

Battery Pack Cell Balancing and Diagnosis Device for Electric Bikes

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We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of BS(EE).

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Dedication

We dedicate this project to our beloved parents, whose endless support, prayers and love have been our strength through every step of this journey. Their sacrifices and encouragement have inspired us to strive for excellence. We also dedicate this work to our teachers and friends who stood by us with motivation, ideas and kindness throughout our academic years.

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Thank you all for your support and encouragement.

Abstract

Electric bikes commonly utilize Lithium Iron Phosphate (LiFePO₄) battery packs composed of multiple cells connected in series to achieve high voltage requirements, where the overall performance, safety, and lifespan depend heavily on the equilibrium of individual cells. A single weak or degraded cell can significantly reduce the overall capacity and reliability of the entire pack, yet professional cell-level diagnostic equipment remains expensive and inaccessible to local workshops and general EV users in Pakistan. This project presents a low-cost, discrete component-based Passive Battery Cell Balancing and Diagnostic Device designed specifically for a battery configuration. Unlike active balancing systems that require complex energy transfer components, this system utilizes a switched shunt resistor technique to dissipate excess energy from higher-voltage cells through power resistors, ensuring all cells reach a uniform state of charge. The device performs comprehensive diagnostics by monitoring real-time voltage and status through an analog control logic powered by NE555 timers and Darlington pair drivers. By enabling precise detection and balancing of cells through manual threshold tuning, the proposed solution prevents unnecessary full-pack replacements, making EV maintenance more economical and sustainable. Portable, user-friendly, and locally manufacturable using readily available electronic components, this device offers an affordable alternative to industrial-grade analyzers and directly supports the growing electric vehicle ecosystem.

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Chapter 1

Introduction

The electrification of the transportation sector has made the battery pack the key element of modern electric vehicles (EVs), particularly for electric bikes that require high-energy-density storage to deliver sufficient range and performance [1]. A battery pack is composed of multiple cells, such as the 10S LiFePO₄ configuration used in this project, where the overall health is determined by the weakest cell [2]. Maintaining balanced cell voltages is a major engineering challenge, as differences in internal resistance and capacity between cells can lead to premature pack failure and potential safety risks [3], [4]. In this work, a cost-effective passive balancing and diagnostic system has been developed using NE555 timer ICs, Darlington transistor drivers, and resistor-based energy dissipation to improve voltage uniformity and monitor cell temperature [5], [6]. By providing real-time monitoring and safe, controlled balancing, the system offers a practical alternative to expensive industrial diagnostic tools, with the aim of improving the sustainability and reliability of electric bikes in the local transport industry [7], [8].

1.1 Project Background

The global transition toward green transportation has led to increased adoption of electric vehicles, particularly electric bikes, which are widely used in urban areas such as Pakistan [1]. These vehicles rely on high-energy battery packs instead of combustion engines, often connected in series to achieve the

required voltage. The performance of these packs depends heavily on cell stability [9]. Managing large series strings, such as 10S LiFePO₄ packs, presents significant challenges in terms of cell aging and safe battery management [10].

In battery management, balance is a critical factor. Over time, differences in cell internal resistance and capacity create voltage imbalance during charging and discharging [3], [11]. This project addresses the need to move from simply using batteries to actively managing them. Within the context of local electric bike consumers, it explores the potential of simple integrated circuits and discrete analog components to monitor and maintain battery packs without requiring large-scale industrial equipment [12].

The motivation for this work is also economic. State-of-the-art monitoring and balancing systems are imported and costly, making them inaccessible for local workshops. This often results in the entire battery pack being discarded due to a single faulty cell [2]. This project addresses that gap by developing a locally manufacturable, repairable tool focused on prolonging the life of the energy storage system.

The project emphasizes passive balancing techniques. Unlike complex active systems that transfer energy between cells, passive balancing dissipates excess energy from higher-voltage cells through resistors, providing a simpler, cost-effective, and reliable approach for maintaining voltage uniformity within the

battery pack [13], [5]. This controlled dissipation improves the overall reliability and usable capacity of electric bike battery packs [14].

