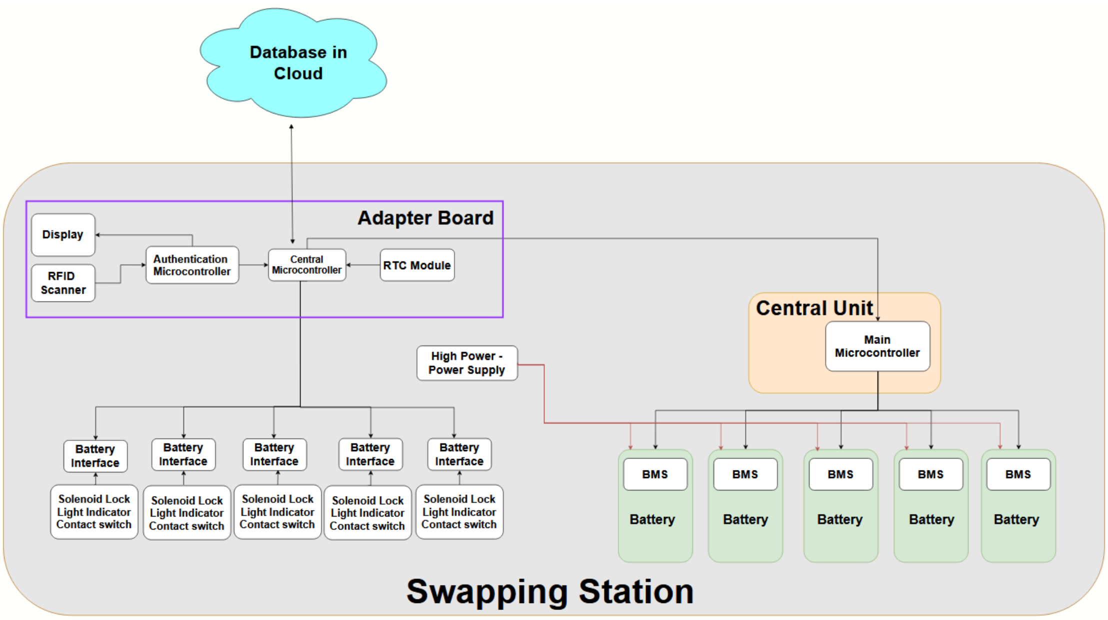

Figure 3.31: High level Architecture of Swapping Station

The docking station's functionality is managed by two main boards; Battery interface unit and Adapter board. Each slot is equipped with an interface unit. All interface units communicate with the adapter board via a CAN bus. That adapter board is also communicate with central unit to ensure the authentication of battery packs. Only the authenticated battery packs can be charged in the docking station.

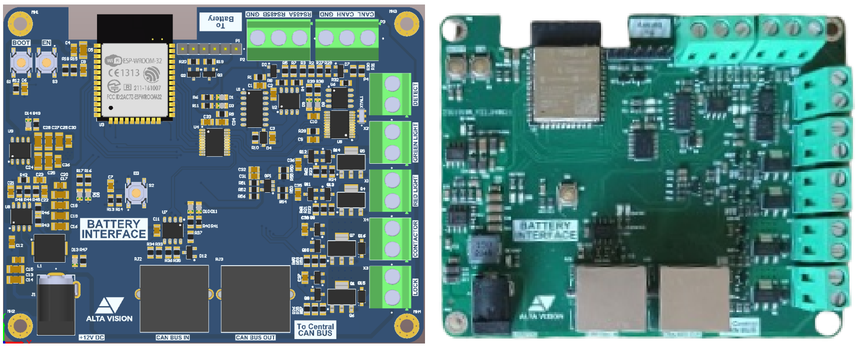

Figure 3.32: Battery Interface Unit in Docking Station

Battery Interface units control the solenoid lock, status indicator lights, and contact switch for their respective slots. When a depleted battery pack is correctly placed into an empty slot, the contact switch is triggered. At this point, the system retrieves the battery's status, including its state of charge (SOC) and state of health (SOH), to ensure it meets the required standards for recharging. If the battery is in good condition, the solenoid lock secures the slot, and the charging process begins. Two LEDs provide status indications: a red LED signals that charging is in progress, while a green LED indicates the battery is fully charged.

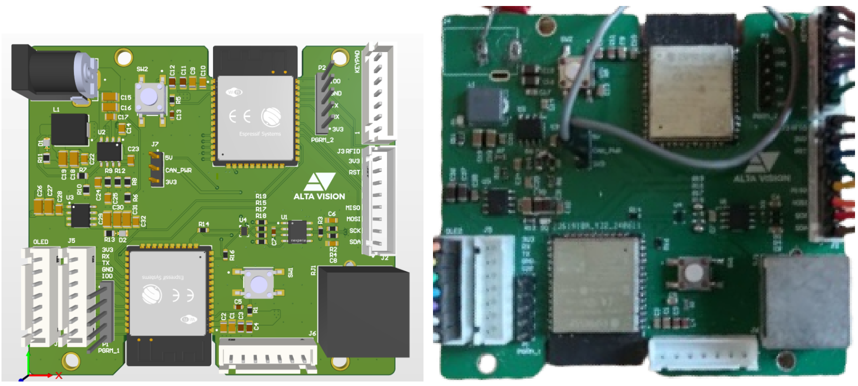

Figure 3.33: Adapter Board in Swapping Station

The adapter board is responsible for communication and authentication within the docking station. It connects to the cloud, manages the RFID scanning process, and interacts with the central unit to verify battery authenticity. Each user has a unique RFID tag, and upon scanning, the adapter board sends the ID to the cloud database via a REST API. The system then checks the user's account to determine if they have sufficient credits. Based on this verification, the user is either granted or denied permission to swap their battery.

For both boards, we chose the ESP32 as the MCU due to its built-in WiFi for cloud connectivity and integrated CAN controller. For CAN communication, we use the TJA1050T transceiver along with a logic level shifter. The RFID system operates at a 13.56MHz frequency, and for debugging purposes, we utilize RS485.

3.2.4 Firmware Development

We selected the STM32F103C8T6 [datasheet] as the MCU for our BMS board because it offers all the required peripherals CAN, UART, and I2C,while remaining cost-effective. It also has strong library support, making firmware development easier. Since each battery pack requires a separate BMS, minimizing the cost per unit is essential. Compared to other STM32 variants, this MCU provides a good balance of performance, features, and affordability.

