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Swappable BMS

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Approval

Approval of the project supervisor(s).

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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.

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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 decisions are made by MCU of BMS 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.

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.

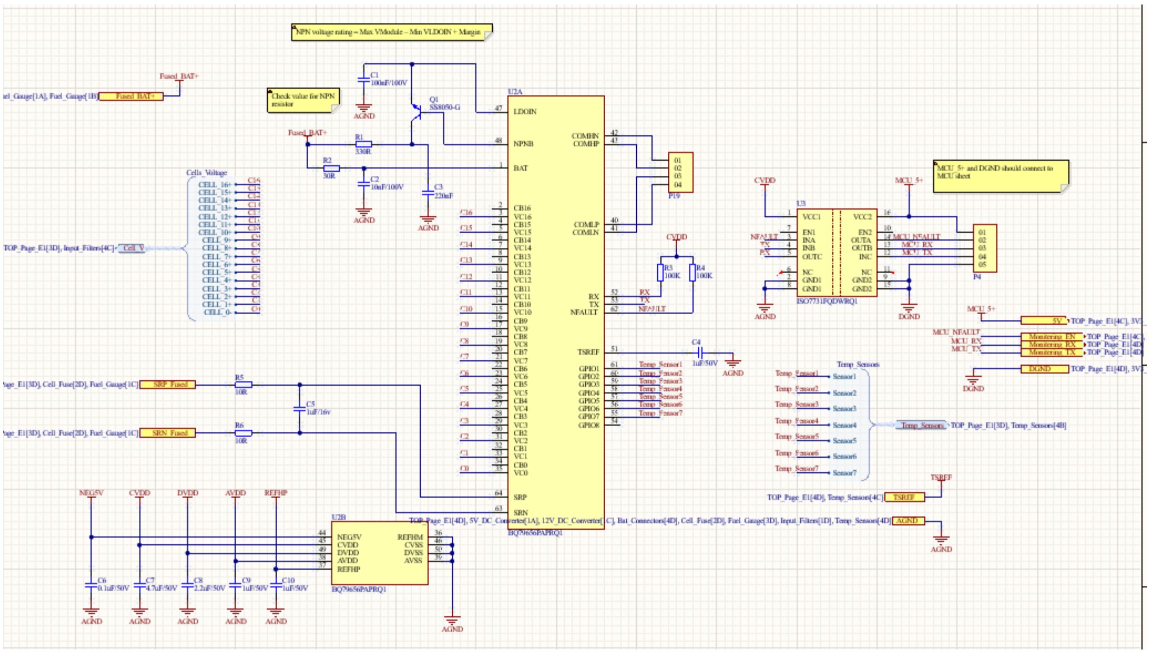

Figure 3.1: Schematic for Monitoring IC

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.

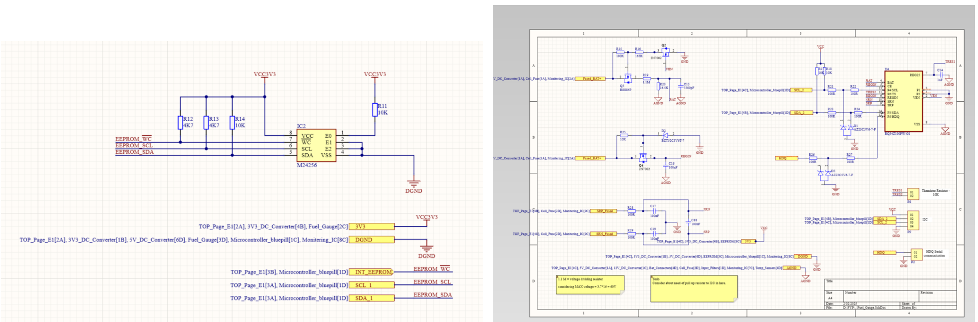

Figure 3.2: Schematic for EEPROM and Fuel Gauge

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.

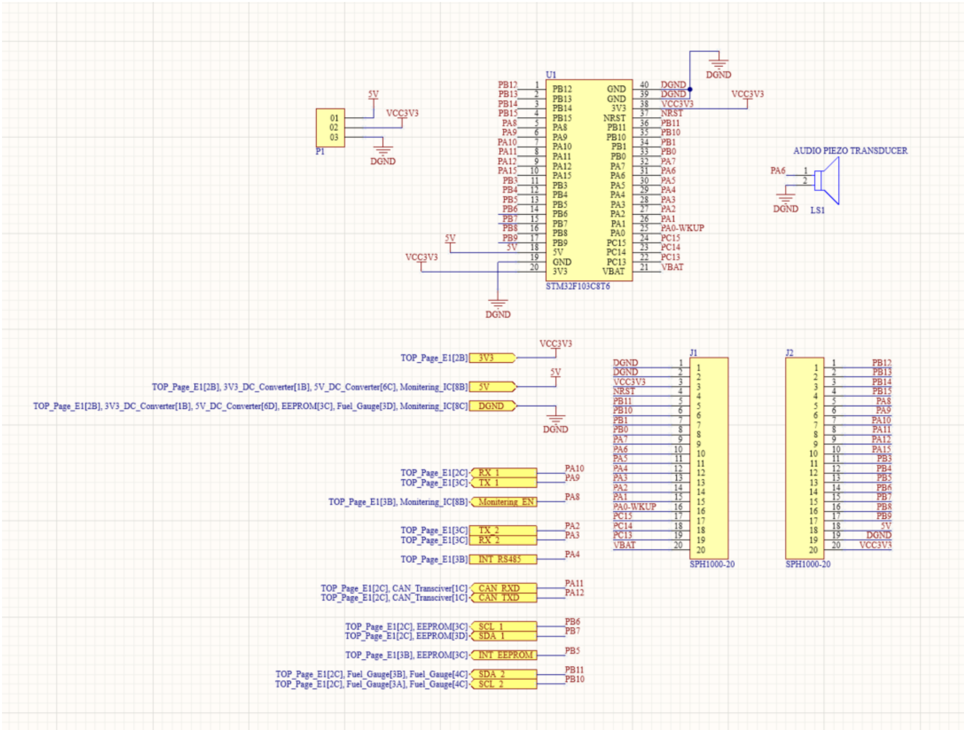

Figure 3.3: Schematic for STM32 MCU

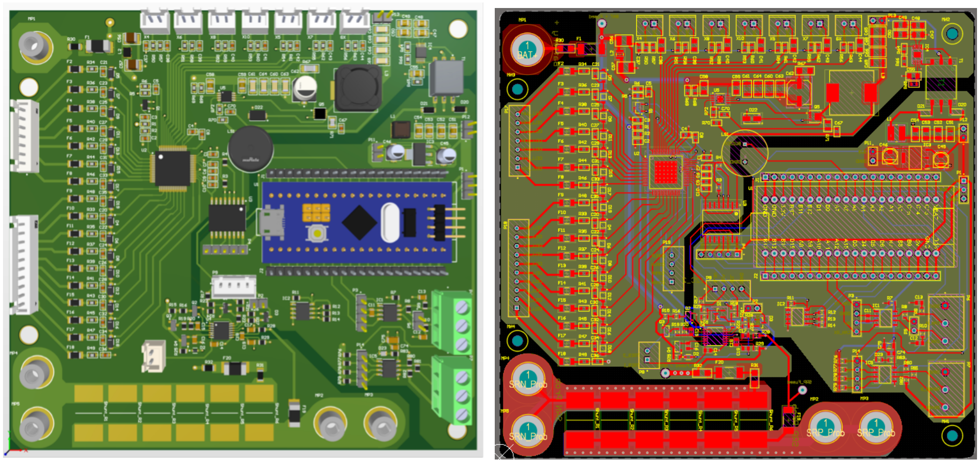

Figure 3.4: PCB layout of monitoring IC with MCU

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.

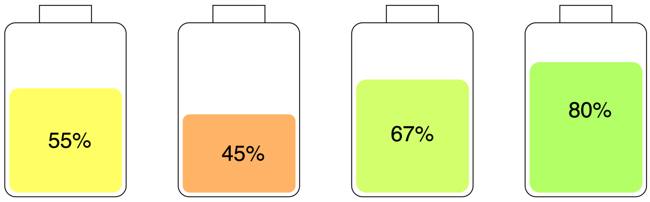

Figure 3.5: battery cells in a series connected battery pack

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

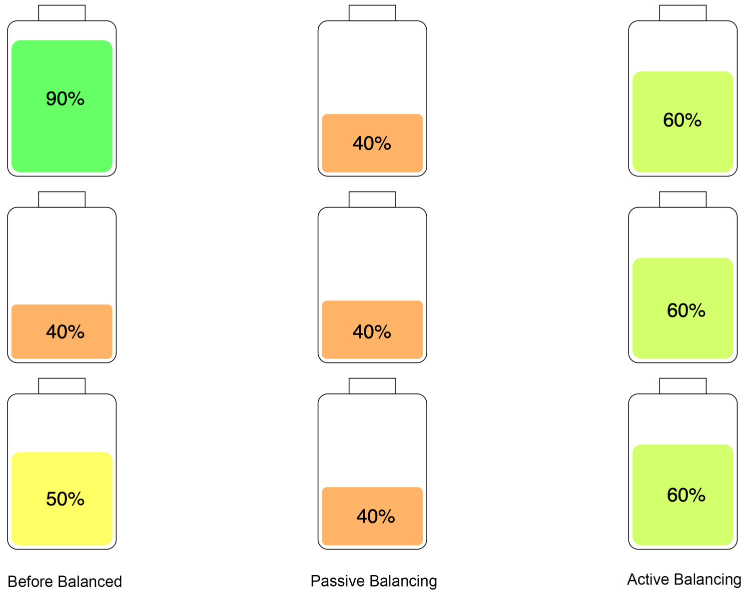

Figure 3.6: Active cell balancing vs passive cell balancing

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

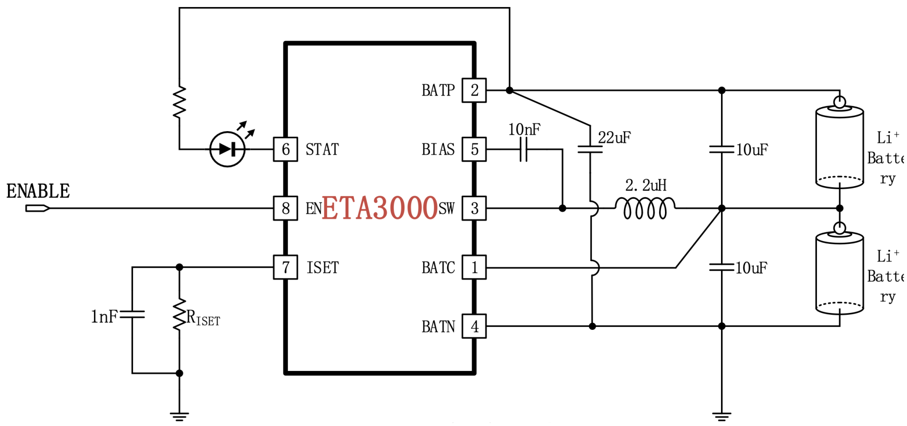

Figure 3.7: Example circuit for balancing two series connected cells - Datasheet

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.