Finally, the use of a discrete analog control architecture with NE555 timer ICs and Darlington pair driver stages provides a strong and accessible foundation for this work. This design enables effective voltage monitoring and balancing control without requiring expensive or specialized integrated circuits. By leveraging widely available components, the project achieves a low-cost, portable, and transparent power management solution that is easy to maintain, troubleshoot, and manufacture locally.

1.2 Problem Description

The primary focus of the project is to overcome the “weakest link” problem in series battery strings. In a 10S battery pack, the overall string capacity is limited by the cell with the lowest capacity [2]. When this weakest cell reaches its discharge limit, the entire pack shuts down to protect all cells, even though the remaining cells may still contain significant energy. This reduces the apparent range and efficiency for the EV user.

A second key challenge is the lack of diagnostic information available to technicians and consumers. Standard chargers and local BMS units do not provide insights into cell health, making it difficult to identify which cell is

underperforming [11], [15]. As a result, users are often forced to replace the entire pack, which is costly and wasteful.

Most local battery balancing technologies, including the system developed in this project, use passive balancing [3]. These systems dissipate excess energy from higher-voltage cells using resistors to maintain balanced cell voltages. In a hot country like Pakistan, heat from resistors can accelerate cell degradation and raise safety concerns [4]. Therefore, a safe and efficient balancing strategy is required.

Additionally, thermal runaway is a potential risk in high-power applications [16]. Without integrated temperature monitoring via thermistors and over-current protection, cell degradation can remain undetected until it becomes critical. Current designs rarely provide multi-level safety features at an affordable price, potentially exposing EV users to pack failure [17].

Finally, the widespread use of imported, black-box BMS units limits the ability of local engineers to troubleshoot or repair packs. When a BMS fails or a pack becomes unbalanced, there are few strategies to recondition the battery. This project aims to provide a specialized, portable tool for diagnostics, enabling controlled charge-discharge cycles and practical assessment of the State of Health (SOH) of individual cells in the field [8], [18].

1.3 Project Objectives

The primary objective of this project is to develop a passive balancing system that uses resistive energy dissipation to maintain uniform voltage levels among cells in a 10S battery pack, ensuring reliable and cost-effective battery management [5], [14]. The system is designed to provide real-time monitoring of key battery parameters, such as individual cell voltages and temperatures, through a discrete analog sensing network integrated with NE555-based comparator logic and visual feedback indicators for the technician [12]. The project also aims to implement basic diagnostic capabilities to detect weak or underperforming cells by observing voltage deviations and controlled discharge behavior, helping technicians make informed maintenance decisions [18], [19]. Another goal is to build a portable, low-cost hardware platform that can be easily deployed by local electric vehicle (EV) workshops to perform battery triage and servicing on-site. Finally, the system is designed to improve battery safety through the inclusion of hardware-based protection against over-voltage, under-voltage, and excessive temperatures, ensuring safe operation in workshop environments [4], [16].

1.4 Project Scope

This project is focused on 10S lithium-based battery packs, typically operating between 32V and 37V, as used in electric bicycles and scooters. The passive balancing design is optimized for the power level and number of cells in light electric vehicles, ensuring safe, reliable, and cost-effective operation for a 10S battery pack [3]. The hardware design is centered around NE555 timer ICs for passive balancing and discrete analog measurement circuits for voltage and temperature accuracy [6], [12]. From a diagnostic perspective, the system can measure cell voltages and temperatures and observe internal resistance and capacity (Ah) using controlled testing; however, it is not intended to function as a high-speed motor controller [11]. The primary role of the device is as a diagnostic and maintenance tool, although the design could be adapted for on-board applications in the future.