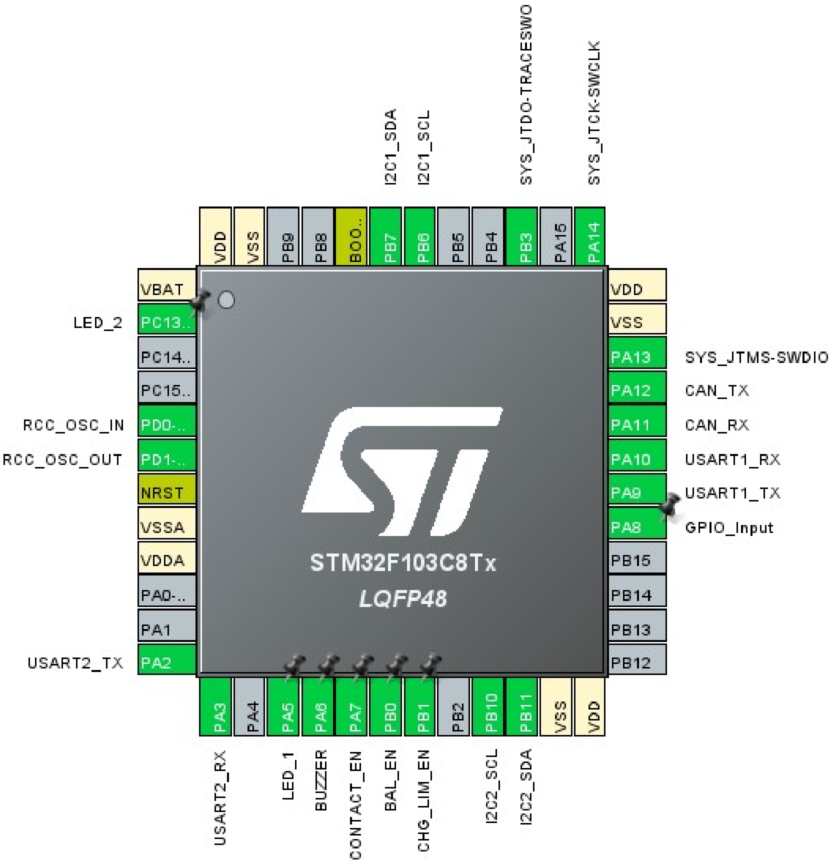

Figure 3.34: STM32F103 Pinout and Connections setup for BMS using STM32CubeIDE

Table 3.1: STM32F103C8T6 Peripheral Configuration

Peripheral	**Configuration**	**Remarks**
HCLK	72 MHz (max)	System clock
CAN	Baud Rate: 500,000 bit/s	Communication with Central Unit
USART1	Baud Rate: 1,000,000 bit/s Word Length: 8 bits (incl. parity) Parity: None Stop Bits: 1 RX: Pull-up enabled	Communication with Monitoring IC
USART2	Baud Rate: 115,200 bit/s Word Length: 8 bits (incl. parity) Parity: None Stop Bits: 1	Debugging and UI Communication
I2C1	Standard Mode Clock Speed: 100 kHz	EEPROM communication
I2C2	Standard Mode Clock Speed: 100 kHz	Fuel Gauge communication

Table 3.2: STM32F103C8T6 GPIO Configuration

GPIO Pin	**Default State**	**Function**
Active Buzzer	Pull-down	Audio alert
Contactor Enable	Pull-down	Main power relay control
Active Balancer Enable	Pull-up	Balance circuit control
Charge Limiter Enable	Pull-down	Controls charging circuit
2x LEDs	Output	Status indication
SWD (Trace Async)	Debug interface	Programming and debugging

The BMS firmware was developed with a primary focus on authentication, protection, and data communication with the central unit. In real-world deployment, troubleshooting is often handled by technicians who require a simple and effective way to monitor and configure BMS parameters. It was design as 4 Main States State Machine and Controlling others using Interrupts. To support this, a Windows-based user interface application was developed along with the firmware, providing an intuitive interface for diagnostics, configuration, and visualization of real-time data.

1.)Main State Machine

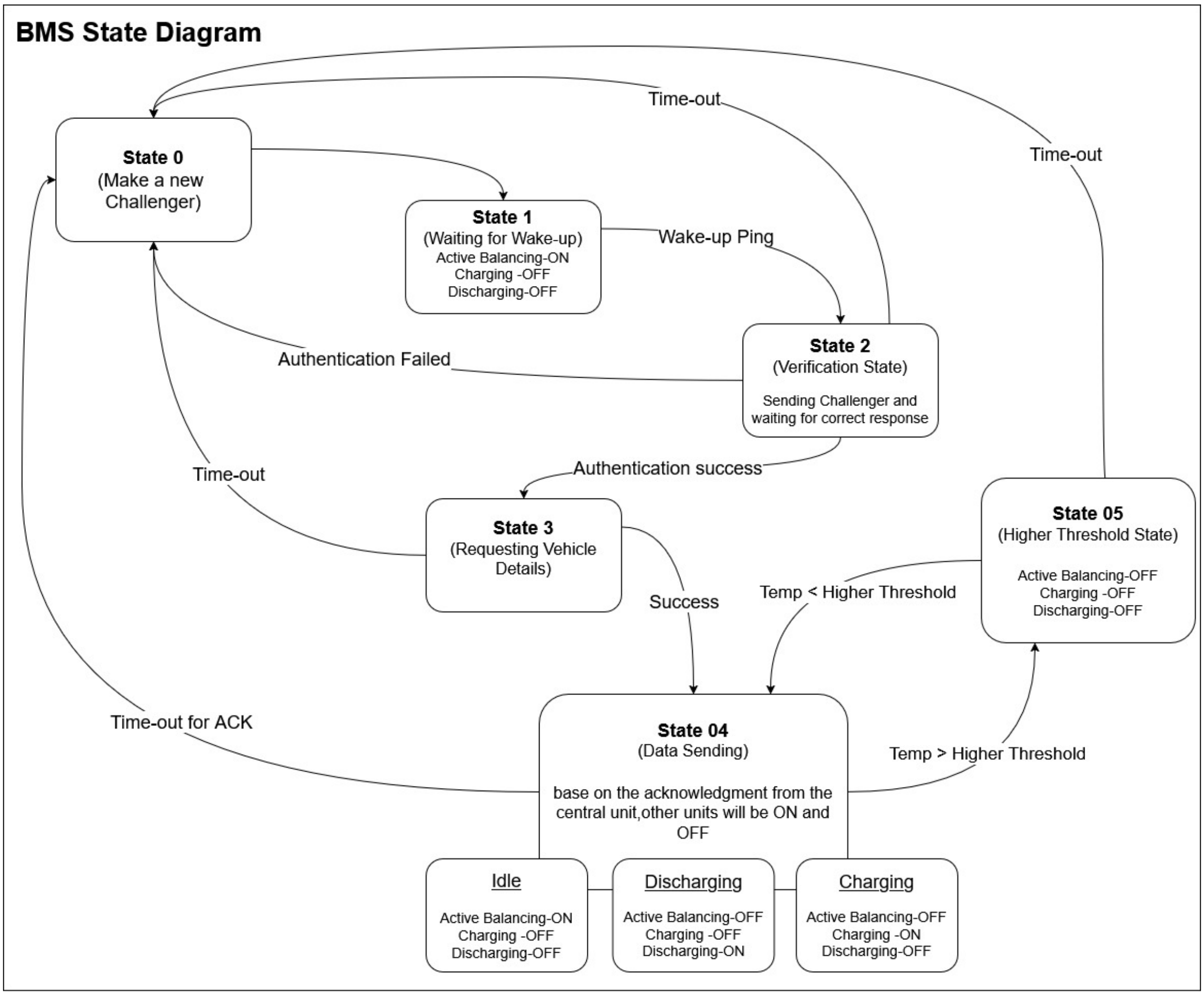

Figure 3.35: State Machine

2.) Custom Communication protocols

A custom communication protocol with structured frames was developed to enable efficient data exchange and scalable system integration.