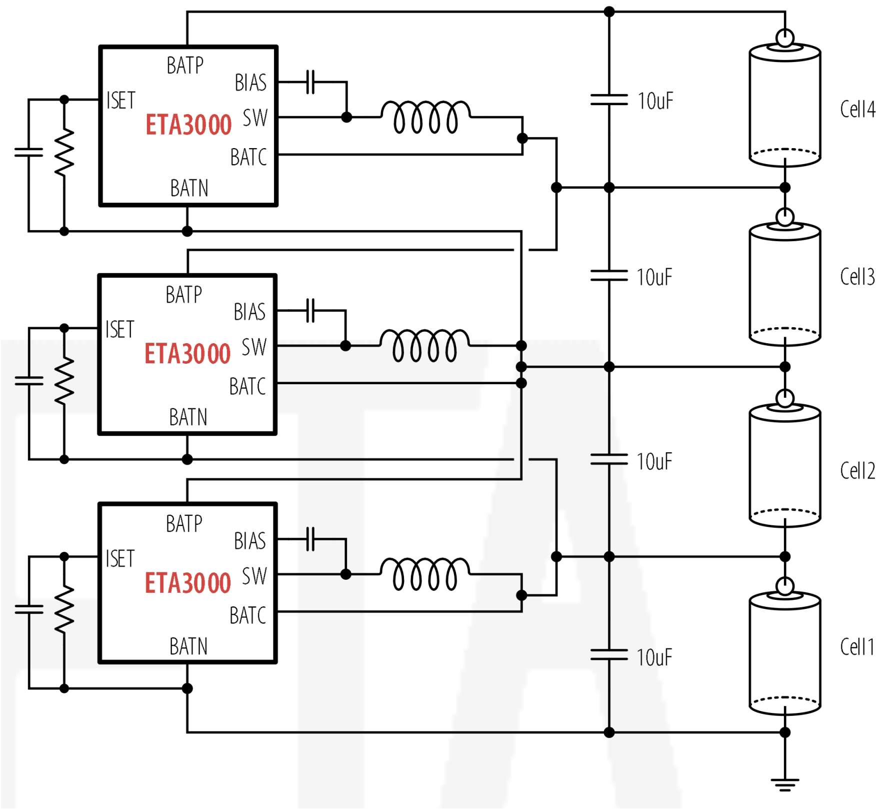

Figure 3.8: Example circuit for balancing series connected cells - Datasheet

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.

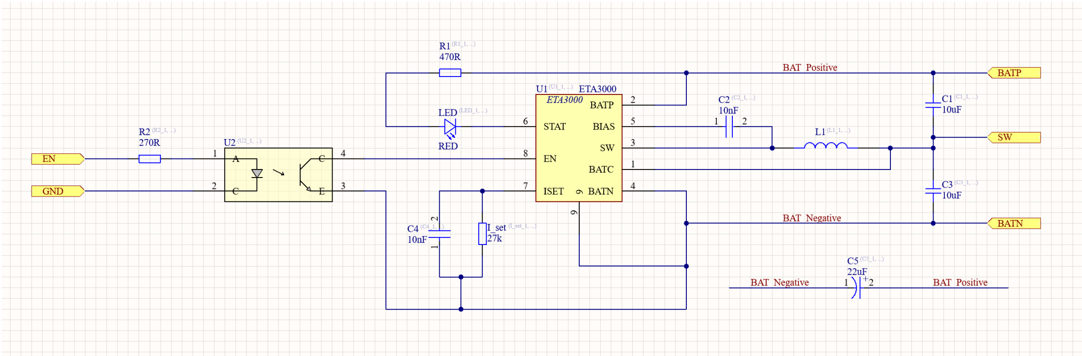

Figure 3.9: Schematic of balancing two series connected cells circuit

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

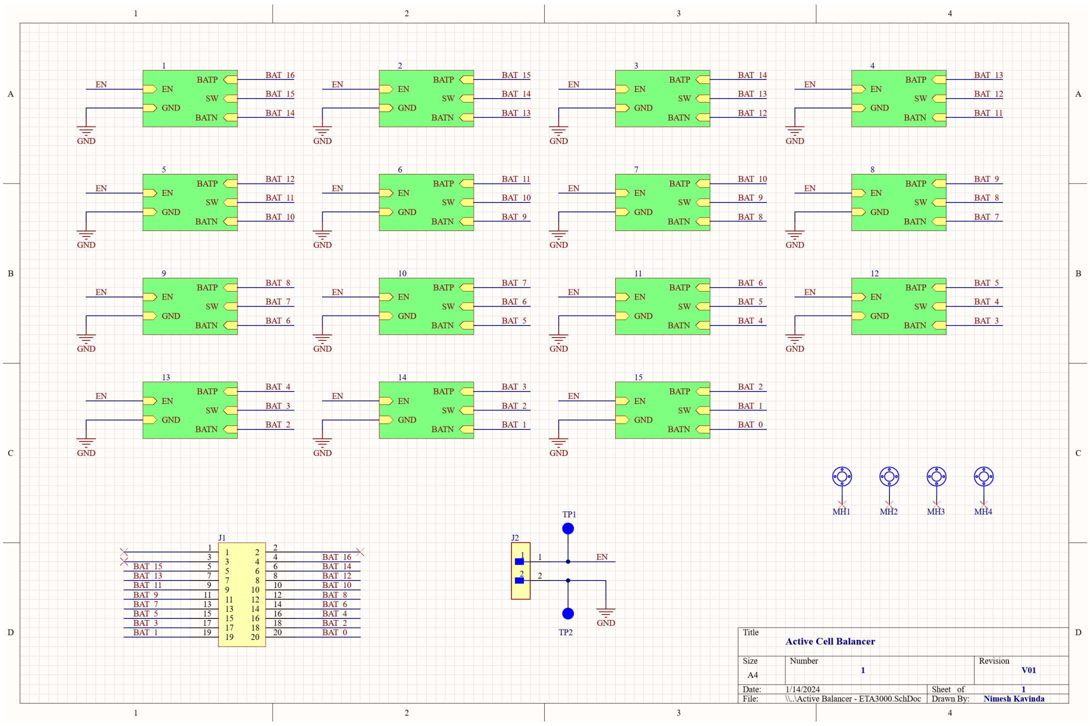

Figure 3.10: Schematic of balancing 16 series connected cells circuit

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.

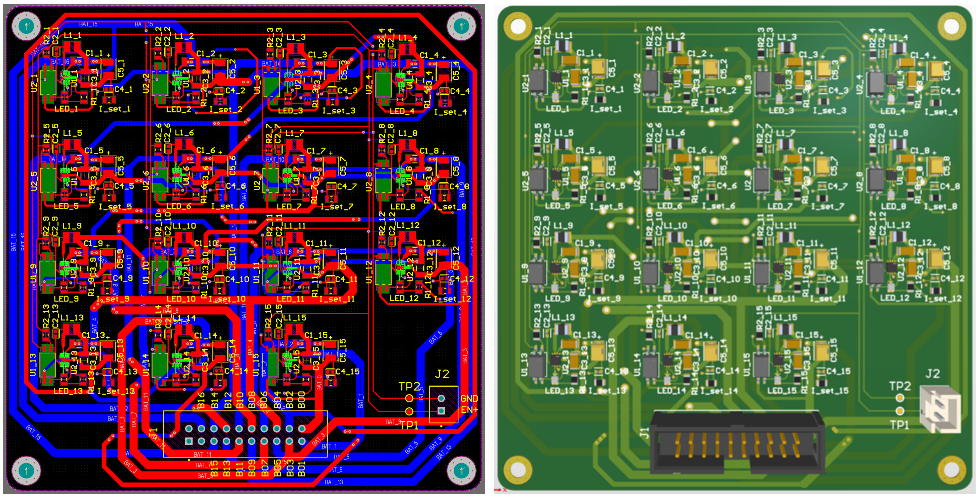

Figure 3.11: 16-Cell inductive cell balancer - layout and 3D view

Charging current limiting circuit

The charging station is equipped with a charger capable of delivering a maximum current of 100A. However, the batteries connected to the charger in parallel have a critical limitation: if the charging current exceeds 20A, it can negatively impact the 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.