The scope of the project includes the design and layout of the Vero Circuit Board (VCB), selection of appropriate power resistors for balancing, and the creation of the logic circuits to initiate balancing based on cell voltage differences [20], [21]. Additionally, the project includes development of a User Manual (Appendix A) to guide local technicians in safely performing diagnostics and balancing procedures. Geographically and economically, the system is designed for the Pakistani market, prioritizing locally available components and manufacturable designs, offering a practical alternative to costly industrial analyzers while balancing accuracy with workshop-level durability. Finally, the project does not address chemical recycling of cells. Its focus is on prolonging battery life through

electronic intervention, ensuring that each cell in a 10S string operates optimally, thereby maximizing the return on investment for EV owners and reducing unnecessary battery disposal [22].

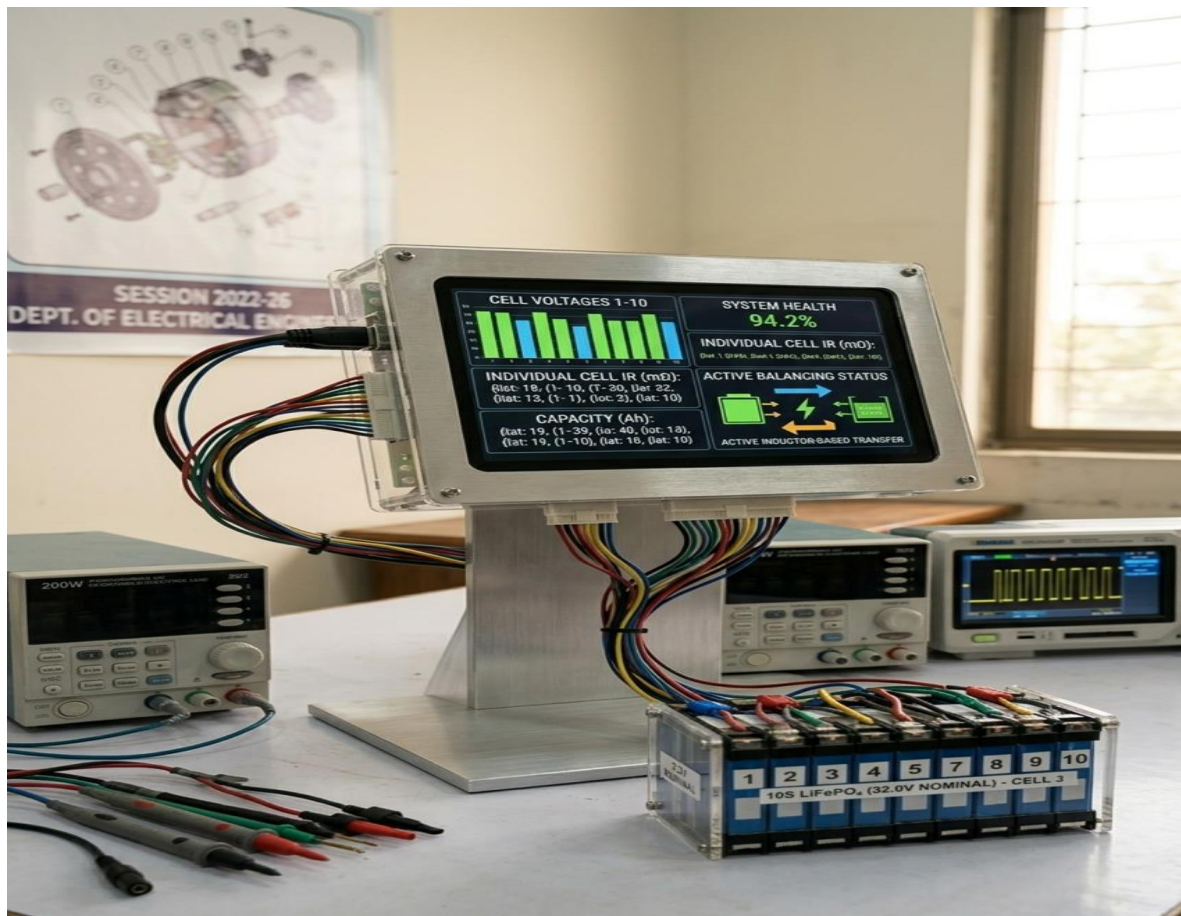


Fig : 1.1

Chapter 2

Literature Review

This chapter presents a structured review of previous work and technological developments relevant to this project. It provides technical background by examining the evolution of Battery Management Systems (BMS), with particular emphasis on passive cell balancing techniques and their role in ensuring safe and reliable operation of series-connected battery packs [3], [23]. Additionally, this chapter explores prior research in the areas of power electronics and energy storage to identify the need for a low-cost, portable diagnostic tool for the emerging electric vehicle industry in Pakistan [20], [21]. A theoretical basis for resistive passive balancing and IC-based voltage sensing is established, laying the foundation for the design of this project's system [5], [12].