CAN communication

Communication between the BMS and the central unit is handled using Standard CAN identifiers, which use 11-bit IDs, allowing for a total of 2048 unique CAN IDs. To transmit different types of data, each message type is assigned a dedicated CAN ID, and each BMS is also given a unique CAN ID. Approximately 10 CAN IDs are reserved for special or system-level messages, leaving around 2038 IDs available for BMS devices. While two BMS units may technically share the same CAN ID without functional issues, it becomes problematic when both are present in the same vehicle, especially when displaying data on the vehicle dashboard. To support vehicle-level targeting, each BMS also stores a separate unique identifier in EEPROM.

Table 3.3: Custom CAN Headers Used in BMS Communication

CAN Header	Purpose
AUTH_CAN_HEADER	Transmits BMS authentication Challenger
DATA_CAN_HEADER	Transmits Real time data
ACK_CAN_HEADER	Receiving Acknowledges commands
CENTRAL_DETAILS_CAN_HEADER	Requesting Vehicle or Docking Station Details
WARNINGS_CAN_HEADER	Sends warning or fault messages

Unique BMS CAN ID is used in these communication scenarios:

- Receiving the digest of the authentication challenge
- Receiving central unit details (e.g., Vehicle ID or Docking Station ID)
- Tagging real-time data frames
- Tagging warning message frames

Custom CAN Data Frame Send by BMS

The CAN protocol allows a maximum of **8 bytes** of data per message. We designed a custom data frame format to efficiently transmit key BMS parameters as floating-point values.

Table 3.4: Structure of 8-Byte Custom CAN Data Frame

Bytes	Field	Size	Description
0–1	Data Type Identifier	2 bytes	Specifies the type of data
2–3	BMS ID	2 bytes	Unique identifier for the BMS unit
4–7	Data Payload	4 bytes	Data value in IEEE 754 float format

This structure allows for consistent interpretation and scaling across multiple BMS units.

Data Type Identifiers:

Table 3.5: Custom Data Type Identifiers for CAN Messages

Hex Code	Data Type
0x01	Total Voltage
0x02	Total Current
0x03	Average Temperature
0x04	State of Charge (SOC)
0x05	State of Health (SOH)

Custom CAN Warning message Frame Send by BMS

This frame is used to send warning messages from the BMS to the Central Unit.The 8 Bytes of CAN message is divided as above.

Table 3.6: Structure of Custom CAN Warning Message Frame

Byte(s)	**Description**
First 2 bytes	”WN” identifier (Warning Message)
Second 2 bytes	BMS ID
Last 4 bytes	Warning Message Code

Warning Message Codes:

- WHVT – Total voltage exceeds the upper voltage threshold
- WLVT – Total voltage below the lower voltage threshold
- WHVD – Voltage difference exceeds the warning threshold
- WHTD – Temperature exceeds disconnection threshold
- WHTW – Temperature exceeds warning threshold
- WLSC – SOC below the minimum threshold
- WLSH – SOH below the minimum threshold

3.) Authentication

The BMS is restricted to operate in either charging or discharging mode only while it is connected to the central unit. This design ensures that batteries cannot be discharged by unauthorized users or charged using third-party chargers instead of the official docking station.

To enforce authentication, an HMAC-SHA256 based challenge response mechanism is used. A secret HMAC key is securely stored in each BMS and central unit. When the BMSs connects to the central unit via the CAN bus, it initiates authentication by sending a randomly generated 4-byte challenge number.Upon receiving the challenge, the central unit computes a digest using the shared HMAC key and responds via the BMS's unique **bms ID**.To protect against replay attacks, a new random challenge is generated for each authentication session.

SHA-256 is a computationally intensive algorithm that involves complex mathematical operations. Implementing such an algorithm directly on an embedded system can be resource-demanding. To address this, we use the TinyCrypt Cryptographic library, which is specifically designed to provide cryptographic functions optimized for low-resource embedded systems. This allows us to perform SHA-256 hashing efficiently within the constraints of the BMS microcontroller.

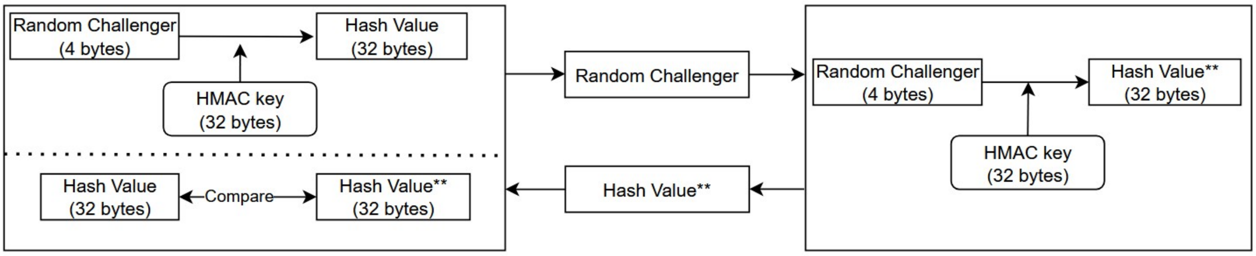

Figure 3.36: Authentication using SHA-256

4.) Protections

Protecting the battery cells is one of the primary responsibilities of the BMS microcontroller. Although the monitoring IC provides overvoltage (OV) and overtemperature (OT) flag mechanisms, the MCU is used to relay these flags to the central unit, giving us greater control and flexibility in handling fault conditions.

Warning messages are sent to the central unit under the following conditions:

- Over Voltage
- Under Voltage
- Over Current
- High Cell Voltage Imbalance
- Low State of Charge (SOC)
- Low State of Health (SOH)

Temperature protection is handled with two thresholds:

- If the temperature exceeds the first threshold, a warning message is sent.
- If it exceeds the second threshold, the BMS stops charging or discharging to ensure battery safety.

The over voltage warning helps to terminate charging, while the under voltage alert notifies the user to replace or recharge the battery. The threshold values can be configured using the Windows application, allowing the BMS to be easily adapted for different types of battery cells.

Discharging from the BMS occurs through a contactor, which is controlled by the BMS MCU. The contactor is only enabled when the BMS is connected to the central unit. This design ensures that the user does not have access to the output voltage while transporting the battery pack between the docking station and the vehicle, thereby enhancing safety.

5.) Non-Volatile Memory

We used a 256KB EEPROM to store essential configuration data and user logs. The table below illustrates how memory pages and addresses are allocated.