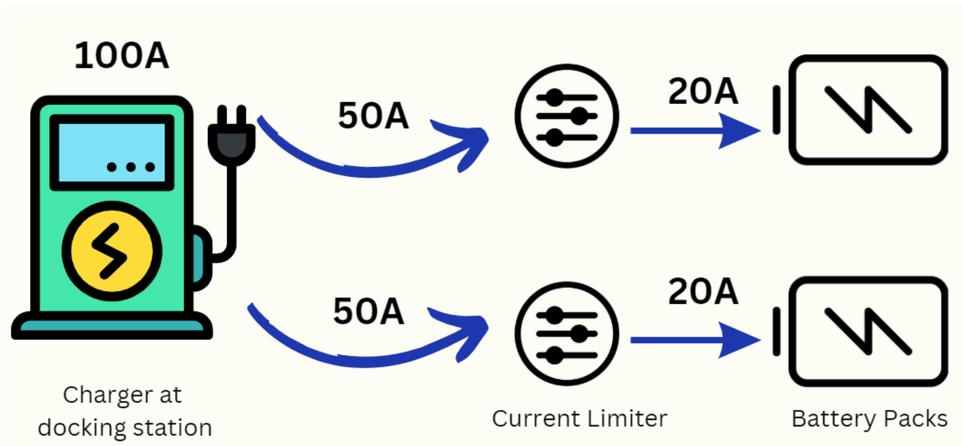

Figure 3.12: Concept of current limiter

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.

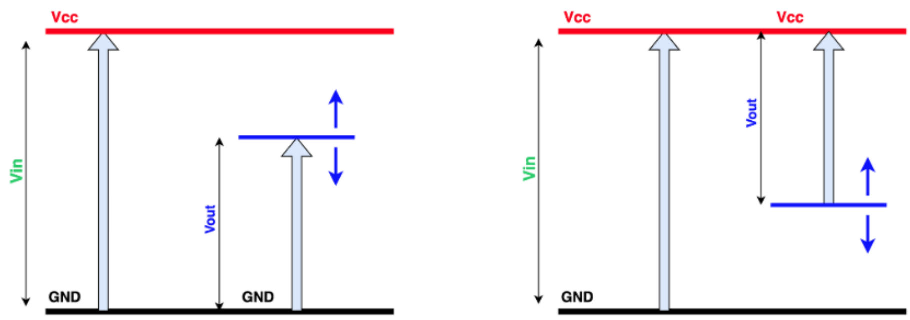

Figure 3.13: Voltage levels of both configurations

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.

Asynchronous buck converter

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.

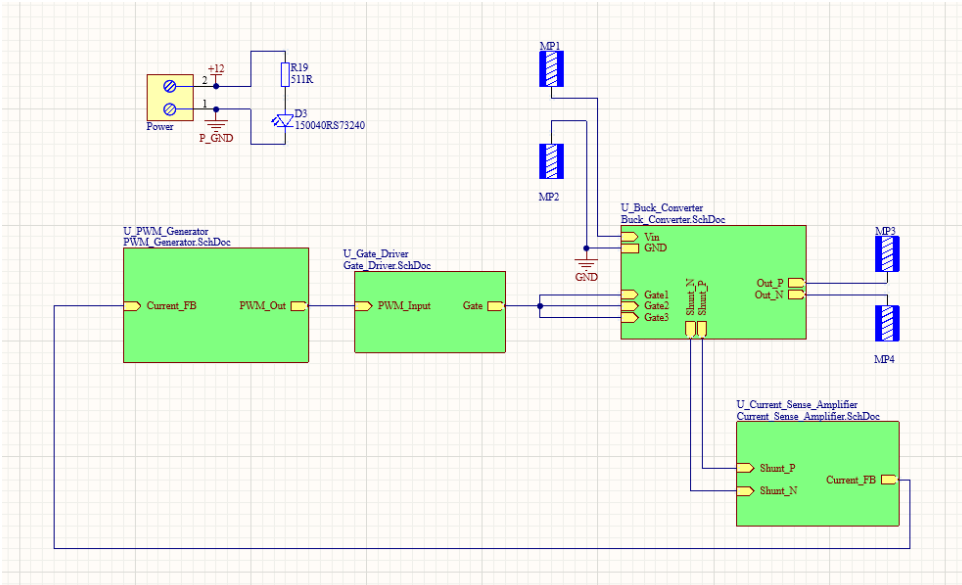

Figure 3.14: High Level Schematic

PWM controller IC

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.

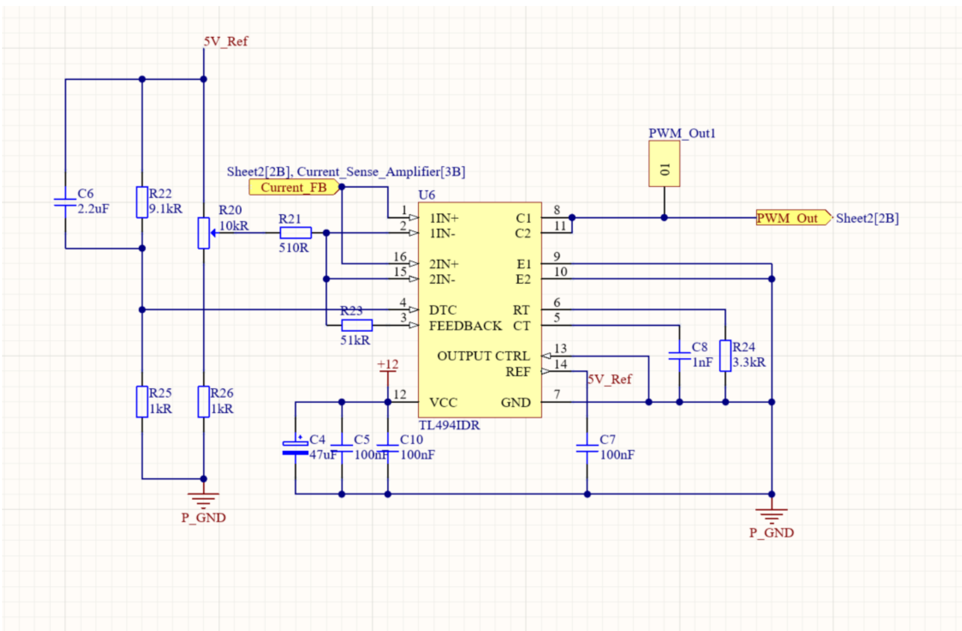

Figure 3.15: /PWM Controller Schematic

Gate driver circuit

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.

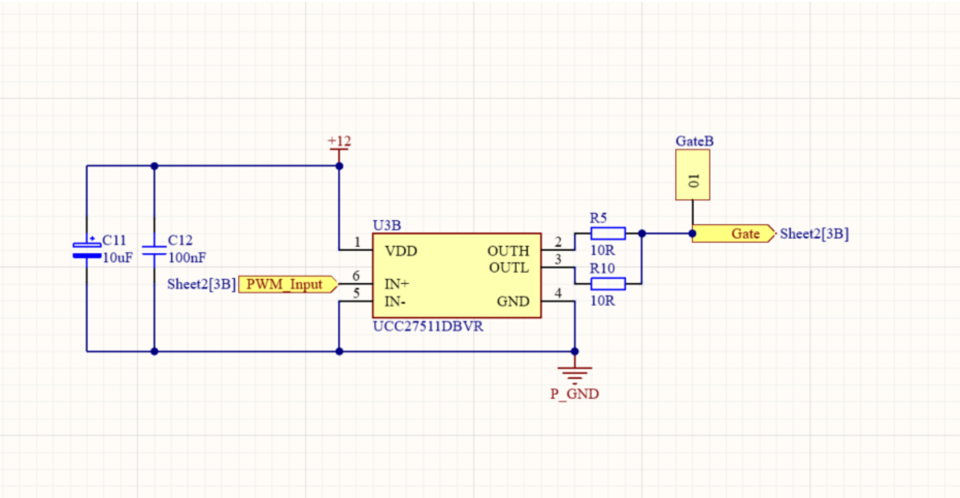

Figure 3.16: Gate driver Schematic

Current sense amplifier

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 over-current detection. The processed current feedback signal is sent to the PWM generator, enabling closed-loop current regulation.

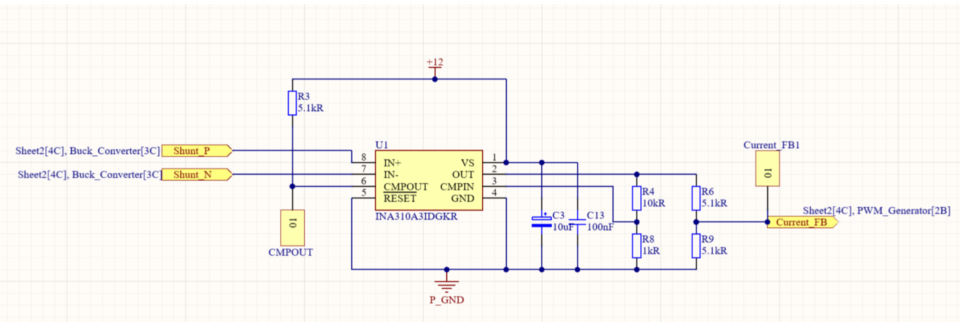

Figure 3.17: Current Sensing Amplifier Schematic

Buck converter circuit

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.