2.1 Understanding the Battery Management System (BMS)

The recent growth of electric mobility has made the BMS a critical electronic component for the safe and efficient operation of lithium-based energy storage systems [9], [24]. A BMS serves as the central controller that monitors the battery pack and ensures it remains within the Safe Operating Area (SOA). In high-voltage packs, such as the 10S LiFePO₄ packs used in electric bikes, the BMS must manage multiple technical tasks, including voltage measurement, thermal monitoring, fault protection, and cell balancing [2]. Without a BMS,

inconsistencies between individual cells can lead to pack failure, resulting in both economic loss and potential safety hazards.

Research indicates that during charge and discharge cycles, Li-ion cells exhibit differing chemical behaviors due to manufacturing variations, uneven operating temperatures, and chemical degradation over time [10]. Literature highlights that the weakest cell in a series string often dictates the overall performance and capacity of a 10S pack [8]. Consequently, modern BMS design emphasizes cell-level monitoring to ensure reliable operation and effective maintenance [18].

The development of discrete ICs, such as the NE555 timer, has further advanced BMS design by enabling accurate measurement of cell voltages along with basic current and temperature monitoring [12]. Precision in these measurements is essential; even a 10 mV error in voltage sensing can result in inaccurate assessment of the State of Charge (SOC) [25]. Using dedicated ICs and discrete circuits ensures that diagnostic information can be relied upon for battery triage and maintenance decisions in local workshops.

Economically, the EV market in Pakistan faces constraints due to the high cost and non-repairable nature of imported BMS units. This often encourages technicians to replace entire battery packs instead of repairing individual cells [22]. Literature on sustainable engineering highlights the importance of locally serviceable, hardware-focused systems. This project contributes to that

direction by offering a simple, open architecture that enables local repair, maintenance, and improved longevity of high-cost battery packs.

A further trend in modern BMS design is the growing emphasis on diagnostic information, such as cell voltage imbalances, thermal monitoring, and practical assessment of weak cells [15], [11]. By integrating accessible ICs with discrete analog circuits, this project demonstrates that laboratory-grade measurement accuracy can be achieved in a portable, cost-effective package suitable for small EV workshops [26], [27].

2.2 Cell Balancing: Passive Approaches

Cell balancing is a critical technique used to ensure that all cells in a series string operate within safe voltage limits, avoiding overcharge or over-discharge [3]. In commercial and low-cost EV products, passive balancing is the most widely implemented technique. Passive balancing dissipates the excess energy of high-voltage cells as heat through resistors, maintaining voltage uniformity across the pack [3], [13]. Although the method is simple and cost-effective, it has well-documented drawbacks, including energy loss and additional thermal load within the battery pack.

Heat generation in passive balancing can accelerate cell aging, especially in hot climates such as Pakistan, where the additional temperature stress can reduce

the pack's lifespan [4]. Despite this, passive balancing remains a practical solution for low-cost, workshop-deployable systems, as it avoids the complexity, cost, and calibration requirements of more advanced active balancing circuits.

Modern literature emphasizes that balancing strategies should be selectively triggered rather than continuously applied [27], [30]. Using IC-based comparator logic, such as NE555 timers, enables the balancing circuit to activate only when cell voltage differences exceed a predefined threshold. This reduces unnecessary energy dissipation, minimizes heating of the resistors, and prolongs component life [5], [12]. The passive approach also allows multiple cells to be balanced in parallel, providing practical voltage uniformity across a 10S string without adding significant cost or complexity.