Page 01 – Device Information (Start Address: `0x0000`)

Variable	Address	Size (Bytes)
BatteryID	0x0000	20
FirmwareVersion	0x0014	4
CellType	0x0018	6

Page 02 – Configuration Parameters (Start Address: `0x0040`)

Variable	Address	Size (Bytes)
MaxVoltageDiff	0x0040	4
MaxVoltage	0x0044	4
MinVoltage	0x0048	4
WarningTemperature	0x004C	4
DisconnectTemperature	0x0050	4
MaxCurrent	0x0054	4
MinSOH	0x0058	4
MinSOC	0x005C	4

Page 03 – Reserved (Start Address: `0x0060`)
Skipped 96 bytes for future use

Page 04 – Program Variables (Start Address: `0x00A0`)

Variable	Address	Size (Bytes)
Log_Index	0x00A0	1
Latest User Log	0x00A2	8

Page 05 – User Logs (Start Address: `0x00E0`)

Variable	Address	Size (Bytes)
USER_LOG[0]	0x00E0	8
USER_LOG[1]	0x00E8	8
USER_LOG[2]	0x00F0	8
USER_LOG[3]	0x00F8	8
USER_LOG[4]	0x0100	8
USER_LOG[5]	0x0108	8
USER_LOG[6]	0x0110	8
USER_LOG[7]	0x0118	8

In this firmware version, only the most recent 8 user logs are stored. However, the system can be expanded to store additional logs if required.

We chose STM32F446RE [datasheet] as the microcontroller for the Central Unit, primarily due to its support for two independent CAN peripherals, which are essential for simultaneous communication with both the BMS and the vehicle system. Compared to other STM32 MCUs, the STM32F446RE offers higher performance with a 180 MHz Cortex-M4 core, floating-point unit (FPU) support, and larger memory options—making it well-suited for more demanding control and communication tasks.

ESP32 microcontroller choose for both the adapter board and the battery interface unit at the docking station, primarily due to its built-in Wi-Fi and Bluetooth capabilities. This allows seamless internet connectivity for real-time access to the cloud database, enabling updates of user information and State of Charge (SoC) levels for each battery. The ESP32 also offers sufficient processing power and peripheral support for handling communication and control tasks efficiently.

3.2.5 Windows Application for BMS Interface

To simplify diagnostics, configuration, and real-time monitoring, we developed a Windows application for the BMS. Manually modifying firmware parameters for different battery types or troubleshooting scenarios is time-consuming and error-prone; this application addresses that challenge by providing a user-friendly interface.

The application is organized into **three main tabs**:

- **Real-Time Data:** Displays live values from the BMS, including individual cell voltages, cell temperatures, current, State of Charge (SOC), and State of Health (SOH).
- **Device Info:** Shows essential device information such as the BMS ID, firmware version, cell type, and logs of the last users.
- **Configuration:** Allows users to set threshold levels for warnings (e.g., voltage limits, temperature thresholds, SOC, and SOH).

To use the application, connect the BMS to a PC via a USB-to-UART converter, wired to the USART2 port of the STM32. After selecting the correct COM port and pressing the `Connect` button in the application, communication is established. All data exchanges that are both reading and writing, are performed using a custom communication protocol.

UI → BMS: Read Requests

Command	Description	Format
DINFO	Request Device Information	ASCII string
RDATASTART	Start real-time data transmission	ASCII string
RDATASTOP	Stop real-time data transmission	ASCII string
GCONFIG	Request Configuration Data	ASCII string

Table 3.7: Read Requests from UI to BMS

BMS → UI: Read Responses

Field	Example	Notes
FMVERSION	FMVERSION:1.0.0	Firmware version
BMSID	BMSID:LFP16-2025/04/21-010	BMS version
CELLTYPE	CELLTYPE:LFP	Lithium type (e.g., LFP, NMC)
USERLOGS	USERLOGS:U1=Log1;...;U10=Log10	User log entries
BALANCESTATE	BALANCESTATE:ON	Balancing state (ON/OFF)
CHARGESTATE	CHARGESTATE:CHARGING	Charging status
DISCHARGESTATE	DISCHARGESTATE:ENABLED	Discharge status

Table 3.8: Device Info Fields

Device Information Format **BMS ID Structure:**

- First segment (e.g., `LFP16`): Battery chemistry and number of cells
- Second segment: Manufacturer data
- Third segment: Unique identifier similar to CAN header for the BMS

Field	Example	Description
TV	TV:48.76	Total Voltage (V)
TC	TC:-12.34	Total Current (A)
BTS	BTS:T1=100;...;T6=200	Battery temperature sensors
CV1	CV1:C1=2.45;...;C8=1.00	Cell voltages (Cells 1–8)
CV2	CV2:C9=2.45;...;C16=1.00	Cell voltages (Cells 9–16)

Table 3.9: Real-Time Data Fields

Real-Time Data Format **Note:** All responses are newline-terminated (`\n`). Values are in float format unless otherwise specified.

Configuration Data

Read Requests

- TWT: `temp_warning_threshold`
- TDT: `temp_disconnecting_threshold`
- VHT: `voltage_higher_threshold`
- VLT: `voltage_lower_threshold`
- CHT: `current_higher_threshold`
- SLT: `soc_lower_threshold`
- VDT: `voltage_different_threshold`

Write Requests

- `STWT:{value:.2f}` – Set temperature warning threshold
- `STDT:{value:.2f}` – Set temperature disconnecting threshold
- `SVHT:{value:.2f}` – Set voltage higher threshold
- `SVLT:{value:.2f}` – Set voltage lower threshold
- `SCHT:{value:.2f}` – Set current higher threshold
- `SSLT:{value:.2f}` – Set SOC lower threshold
- `SVDT:{value:.2f}` – Set voltage difference threshold
- `SHLT:{value:.2f}` – Set SOH lower threshold (not yet implemented)

3.3 Techniques and Tools

3.3.1 Draw.io

For system architecture and block diagram design, we use draw.io, a versatile and user-friendly tool for creating detailed schematics and flowcharts. It offers a wide range of shapes, templates, and collaboration features, making it ideal for documenting system designs clearly and efficiently.

3.3.2 Altium Designer

For PCB design, we use Altium Designer which provides advanced tools for schematic capture, layout, and simulation. Altium 365 cloud-based collaboration and version control features allow multiple team members to work seamlessly on designs, ensuring efficient workflow management and real-time updates.

3.3.3 LTSpice

LTspice is a powerful and widely used circuit simulation software developed by Analog Devices. It is a SPICE-based simulator that allows engineers to model, test, and optimize analog and power electronics circuits before hardware implementation. LTspice provides an extensive library of semiconductor models, passive components, and switching regulators, making it ideal for simulating complex power electronics systems. In our project, we used LTspice to simulate the boost and flyback converters in our DC-DC converter-based active cell balancer, using controller ICs from Analog Devices. Additionally, we simulated a buck converter for our active charging limiting circuit, ensuring its efficiency and performance before prototyping.

3.3.4 PSpice for TI

PSpice for TI is an advanced circuit simulation tool developed by Texas Instruments (TI), based on the widely used PSpice simulation engine. It allows engineers to design, analyze, and optimize analog, power, and mixed-signal circuits using TI's extensive library of power management ICs, amplifiers, and other semiconductor components. In our project, we used PSpice for TI to simulate the boost and flyback converters in our DC-DC converter-based active cell balancer, utilizing controller ICs from Texas Instruments. Additionally, we simulated a buck converter for our active charging limiting circuit, ensuring accurate performance validation and efficiency optimization before moving to hardware implementation.