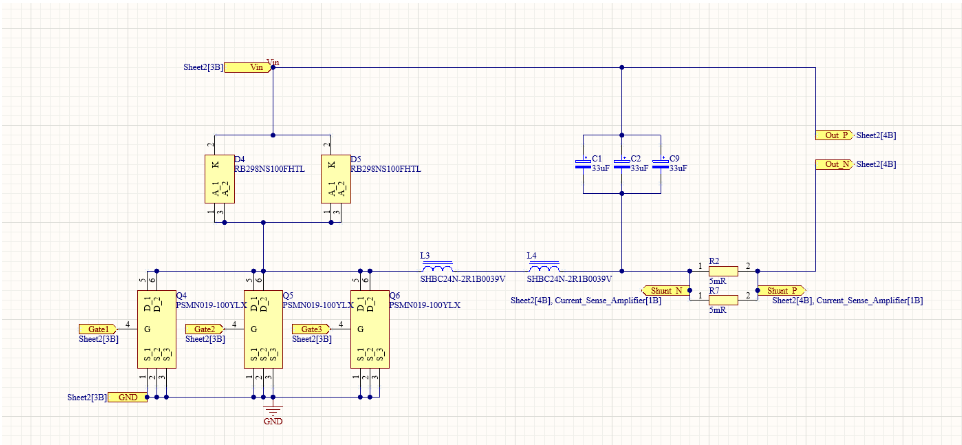

Figure 3.18: Buck Converter Schematic

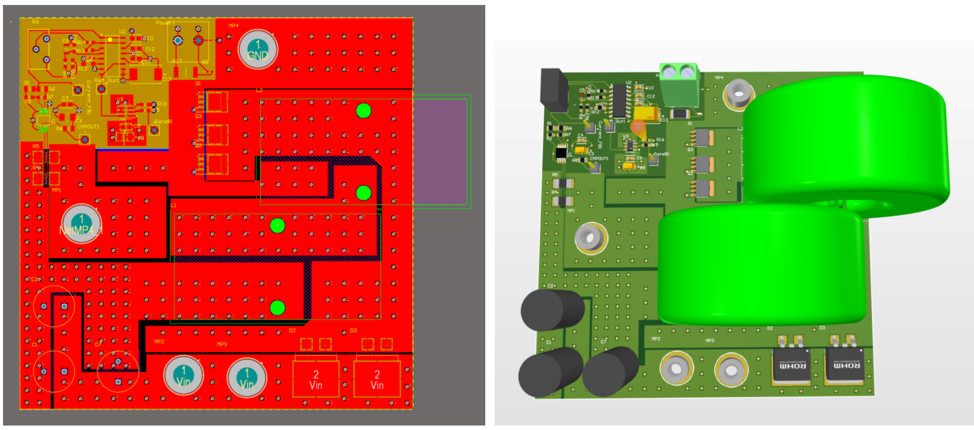

Figure 3.19: Current Limiting PCB

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.

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.

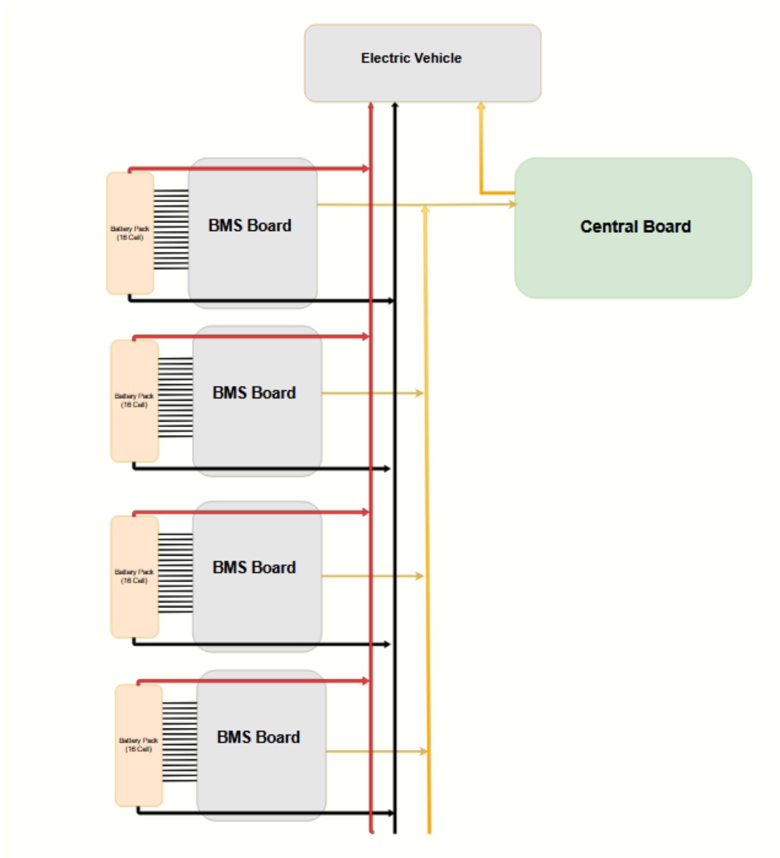

Figure 3.20: Designed Swapping Station

3.2.3 Battery Swapping Station (Docking Station)

Figure 3.21: 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.

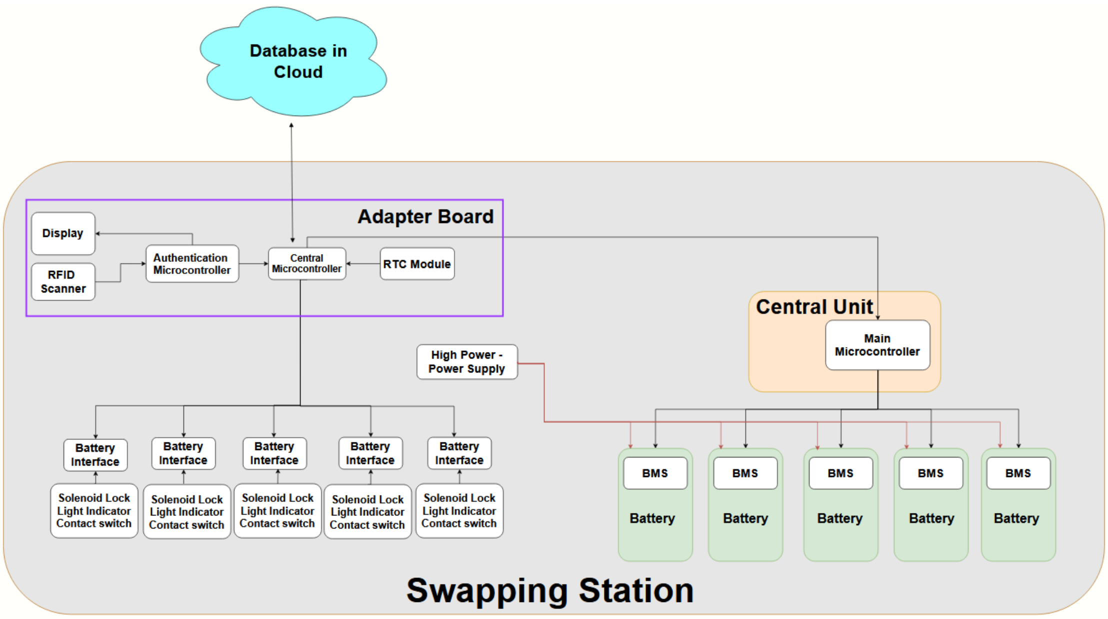

Figure 3.22: High level Architecture of Swapping Station

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.

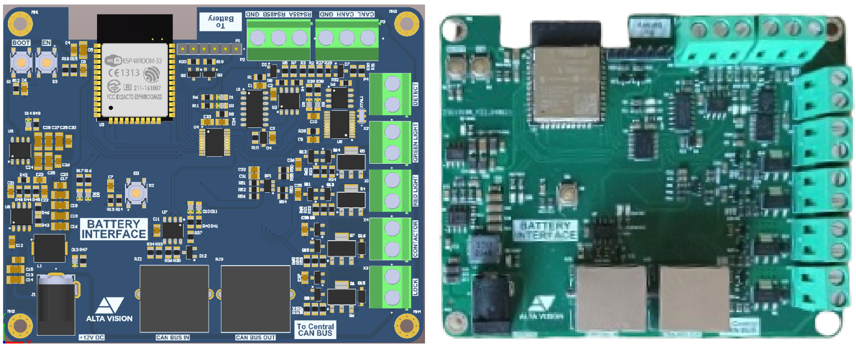

Figure 3.23: Battery Interface Unit in Docking Station

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.

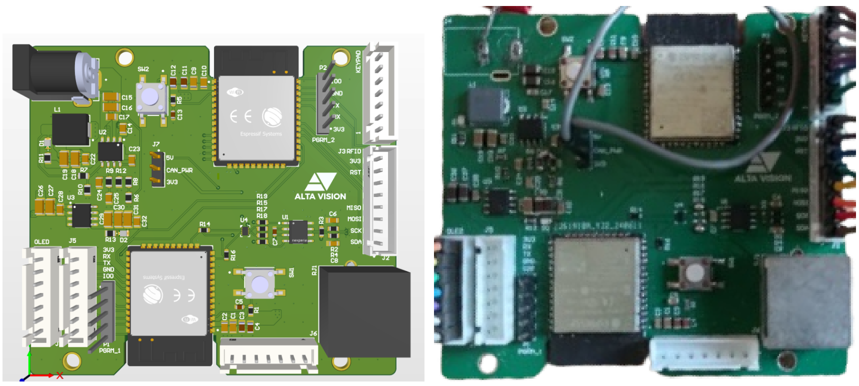

Figure 3.24: Adapter Board in Swapping Station

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.

3.3 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.

3.4 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 3.1: 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 3.25: 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.