While active balancing techniques can theoretically improve energy efficiency by transferring charge between cells, they require inductors, MOSFET drivers, or capacitors, which are expensive and more difficult to implement in a small, portable tool. In contrast, passive balancing with NE555-controlled MOSFET-resistor paths provides a robust, reliable, and low-cost alternative, particularly for emerging markets [3], [5], [13].

Finally, passive balancing can be integrated with thermistor-based temperature monitoring, ensuring safe operation while maintaining simplicity [4]. By monitoring cell temperatures and controlling energy dissipation only when needed, passive balancing achieves a practical balance between safety, cost, and

usability, making it the preferred solution for workshop-grade diagnostic systems aimed at 10S LiFePO₄ battery packs [23].

2.3 Passive Balancing Systems: Goals and Insight

Passive balancing, also known as resistive balancing, is a widely used approach in battery management where excess energy from higher-voltage cells is safely dissipated as heat through resistors rather than being transferred to other cells. The primary goal of this project's architecture is to use simple switching control, such as NE555-based comparator logic and MOSFET drivers, to discharge cells with higher voltage until all cells reach a similar voltage level. Literature consistently highlights passive balancing as a preferred solution in low-cost and workshop-deployable systems due to its simplicity, affordability, and ease of implementation compared to more complex active balancing methods [3], [5], [13].

The balancing process is typically executed through a single discharge stage. When a cell exceeds the defined reference voltage, the control circuit activates a MOSFET switch, allowing current to flow through a power resistor (e.g., 5.6 Ω in this design). The excess energy is converted into heat and removed from the cell, enabling it to approach the voltage of weaker cells. Although energy is not transferred between cells, this method effectively reduces voltage imbalances

and enhances overall pack stability, which is crucial for 10S LiFePO₄ battery packs used in electric bicycles and scooters [14].

Another key insight from the literature is the modularity and scalability of passive balancing systems. Each cell in a series pack has its own dedicated balancing path, allowing independent operation of multiple channels. This modularity ensures that even if one channel fails, the remaining cells continue to operate safely, maintaining the basic reliability of the battery system. Such a design also makes troubleshooting and local repair easier, which is particularly important in regions with limited access to imported diagnostic tools [3], [5].

Additionally, passive balancing systems significantly reduce control complexity compared to active methods. They require only simple voltage threshold detection and switching logic rather than complex energy transfer circuits or high-frequency inductor management. Modern implementations often use discrete ICs, comparators, and NE555 timer architectures, which improves system reliability, reduces electromagnetic interference (EMI), and minimizes maintenance challenges [12], [20].

In summary, the main goal of passive balancing is to maintain uniform voltage across all cells by safely removing excess energy as heat. By continuously or periodically discharging overcharged cells, the system prevents voltage imbalance, overcharging, and potential safety hazards, thereby improving both battery safety and lifespan. Literature supports this approach as a practical, low-

cost, and reliable method for maintaining stability in a 10S LiFePO₄ battery system, particularly in workshop environments where repairability and local maintenance are priorities [23].

2.4 Security and Safety Issues

Safety remains a central concern in battery management due to the potential for thermal runaway in lithium-based chemistries [16]. Over-voltage can trigger electrolyte decomposition, while under-voltage may cause copper dissolution and internal short circuits, making them critical issues for 10S battery packs [17]. Literature emphasizes that even basic diagnostic and balancing tools must include voltage monitoring to detect abnormal operating conditions and facilitate preventive maintenance, reducing the risk of catastrophic failure.

Thermal management is especially important for LiFePO₄ cells, which, although safer than other lithium chemistries, still require monitoring to prevent overheating and premature ageing [4]. In this project, 10 k Ω NTC thermistors are used to monitor temperature at multiple points throughout the battery pack. Research shows that multi-point thermal monitoring can detect localized heating or cell stress, which is indicative of imbalance or degradation, allowing technicians to intervene before serious failure occurs [34].