3.3.5 STM32Cube IDE

For firmware development, we used STM32CubeIDE, a professional integrated development environment (IDE) provided by STMicroelectronics. It offers a complete tool chain, including code editing, compilation, and debugging, making it ideal for STM32-based embedded systems. The IDE integrates with STM32CubeMX, enabling easy peripheral configuration, code generation, and project setup, which helps reduce development time and improve hardware efficiency. It also includes powerful debugging features such as real-time variable monitoring, breakpoints, and SWO tracing, allowing for effective firmware optimization and system stability. As an officially supported and regularly updated tool, STM32CubeIDE ensures reliability and long-term compatibility for embedded development.

3.3.6 ST-Link V2 Programmer

For debugging and programming, we use ST-Link, which provides a reliable SWD (Serial Wire Debug) and JTAG interface for seamless communication with Cube IDE. It enables efficient firmware uploads, real-time debugging, and step-by-step execution, making it easier to monitor variables, set breakpoints, and optimize system performance.

3.3.7 Qt Designer

The application was developed using PyQt with Qt Designer. Qt is a widely used framework for professional application development, providing a powerful toolkit for creating modern, cross-platform graphical user interfaces. PyQt allows integration of Qt's capabilities with Python to implement the application's functionality.

3.4 Resource Requirements

In this section, resource requirements are listed from each resources.

Hardware Resources

- Our project is hardware based project, hardware resources are as follows.
- STM32 Development Boards, Battery Packs, CAN Bus , RS485 module, Prototyping tools, Testing Equipment

Software Resources

- We need software tools for designing, programming and simulation purpose.
- STM32CubeIDE, Simulation tools, Altium Designer

Financial Resources

- Most of hardware resources need to buy and have to pay for the logitics sevices as well.

Logistical Resources

- Logistical resources are required for component sourcing, supply chain management.

Facilities

- Lab facility is need for testing and developing purposes.

3.5 The Budget

In Table 3.1 we present the estimated budget for the project. All the electronic components and PCB are imported from aboard, considerable proportion have to be for supply chain. We try minimize the prototyping cost aswell.

Table 3.10: Estimated Budget

Item	**Cost (USD)**
Electronic Components	140.00
PCB printing	150.00
Supply chain	60.00
Prototyping Testings	60.00
Total	**410.00**

3.6 Steps Undertaken

The development of the swappable BMS followed a structured approach, consisting of several key steps:

- Problem Identification: The project began with an analysis of the limitations of conventional EV charging and the need for a faster, more efficient battery swapping solution.
- Research Feasibility Study: A thorough literature review was conducted to explore different BMS architectures, cell balancing methods, and communication protocols. Simulations were carried out to evaluate various design options.

- Design Planning: The system architecture was developed, including circuit schematics for active balancing, CAN communication, and docking station integration. Hardware components were selected based on performance and cost considerations.
- Prototyping: Initial prototypes were built and tested, with a focus on verifying the efficiency of cell balancing, power regulation, and data communication.
- Testing Validation: The prototypes underwent extensive testing, including charge and discharge cycle evaluations, thermal stability analysis, and communication reliability tests.
- Addressing Issues Optimization: Based on test results, necessary design modifications were made. This included shifting from DC-DC converter-based balancing to inductive active balancing and refining the CAN communication framework.
- Final Implementation: The improved design was finalized, integrating all components into a functional system. The BMS was assembled for full-scale testing with the docking station.
- Deployment Evaluation: The system was deployed in a controlled environment to assess real-world performance, ensuring seamless battery swapping and safe operation under various conditions.

By systematically following these steps, the project has successfully progressed toward developing a high-performance, efficient, and scalable swappable BMS that meets the needs of modern electric vehicle applications.

3.7 Task Delegation

The task delegation chart shows how project responsibilities are divided among the team members. Each person is assigned specific tasks, ensuring that all aspects of the project are covered efficiently. This organized approach helps the team work together effectively toward the project's success.

Task	Sandeepa	Upeksha	Nimesh	Hashika
Block diagram	✓		✓	✓
Literature Review	✓	✓	✓	
Cell balancing schematic design		✓	✓	
BMS schematic design			✓	✓
Central controller schematic design	✓	✓		
PCB Routing		✓	✓	
Firmware developing	✓			✓
Prototype testing	✓	✓	✓	✓
Assembling PCBs		✓	✓	
Cascading of system	✓			✓

Figure 3.37: Task Delegation of project

3.8 Timeline

The project timeline is shown below, and up to this point, we have adhered to the planned schedule. We are confident that we will continue to follow the timeline for the remaining phases of the project and complete the tasks as outlined.

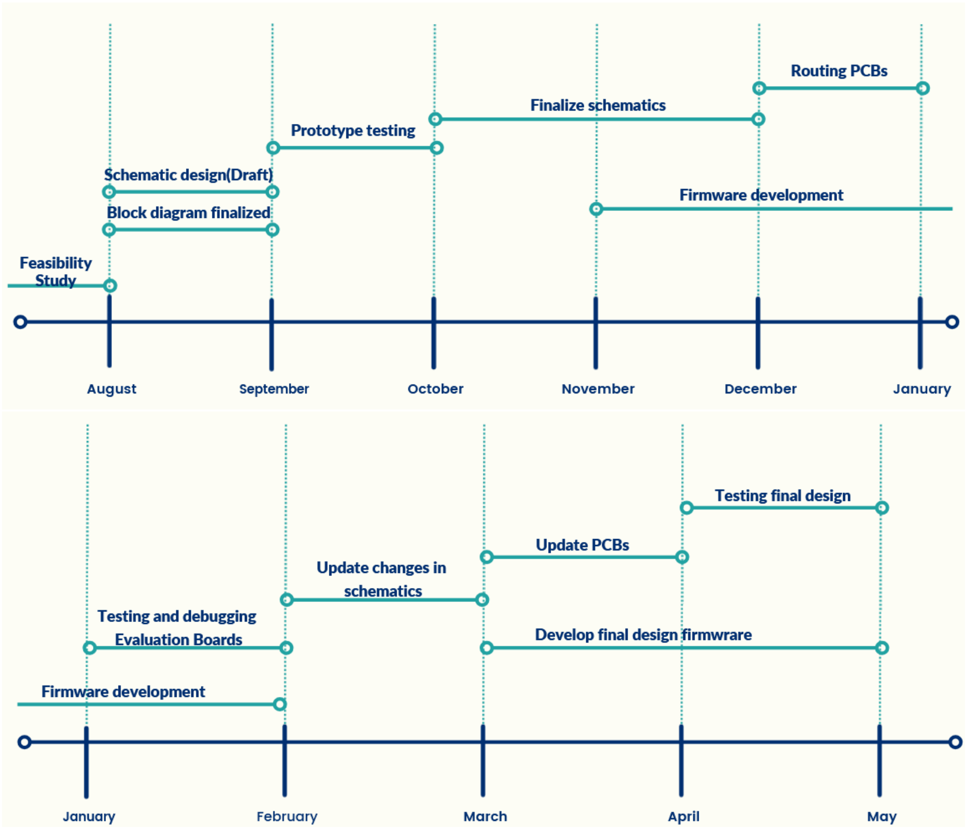

Figure 3.38: Timeline of the Project

3.9 Project Deliverable

At the conclusion of this project, we aim to deliver an electric tuk-tuk which has capability to swap battery packs, as outlined in the design. Additionally, a Swapping Station will be delivered, where the battery pack exchange process will take place.