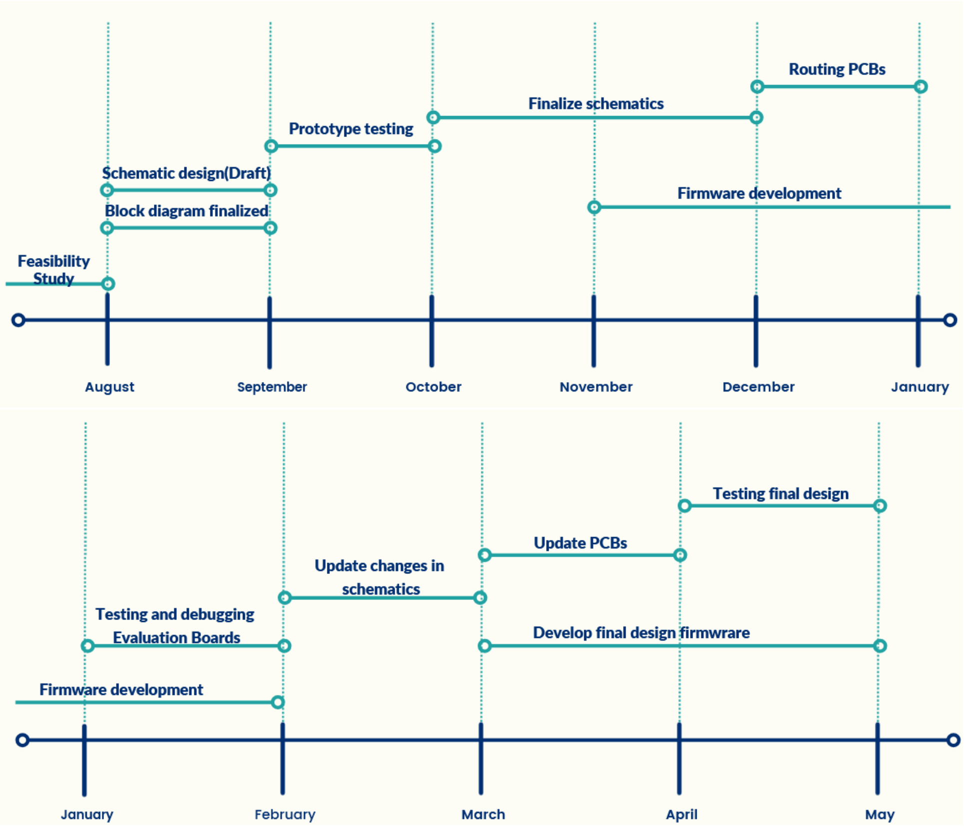

Figure 3.26: Timeline of the Project

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.

3.12 Future Work in Methodology

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.

Chapter 4

Results

4.1 DC-DC Converter based Cell Balancing

In the DC-DC converter-based method, we will extract charge from the highest voltage cell and boost the voltage to more than 16 times the voltage of a single cell (typically from 3V to 70V) to charge the entire series-connected 16-cell pack. To achieve this, we need an isolated boost converter capable of stepping up the voltage from 3V to 70V. On the input side, we must be able to individually switch each cell to the boost converter. To accomplish this, we have designed a relay matrix that allows independent cell selection and connection to the boost converter.

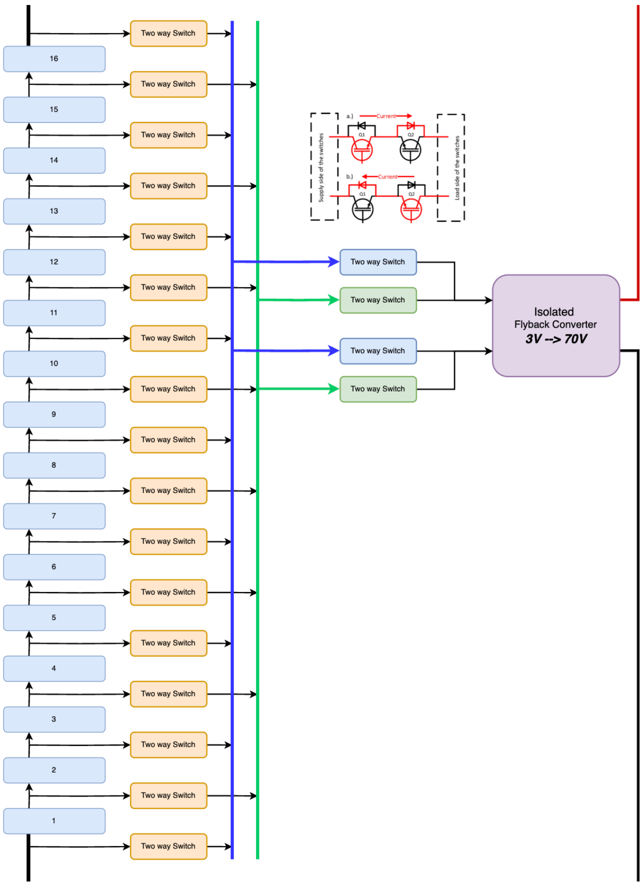

Figure 4.1: Relay matrix for switching cells to boost converter

When considering voltage boosting for our active cell balancing system, we determined that a voltage gain of 20x with isolation is required. This means we need to step up the voltage from approximately 3V (the voltage of a single $LiFePO_4$ cell) to around 70V to charge the entire 16-cell series-connected pack. However, after extensive research, we found that there are no commercially available boost converter ICs or standard circuit configurations capable of achieving such a high voltage gain in a single stage while maintaining efficiency and isolation. Traditional boost converters are typically limited in their voltage gain due to constraints such as duty cycle limitations, component stress, and efficiency losses at extreme conversion ratios.

Given these challenges, we decided to adopt a cascaded boost converter approach, which allows us to gradually increase the voltage in multiple stages rather than attempting an impractical single-stage conversion. This method significantly improves efficiency, reduces component stress, and ensures better control over voltage regulation. To achieve the desired voltage gain while maintaining electrical isolation, we opted for a three-stage conversion topology. The first two stages consist of boost converters, which progressively step up the voltage in smaller increments. The third stage is a flyback converter, which provides both the final voltage increase and the required galvanic isolation between the input and output. The flyback topology is particularly suitable for this application, as it efficiently handles high step-up ratios while ensuring safety through isolation.

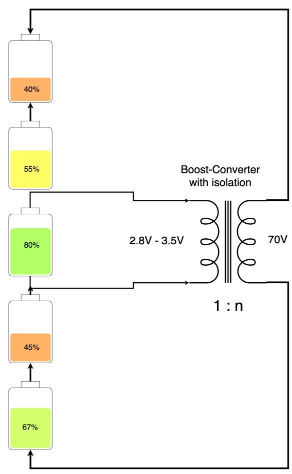

Figure 4.2: DC-DC Converter based Active Balancing Methodology

To implement this design, we carefully selected suitable controller ICs that meet our voltage range and current handling requirements. Choosing the right ICs is critical, as they need to support high-efficiency operation, stable feedback control, and the ability to handle transient conditions. After selecting the appropriate components, we proceeded with circuit simulations to verify the design. We simulated each stage separately using LTSpice and PSpice for TI software to analyze performance, efficiency, voltage regulation, and transient response under different load conditions. These simulations helped us fine-tune the circuit parameters and validate the feasibility of our approach before proceeding with hardware implementation.

The following images show the simulation results, illustrating the voltage boost achieved at each stage and verifying the proper operation of the cascaded topology. Through this multi-stage approach, we can successfully achieve the required 20x voltage gain while maintaining efficiency and ensuring reliable operation of the active balancing system.

4.1.1 Boost Converter - Stage 01 (2.7V to 12V)

We have decided to use the TPS61088RHL boost converter controller IC from ti(Texas Instruments) due to its suitable operating voltage range and high current capability. To achieve even higher current output, we have implemented two of these converters in parallel. The following are the simulation results for Stage 01, verifying its performance and efficiency.

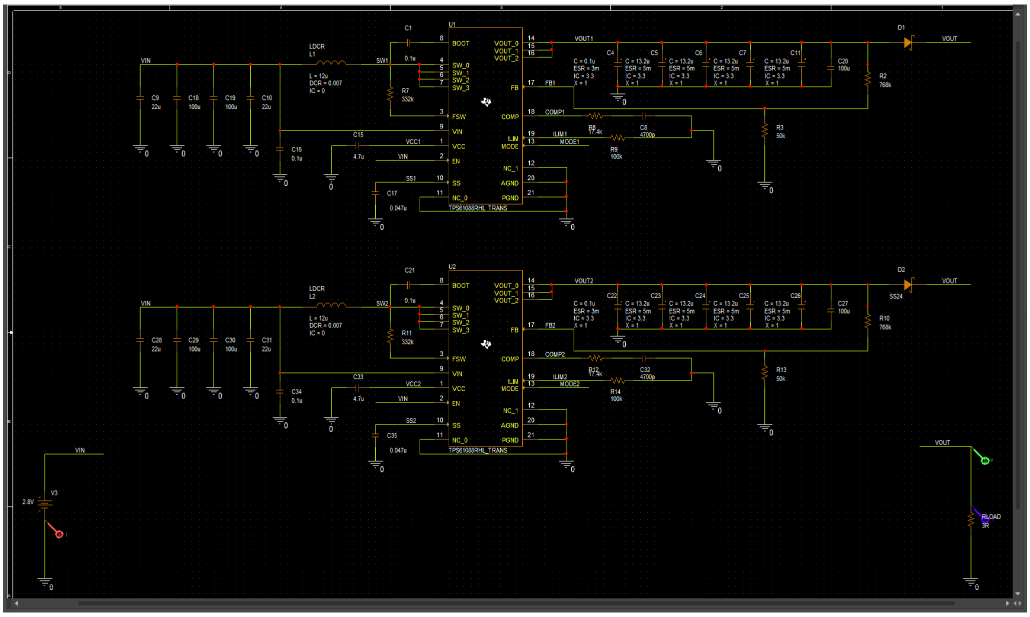

Figure 4.3: Boost Converter - Stage 01 -Schematic

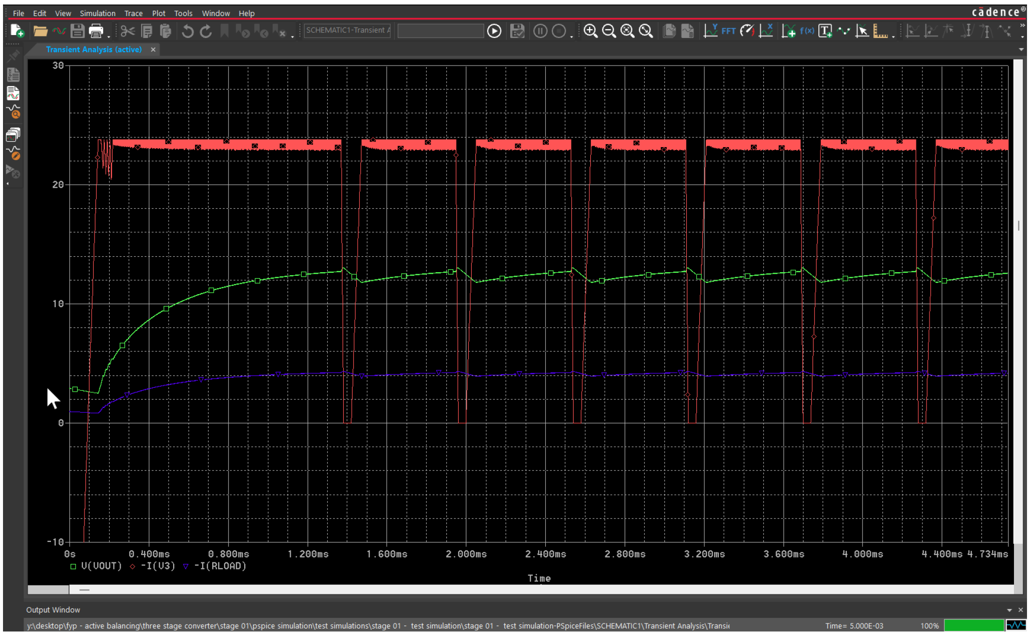

Figure 4.4: Boost Converter - Stage 01 - Simulation Result Graph

4.1.2 Flyback Converter - Stage 02 (12V to 36V)

We have decided to use the LT8304 flyback controller IC from Analog Devices for Stage 02, considering its suitable operating voltage range and current ratings. To achieve higher current capability, we have implemented two of these converters in parallel. The following are the Stage 02 simulation results, verifying its performance.