Accurate measurement and reliability of sensing are also essential for safety. Inconsistent or noisy voltage and current readings can lead to incorrect balancing decisions or misinterpretation of cell health [25]. The circuit design in this project emphasizes robust analog sensing, minimal EMI, and basic filtering techniques, ensuring that the technician receives trustworthy diagnostic information that reflects the actual state of the battery pack.

Over-current events are another common source of failure during battery testing and balancing [20]. To address this, the system incorporates a 3 mΩ shunt resistor for current monitoring. This hardware-based approach allows technicians to observe the current flow during balancing and ensures that the battery is not exposed to excessive currents, which could damage cells or pose a safety risk. By maintaining current within safe limits, the system enhances operational safety and protects the longevity of the battery cells.

Finally, battery safety includes preventing operation under unsafe voltage or temperature conditions. A practical diagnostic and balancing system must incorporate fail-safe mechanisms that prevent activation when the battery pack is outside the safe operating envelope. By applying these principles, this project implements a hardware-focused safety architecture that protects the battery pack, the user, and the balancing system itself, in line with best practices highlighted in the literature [17].

2.5 System Architecture

The system architecture of this project is based on a modular hardware platform designed for passive balancing and battery diagnostics, where sensing, control, and balancing functions are implemented using discrete analog circuitry and widely available IC components, such as the NE555 timer and Darlington transistor pairs. Conceptually, the system can be divided into three functional layers: the Sensing Layer, the Control Layer, and the Balancing/Power Dissipation Layer [20], [21]. This layered structure ensures that high-precision voltage measurements remain stable, even while energy is being dissipated from higher-voltage cells in a 10S LiFePO₄ battery configuration, reducing interference between measurement and balancing operations.

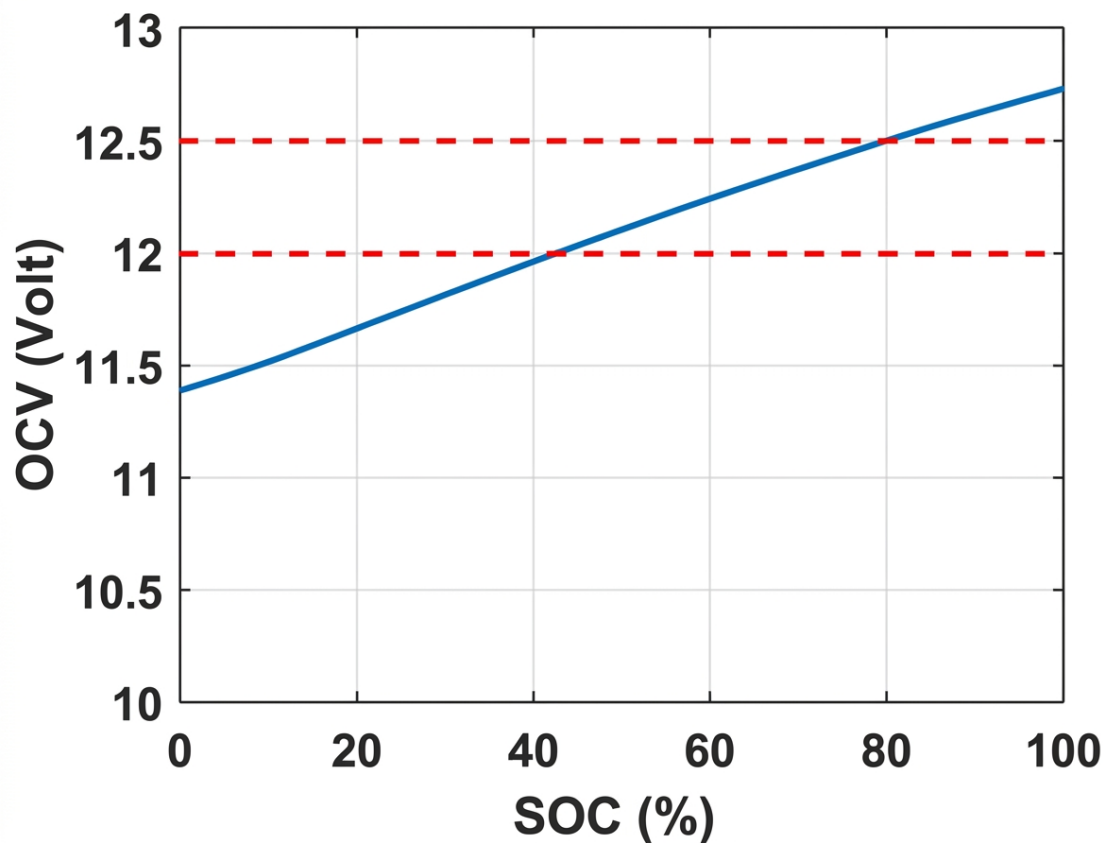
The Sensing Layer functions as the “eyes” of the system. It includes voltage sensing lines for each individual cell, as well as temperature sensing elements for basic thermal monitoring. In a 10S series system, high-side voltage sensing is a key challenge, as each cell is referenced at a different potential relative to ground. Literature indicates that this can be effectively managed using carefully designed resistor-divider networks, buffered comparator circuits, and analog isolation techniques, ensuring millivolt-level measurement accuracy even in workshop conditions [12]. This layer provides the essential data for safe and controlled balancing.