3.10 Validation Plan

In the prototyping phase of a Swappable BMS (Battery Management System) project, the validation process is crucial for ensuring that all individual components and the overall system function as expected. The process begins with testing the core elements of the BMS PCB, starting with the monitoring IC and the microcontroller (MCU). The monitoring IC is responsible for measuring and reporting the voltage, temperature, and health of each cell, while the MCU handles communication and control functions. These components are tested independently to verify their accuracy, with a focus on key parameters such as voltage, current, and state of charge (SOC). The functionality of the fuel gauge is also assessed to ensure the system can accurately track battery usage and life.

After confirming the operation of the monitoring IC and MCU, the next step is to validate the active current-limiting feature of the BMS. This is done by connecting passive loads, such as power resistors, in place of the battery cells to safely test the current-limiting capabilities. By simulating various load conditions, the system's ability to prevent overcurrent situations and ensure reliable operation is validated.

The next phase involves integrating and testing the active cell balancing PCB. This PCB plays a crucial role in balancing the 16 series-connected cells. During this phase, the voltage of each cell is monitored over time to ensure that the system redistributes charge to balance the cells properly, preventing overvoltage and undervoltage conditions. The time taken to achieve full cell balancing is noted, as balancing speed and efficiency are important factors for overall system performance.

The validation process also includes an in-depth evaluation of the firmware running on the BMS. This is divided into two main phases. In the first phase, the communication protocols between the MCU, monitoring IC, fuel gauge, CAN bus, EEPROM, and other GPIO pins are tested. The goal is to ensure that all inter-component communications are stable and error-free, and that all data channels (such as those used for voltage monitoring, SOC, and fault reporting) are functioning correctly. Once the communication protocols are validated, the second phase involves implementing the full BMS process in the MCU. This phase includes running the control algorithms for charging, discharging, cell balancing, and thermal management, ensuring that the MCU can handle all BMS operations as designed.

After the individual components and firmware are validated, the system is assembled with real LiFePO4 cells, and the entire system is tested under realistic operating conditions. Key areas of focus in this phase include charging and discharging behaviors, thermal management, and the efficiency of active cell balancing. Based on the results of these tests, improvements are made to address issues such as thermal dissipation, balancing speed, current handling, and overall system reliability. These adjustments ensure that the final PCB design will meet the performance requirements of the BMS and provide safe, reliable, and efficient battery management in real-world applications.

3.11 Addressing Limitations

Like any engineering project, the swappable BMS system faced several technical and practical limitations, which were identified and addressed through iterative improvements. One of the initial challenges was the high energy loss in the DC-DC converter-based balancing system, which reduced overall efficiency. This limitation was overcome by shifting to inductive active balancing, which significantly reduced power dissipation while improving charge distribution.

Another challenge was ensuring secure and real-time communication between multiple battery packs and the central controller. This was addressed by implementing a structured CAN protocol with fault detection and correction mechanisms, ensuring reliable data transmission even in high-interference environments. Additionally, thermal management was a concern due to the heat generated during high-current charging and discharging. This issue was mitigated by optimizing the battery casing design and using active balancing to minimize heat generation. Addressing these limitations has resulted in a more efficient, scalable, and cost-effective BMS design suitable for swappable battery applications.

Chapter 4

Results and Discussion

4.1 Introduction

When designing the BMS and the overall system, our primary focus was on three key aspects: ensuring battery pack safety through secure authentication and protection mechanisms, maintaining energy efficiency and battery health through effective cell balancing, and implementing current limiting techniques to prevent overcharging during direct charging or high-voltage connections. This chapter presents and discusses the results obtained in each of these areas.

4.2 Results

To test the communication between the BMS and the central unit, we used two BMS nodes. After both BMS units are connected and the wakeup signal is sent by the central unit, their states transition as described above. Below, we present the debugging output obtained from the central unit. These outputs were captured using the PuTTY application, which allows us to monitor serial data transmissions.

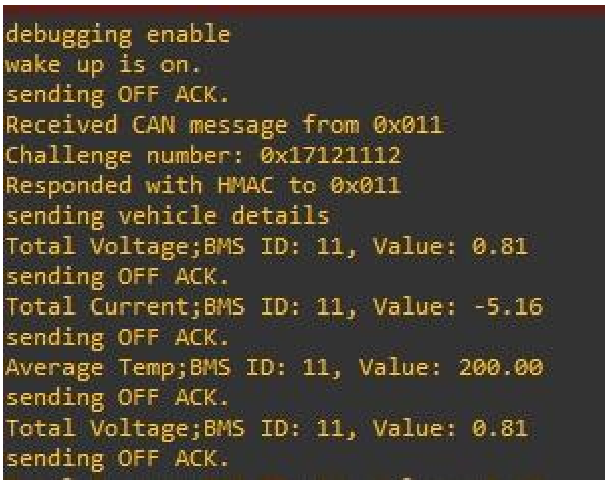

Figure 4.1: Central Unit Authentication Results

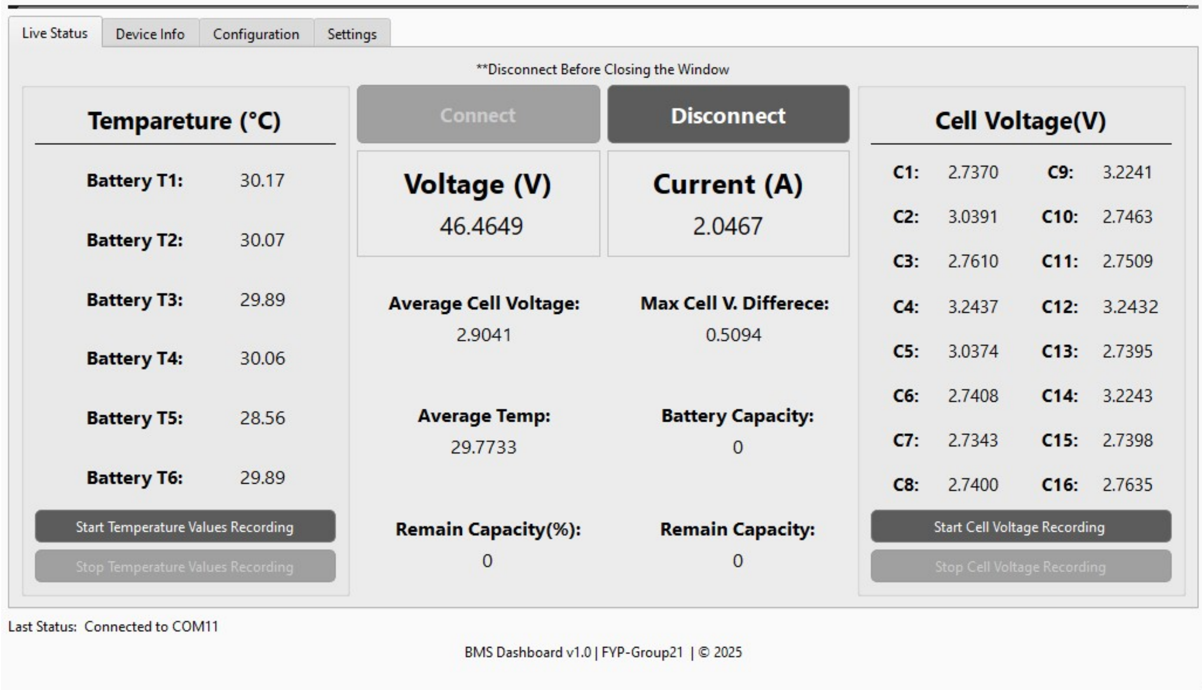

Figure 4.2: User Interface for Getting Real Time Data

We used the Windows application to monitor real-time data from the BMS, and the image below demonstrates how this data was captured. Through this application, we can observe the changes in individual cell voltages over time. These real-time voltage variations were particularly useful during the testing of the active balancer unit.