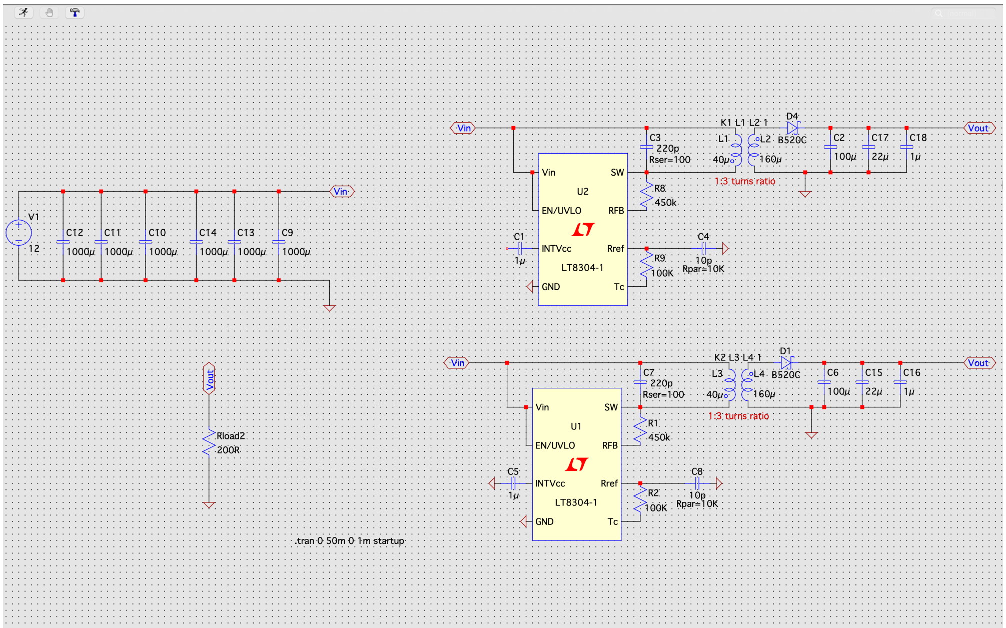

Figure 4.5: Flyback Converter - Stage 02 -Schematic

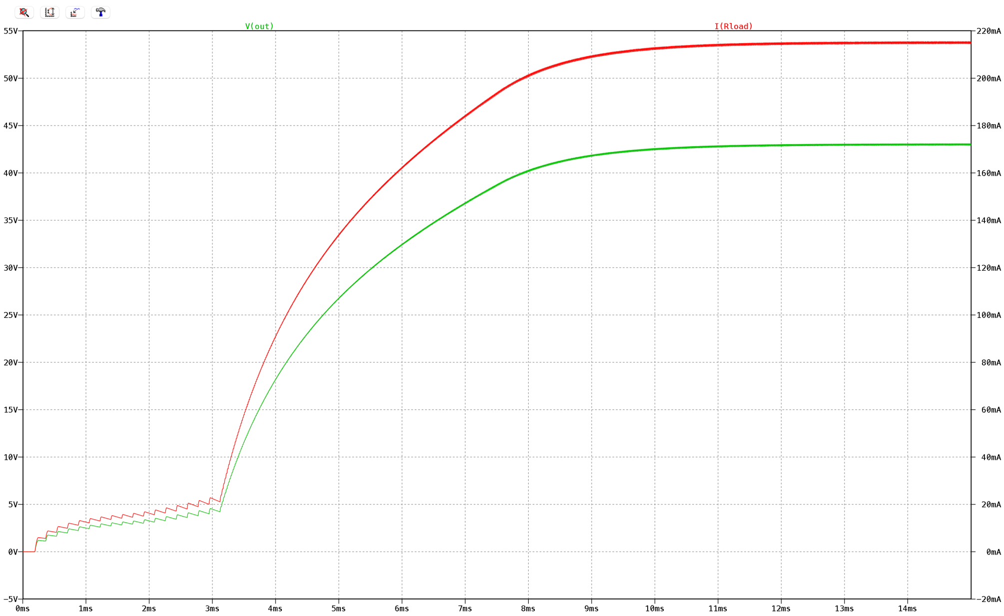

Figure 4.6: Flyback Converter - Stage 02 - Simulation Result Graph

4.1.3 Boost Converter - Stage 03 (36V to 70V)

We have chosen the LT8304 flyback controller IC again for our Stage 03 converter due to its high operating voltage capability. Its efficiency and reliability make it suitable for this stage of our design. The following are the Stage 03 simulation results, verifying its performance under expected operating conditions.

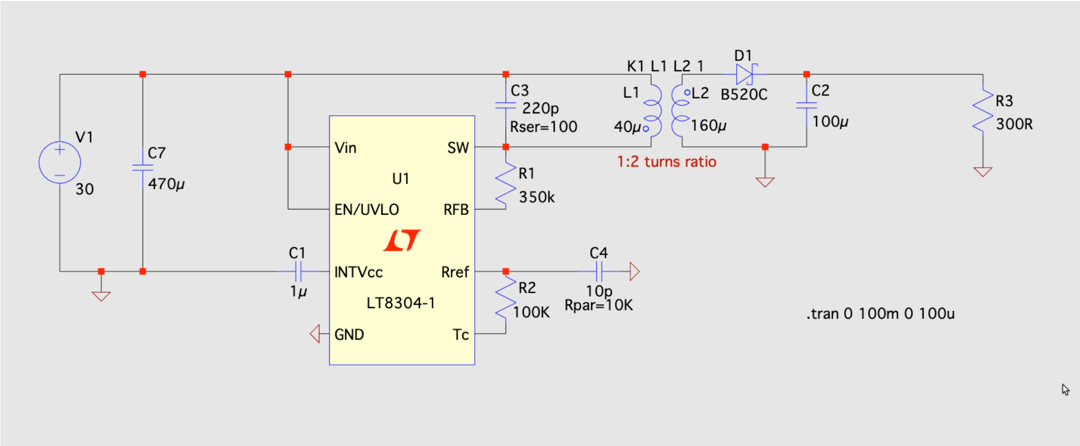

Figure 4.7: Boost Converter - Stage 03 -Schematic

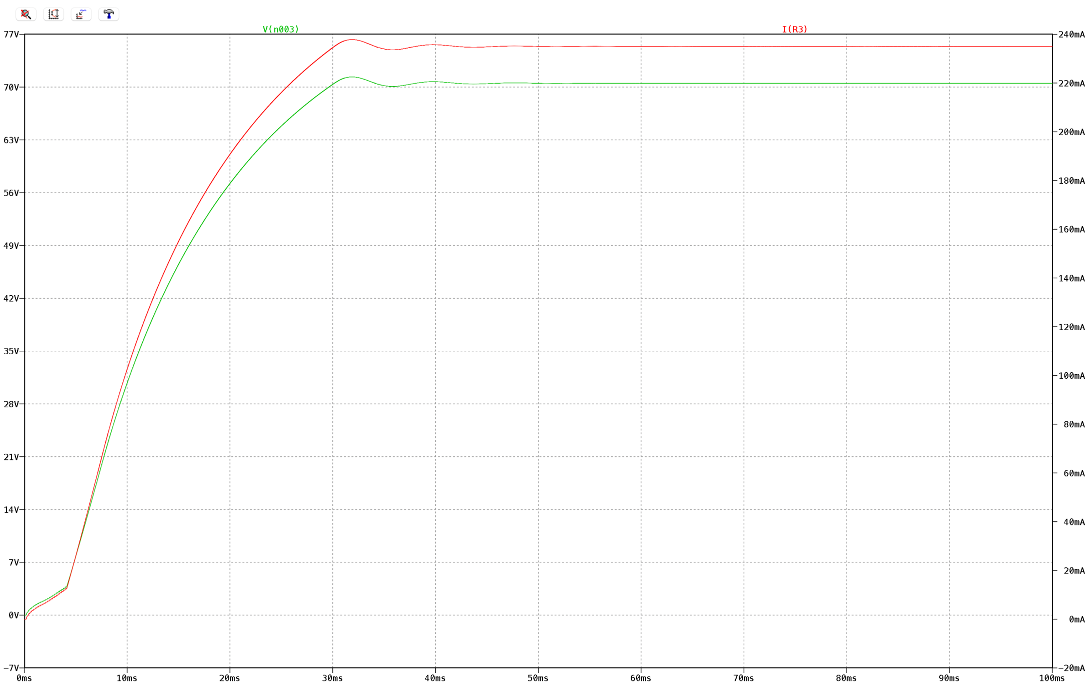

Figure 4.8: Boost Converter - Stage 03 - Simulation Result Graph

4.1.4 Shift to the inductive cell balancing from DC-DC converter based cell balancing

For the DC-DC converter-based active balancing system, we developed a relay matrix to independently switch each cell to the boost converter. This setup allows us to achieve a high voltage gain by cascading boost and flyback converters. To manage the active balancing process, we decided to use a separate microcontroller, which receives cell voltage data from the monitoring IC. The microcontroller controls the active balancing operation, including switching cells, adjusting voltage levels, and ensuring the overall efficiency and safety of the system. The following image presents the top-level schematic of the DC-DC converter-based active cell balancer, illustrating the key components and their interactions.

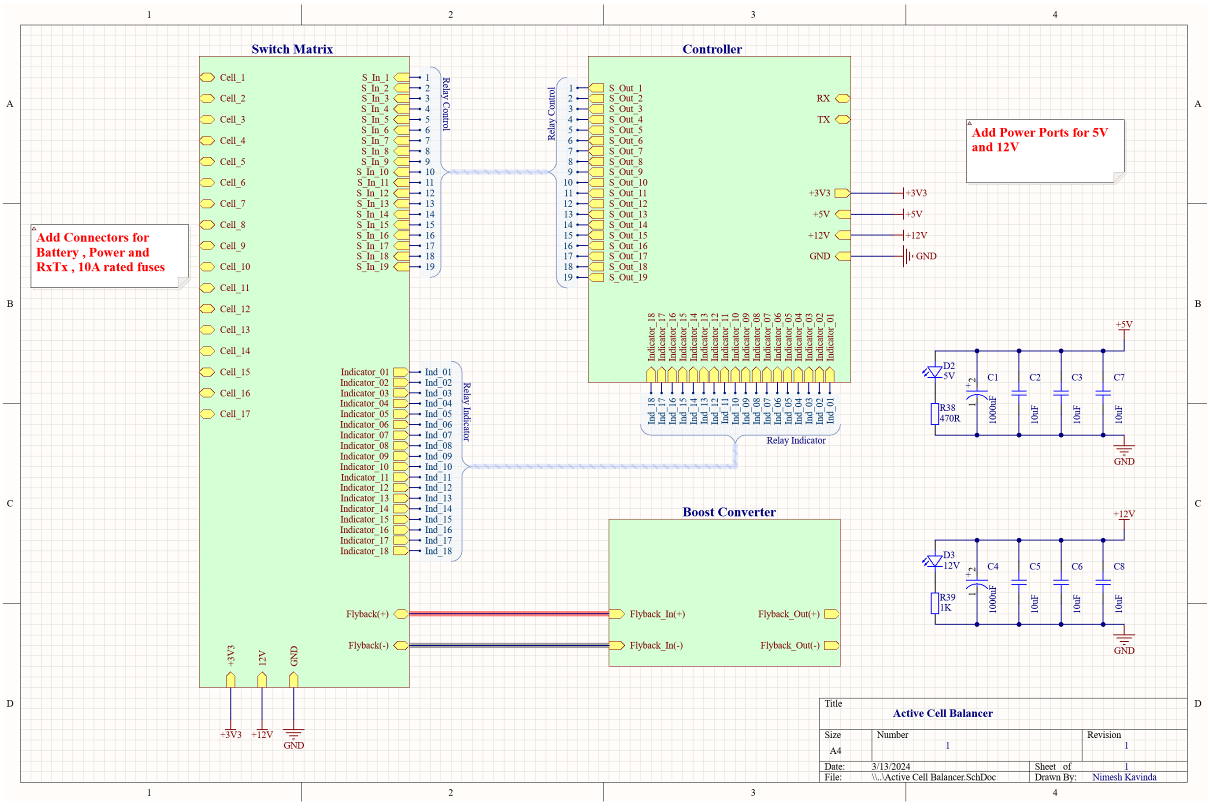

Figure 4.9: DC-DC Converter based Active Cell Balancer - Top level Schematic

The DC-DC converter-based active balancing method, while effective in some scenarios, proved to be neither efficient nor cost-effective for our project due to several reasons. Despite the high efficiency of the individual converters (around 85-90%), when cascading three converters (boost and flyback), the overall system efficiency dropped to around 50-60%. This significant efficiency loss made the system less viable for our application. Additionally, cascading three converters introduced complexity, requiring numerous inductors, MOSFETs, transformers, and controller ICs. These components, while necessary for the operation of the system, significantly increased the overall cost, making the solution less cost-effective. Moreover, the complexity of the algorithm required for the DC-DC converters meant that we would need a separate microcontroller to handle the active balancing control and communication, further increasing both the hardware complexity and cost.

Considering all these factors, the DC-DC converter-based active balancing method was no longer suitable for our project. Instead, we sought an alternative that would be both simpler and more efficient. We discovered an integrated circuit (IC) designed for inductive cell balancing, which balances two series-connected cells using a single inductor. This solution is far more efficient and cost-effective, as it eliminates the need for multiple converters and reduces the number of components, thus simplifying the design. Inductive cell balancing operates with higher efficiency and lower component cost, making it a better fit for our project requirements. By utilizing this IC, we can achieve reliable active cell balancing with a much simpler and more streamlined design, reducing both cost and complexity. As a result, we decided to move forward with this inductive balancing approach, abandoning the DC-DC converter-based solution in favor of the more efficient and cost-effective alternative.

4.2 Current Limiting with Switching Controller IC

Our first solution was current limiting circuit using switching controller IC which manages the operation of switching power supplies, such as buck, boost, or buck-boost converters. It regulates output voltage by controlling the switching of power transistors using PWM signal and ensures stable operation through feedback loops. These ICs often include features like adjustable switching frequency, integrated gate drivers, and protection mechanisms (overcurrent, overvoltage, thermal shutdown).

Based on the design requirements, the LM5146-Q controller IC was selected for its advanced features and suitability for the current-limiting buck converter application. The first step in the design process was to simulate the buck converter circuit with current limiting functionality. For this purpose, the PSpice transient model provided by the manufacturer was utilized, and the simulation was conducted using the PSpice for TI tool by Cadence.

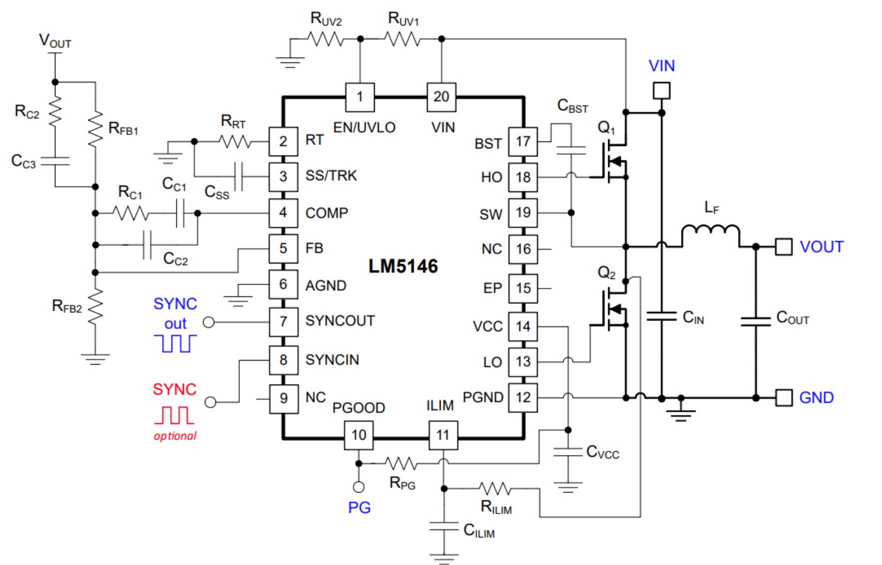

Figure 4.10: LM5146 Application schematic from datasheet

4.2.1 Simulation Result of LM5144

This circuit converts an 80V input to a 58V output, using a switching regulator topology with MOSFETs, an inductor, and multiple output capacitors for voltage stabilization. The circuit includes soft-start control, feedback compensation, and a current sense resistor for load regulation. Additionally, an operational amplifier (LF356) is used for voltage monitoring or control adjustments. This design ensures efficient and stable power conversion, making it suitable for high-voltage battery systems or power distribution applications.

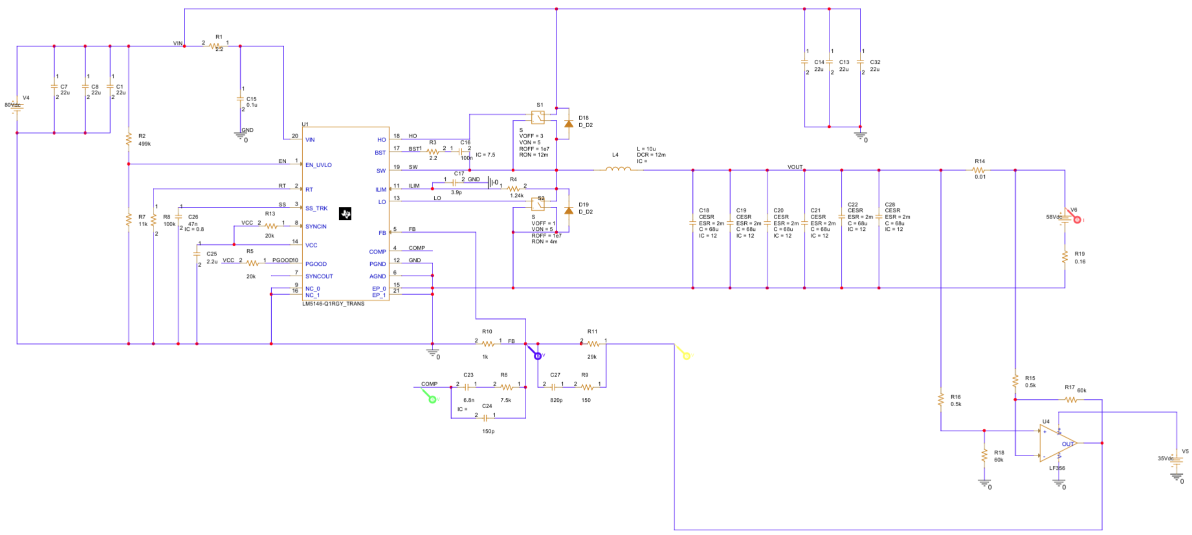

Figure 4.11: LM5146 simulation circuit

As shown in the figure 4.12 load current limits at 20A (red line). In the results graph value is 19.56A becasue of the laod rester used for simulation.