As described earlier, once the BMS units are woken up, real-time data is transmitted to the central unit. The image below shows how this data is received at the central unit, following the format outlined in Section 3.2.4 (Custom CAN Data Frame Sent by BMS). To enhance readability, the received frames are decoded and presented in a human-readable format.

The active cell balancer operates during charging and when the battery is idle (i.e., not charging or discharging). The main MCU monitors the charging and discharging states and provides an appropriate enable signal to activate or disable the active cell balancer accordingly. To test the active balancer, we intentionally created a considerable voltage difference between adjacent cells. Using our Windows application, we recorded the changes in cell voltages over time. These recorded data were then used to interpret and generate graphs that illustrate how the cell voltages changed during the balancing process.

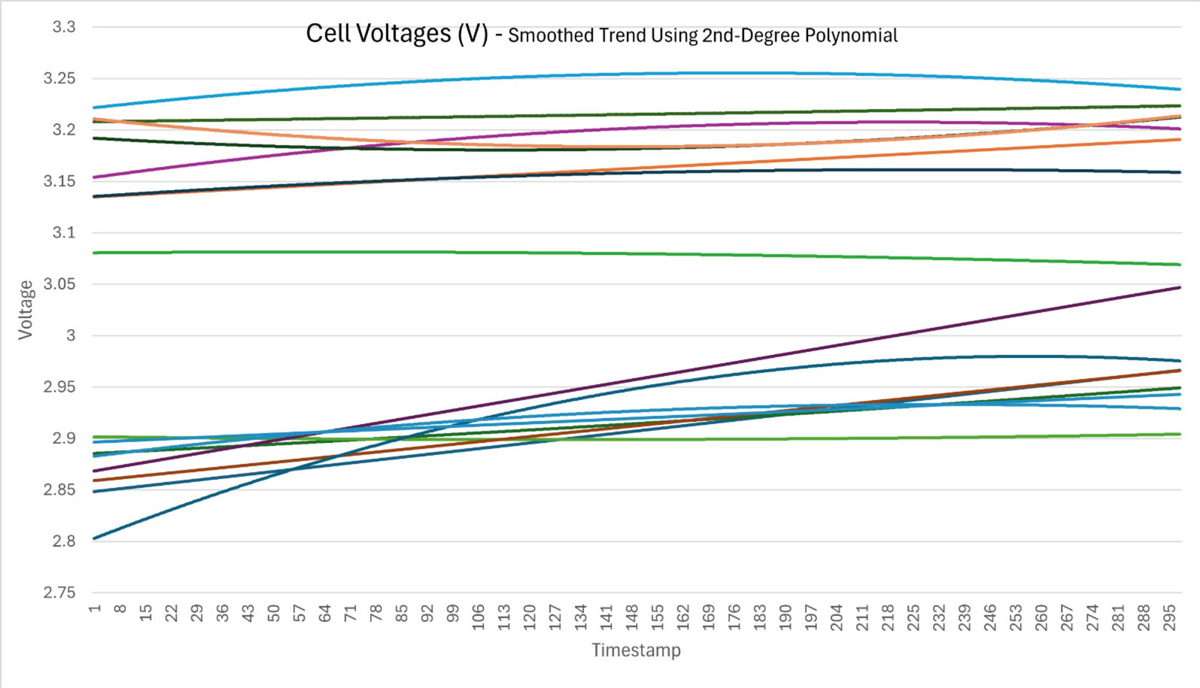

Figure 4.3: Voltages of each cell over time while balancing

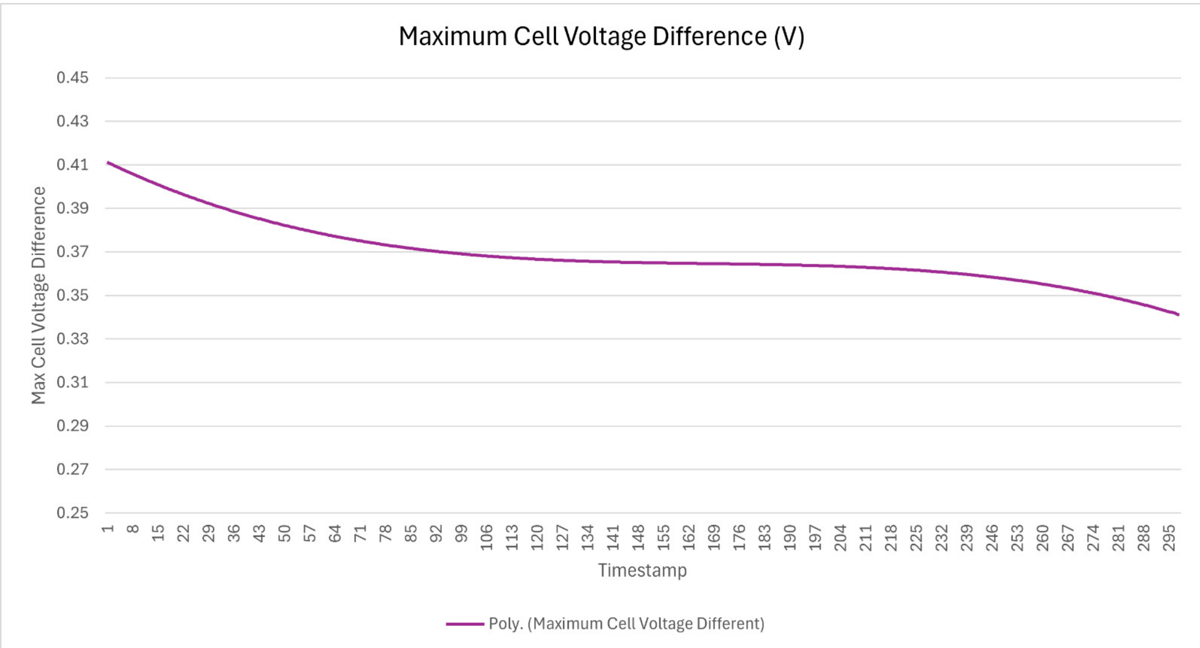

Figure 4.4: Maximum Voltage difference of cells over time while balancing

The version 2 Active Charging Limiter PCB was tested using a laboratory power supply and a resistive load for debugging purposes. During the test, the current limit was set to 2A. The unit successfully regulated the charging current around 2A, with a fluctuation of approximately ±200mA. A slight increase in output current was observed as the input voltage was increased, which remained within acceptable limits. These results confirm the expected current limiting behavior of the circuit under test conditions.