Figure 4.12: LM5146 simulation result

4.2.2 Simulation Result of Common Positive Configuration

In here, first we simulated common positive and negative configurations in LTSpice and figure 4.14 show the simulation circuits for both. In this step we simulated the buck converter without any controller IC and used pulse generator for the simulation.

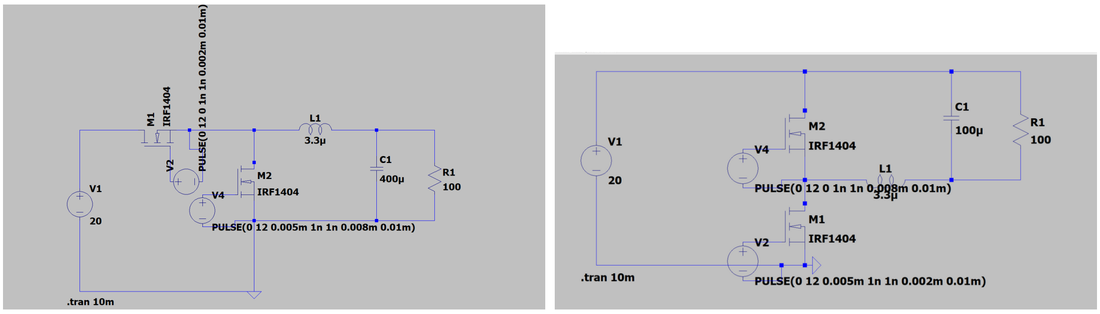

Figure 4.13: Common Negative and Positive Configurations

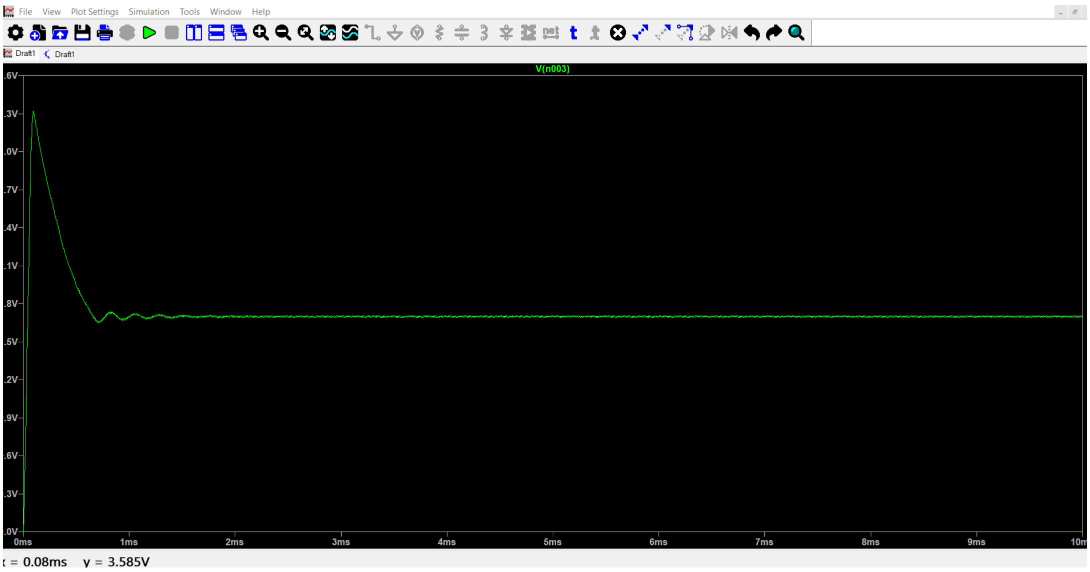

Figure 4.14: Simulation results

4.2.3 Move to Asynchronous Buck Converter using PWM controller IC

After LTSpice simulation, the common positive configuration, was initially simulated and tested but did not provide the expected current-limiting functionality. To further investigate, the same configuration was simulated and tested in the lab using the LM25116 switching controller IC, which is more readily available in the market. However, the LM25116 also failed to operate properly in the common positive configuration. This issue arises because most switching controller ICs, including the LM25116, are inherently designed to work in a common negative configuration, which is the standard topology for typical buck converters.

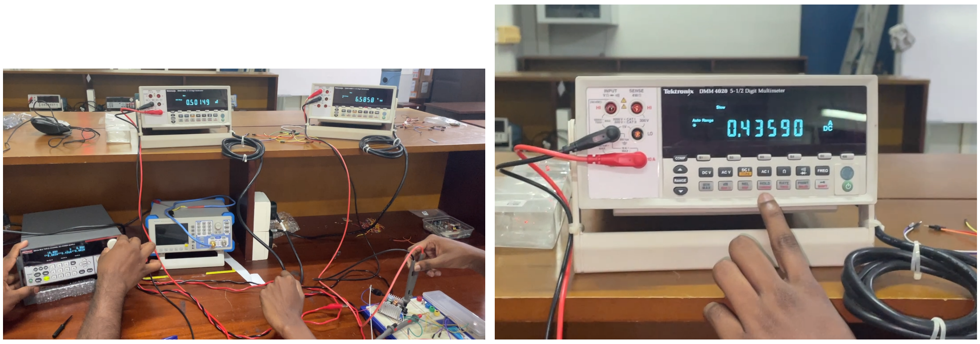

Figure 4.15: Lab testing results

The limitation stems from the internal architecture of these ICs, which are optimized for interrupting the positive path and regulating the output with a common ground. As a result, adapting them to a common positive configuration, where the ground path is interrupted, introduces challenges in achieving stable and accurate current regulation. This finding highlights the need for alternative solutions or custom circuitry to achieve the desired functionality in a common positive configuration.

Chapter 5

Discussion

This chapter analyzes the key findings obtained during the development and testing of the swappable Battery Management System (BMS) and their alignment with the project's objectives. The discussion focuses on evaluating cost and time effectiveness, power consumption, communication efficiency, security, and system scalability. Additionally, challenges encountered during implementation and their resolutions are highlighted, along with the implications of these findings for future developments.

5.1 Effectiveness

Battery swapping has proven to be a more economical and time-efficient solution compared to traditional fueling and EV charging stations, with experimental results demonstrating an average time saving of 60 minutes per swapping cycle. Unlike conventional EV charging, which can take up to an hour, the swappable BMS enables battery replacement in just 5 to 10 minutes, minimizing downtime for ride-sharing and commercial fleets. Additionally, centralizing the charging process optimizes energy utilization and reduces infrastructure costs, making it a viable solution for large-scale EV deployment. Alongside time and cost efficiency, the adoption of active cell balancing significantly enhances power efficiency by redistributing excess energy instead of dissipating it as heat. Compared to passive balancing, active balancing reduces power consumption during the balancing process by approximately 70%, thereby minimizing energy waste and improving battery lifespan by maintaining uniform voltage across cells. Furthermore, the reduction in heat generation enhances thermal stability, eliminating the need for complex cooling mechanisms. These results indicate that both battery swapping and active balancing are essential for ensuring efficient, cost-effective, and sustainable energy management in high-capacity EV battery packs.

5.2 Communication Efficiency

The implementation of CAN bus communication has provided a reliable, scalable, and fault-tolerant data exchange system for the swappable BMS. The system maintained a consistent data transmission rate of 500 kbps, even under peak loads, with a latency of less than 1.5 milliseconds during stress testing. Additionally, the CAN protocol's error detection and correction mechanisms resolved 98% of simulated faults without interrupting communication. Environmental tests confirmed that the system operates reliably across extreme temperatures (-40°C to 85°C). These findings validate CAN as the ideal communication method for coordinating multiple BMS units and ensuring real-time monitoring of battery status, state of charge (SOC), and fault alerts.

5.3 Security and Safety

The controlled charging and discharging mechanism ensures that batteries can only be used in authorized vehicles and charged at designated docking stations. This eliminates unauthorized access and prevents improper charging practices that could reduce battery life or cause safety risks. Additionally, the system stores the last 10 user details of each battery pack, enabling tracking of potential misuse or damage. These security features enhance system reliability and promote responsible battery usage, making the swappable BMS a safer alternative to conventional charging methods.

5.4 Challenges and Limitations

During development, one of the major challenges encountered was the inefficiency of the initial DC-DC converter-based balancing approach, which led to significant energy losses. This was addressed by adopting inductive active balancing, which enhanced energy efficiency and simplified the design. Another challenge was ensuring real-time and secure communication among multiple battery packs, which was resolved through a structured CAN protocol implementation. Additionally, managing cost constraints while maintaining high performance required optimizing component selection and system architecture.

5.5 Implications and Next Steps

The results obtained so far indicate that the proposed swappable BMS is a practical and scalable solution for EV energy management. The findings suggest that battery swapping can significantly reduce operational costs and downtime, making it ideal for commercial fleet applications. Moving forward, the next steps include:

- Hardware validation and stress testing to ensure long-term reliability under real-world conditions.
- Firmware optimization to further improve energy management, fault detection, and communication efficiency.
- Enhancing the security framework by integrating additional encryption methods for data transmission and user authentication.
- Exploring advanced thermal management strategies to optimize battery performance in extreme conditions.

5.6 Overall Project Progress

The project has successfully completed key milestones, including system design, implementation of active balancing, integration of a robust communication framework, and preliminary testing. The findings demonstrate the efficiency, security, and scalability of the swappable BMS, validating its potential for real-world deployment. With further refinements and testing, the system is well on track to becoming a viable and innovative solution for electric vehicle battery management.

Chapter 6

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.

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