4.3 Results and Discussion

From the authentication process, it can be observed that as soon as the central unit sends the wakeup ping, both BMS nodes immediately respond by sending their challenge values. The central unit then sends the correct hashed responses for both challengers without delay. Following this, after transmitting the vehicle details, the central unit successfully receives the BMS information promptly and without any noticeable lag.

Using the Windows application, BMS data can be monitored in real-time with an update interval of less than one second, providing timely and accurate insights into the system status.

4.4 Interpretation and Analysis

In our SHA-256-based challenge-response authentication mechanism ,the challenge consists of a 4-byte random number, allowing for 2^{32} possible unique values. This randomness makes replay attacks significantly more difficult. Upon waking up, the BMS sends a random challenge to the connected device. The authentication process, which includes receiving the challenge and verifying the response, completes in less than 2 seconds. If a new user is detected, the BMS retrieves the user logs. The entire sequence, from wake-up to authentication and user log processing, completes in less than 5 seconds, ensuring both security and responsiveness.

When the BMS is in the connected state, real-time data such as voltages and currents are transmitted to the central unit at intervals of less than 1 second. This update rate is sufficient for the central unit to process and respond to warning messages in a timely manner. If the BMS detects that the battery temperature exceeds the upper threshold, an automatic disconnect mechanism is activated to prevent thermal damage. Once the temperature falls back below the defined threshold, the battery pack becomes usable again. To address potential misuse or neglect of the battery pack, the BMS stores the logs of the most recent users. In case of damage or unusual behavior, these logs enable tracking of user activity, allowing appropriate action to be taken.

4.5 Challenges and Limitations

Although the BMS is designed primarily for electric vehicles, testing each unit with actual EVs posed certain practical challenges. To address this, we successfully conducted tests using loads and power supplies that closely simulate the behavior of EV batteries and load conditions. While the batteries are capable of charging at 40A, due to space and equipment constraints, we performed the charging tests using a 10A programmable power supply. Additionally, since EVs typically use high-power motors as loads, testing with such high-current loads was limited in our setup.

Nevertheless, these alternative testing setups provided meaningful and reliable results that are expected to closely reflect real-world performance with minimal variance.

4.6 Implications and Overall Impact

The successful development and testing of the Swappable BMS demonstrate the feasibility of a modular, high-capacity battery system suitable for electric vehicles with battery swapping capabilities. The project highlights the effectiveness of inductive active cell balancing, closed-loop current limiting, and real-time communication through CAN bus, contributing to improved safety, reliability, and energy efficiency of battery packs.

The system's compatibility with multi-pack parallel operation and its scalable design allow for integration into various EV platforms and infrastructure. The inclusion of authentication mechanisms and EEPROM-based configuration enhances security and traceability, essential for battery-swapping networks.

Economically, the system reduces vehicle downtime and improves battery lifespan, which can lower operational costs and support business models such as Battery-as-a-Service. Environmentally, the optimized usage of cells contributes to longer battery life, reduced e-waste, and more sustainable resource utilization. Overall, the project provides a strong foundation for future development and deployment of swappable battery ecosystems in urban electric mobility.

Chapter 5

Conclusion

Developing a swappable battery management system specifically for multi-pack lithium-based batteries provides a revolutionary solution for the electric vehicle market. Our BMS successfully addresses the inefficiencies in the present BMS designs, long charging periods, and scalability. The suggested design improves user convenience, safety, and efficiency by combining secure charging processes, reliable communication protocols, and inductor-based active balancing. Testing results confirm the system's operational and financial benefits, which include a notable decrease in power usage and enhanced thermal stability when compared to existing techniques. The adoption of safe and scalable communication and charging procedures strengthens the BMS's reliability and versatility for practical uses. This innovative approach to battery management, coupled with active balancing and a centralized control framework, positions the swappable BMS as a critical advancement for sustainable transportation. In addition to making EVs feasible, the system opens up opportunities for wider adoption and infrastructure optimization in the field of electric mobility by facilitating smooth battery swapping.

Future Work

We are primarily focusing on the development of a Battery Management System (BMS) for an electric tuk-tuk, ensuring that we maximize the power output from the battery packs while maintaining high conversion efficiency and minimizing power losses. Efficient energy conversion is crucial to improving the overall performance and range of the tuk-tuk.

Currently, we are using a low-voltage motor, and we have designed the battery pack voltage based on the motor's voltage and current requirements. Since the motor operates at a relatively low voltage, it needs to draw a high current to generate the required torque. As a result, the current through the BMS PCBs and the main power cables is significantly high, reaching around 200A. This high current flow leads to substantial conduction losses, reducing the overall system efficiency. Additionally, low-voltage motors are larger and heavier compared to high-voltage motors, which further increases the total weight of the tuk-tuk. The additional weight negatively impacts the mileage per charge, as the vehicle requires more energy to move a heavier load.

Considering these challenges, we plan to transition to a high-voltage motor in the future. High-voltage motors are generally lighter than low-voltage motors, which will help reduce the overall weight of the tuk-tuk, improving its efficiency and range. Additionally, high-voltage motors require less current to produce the same mechanical power output as a low-voltage motor. This means that the conduction losses in cables and PCBs will be significantly reduced, allowing us to conserve more energy and improve overall system efficiency.

However, switching to a high-voltage motor requires us to increase the battery pack voltage. Currently, our battery pack consists of 16 series-connected cells, but to match the voltage requirements of the new motor, we need to increase this number to 24 cells. A single battery pack with 24 cells would be considerably heavier, making it difficult for a single person to swap the battery at the docking station. Additionally, increasing the number of cells in a single pack would complicate the active balancing mechanism, making battery management more challenging.

To address these issues, we plan to develop a modular battery system. Instead of using a single 24-cell battery pack, we will design two separate 12-cell battery packs. The BMS will be designed to allow two battery packs to be connected in series, providing the required voltage for the high-voltage motor.

This modular approach has several advantages. First, battery swapping will be easier, as a 12-cell battery pack is lighter and more manageable for a single person at the docking station. Second, the weight of each battery pack will be lower, reducing the overall burden on the vehicle and improving efficiency. Third, active balancing will be simpler, as balancing 12 cells at a time is more practical than managing a 24-cell system. Fourth, reducing the total voltage of a single battery pack improves safety, as handling lower-voltage battery packs minimizes electric shock risks and makes the system safer for consumers. Finally, this modular design provides flexibility, allowing the battery system to be adapted for different applications if needed.

By implementing this swappable BMS design, we aim to enhance the practicality, efficiency, and maintainability of the electric tuk-tuk. This approach not only optimizes energy conversion and reduces power losses but also ensures that the vehicle remains lightweight and easy to operate, ultimately extending the driving range per charge while prioritizing user safety.

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