The Balancing/Power Dissipation Layer is the main functional component responsible for passive cell balancing. Each cell has its own dedicated balancing channel, allowing excess energy from higher-voltage cells to be safely dissipated as heat through resistors, activated by NE555-controlled MOSFET switches. This modular approach improves reliability, as individual channels can be tested, maintained, or replaced independently without affecting the remaining cells [33]. Compared to active balancing methods, this passive approach reduces design complexity, minimizes additional heat sources, and ensures thermal stability, which is especially important in the high-temperature environments common in Pakistan.

The Control Layer contains the decision-making logic implemented in discrete analog circuitry. NE555 timers serve as threshold detectors, while Darlington pairs drive the MOSFETs to initiate passive discharge when a cell exceeds the set voltage limit. This layer ensures that balancing occurs only under the correct conditions and eliminates the need for complex digital computation for each cell [11], [19]. By handling the logic in hardware, the system maintains robustness, simplicity, and cost-effectiveness, making it suitable for local workshops with limited access to advanced diagnostic tools.

Finally, the user interface provides basic visual feedback, such as LED indicators for each cell and system status, allowing technicians to quickly assess battery condition during maintenance. Literature highlights that displaying battery

information in a clear, cell-level format improves usability and facilitates informed decision-making in the workshop. Overall, this layered and modular architecture ensures that the system operates as a practical, low-cost, and maintainable battery diagnostic and passive balancing tool, while avoiding the complexity, cost, and maintenance challenges associated with full-scale digital BMS designs



2.6 Development Environment and Languages

A cross-disciplinary development environment was essential to successfully implement the hardware design for this project. The development process incorporated Electronic Design Automation (EDA) tools for schematic capture, circuit simulation, and PCB layout. Literature on power electronics emphasizes that layout decisions directly affect system performance, particularly in circuits handling high currents, voltage sensing, and precise control of multiple cell channels [21].

For hardware development, schematic capture and PCB design tools were used to manage both the power paths for balancing resistors and the sensing lines for voltage and temperature measurements. A critical challenge highlighted in research is PCB trace parasitics, where long or narrow traces can introduce resistance, inductance, or noise, which can compromise voltage measurement accuracy [20]. To address this, Design Rule Checks (DRC) were applied to ensure that power traces could safely handle expected currents while maintaining isolation and routing of sensitive analog signals. This careful design minimizes interference and ensures stable, high-precision sensing across the 10S battery pack.

For system logic, the project uses discrete analog control circuits with NE555 timers for threshold detection and driver stages for MOSFET switching. This approach emphasizes simplicity, reliability, and ease of troubleshooting, avoiding the complexity and cost of embedded microcontroller-based active

balancing systems. Literature on hybrid BMS design supports the use of simple threshold-based logic as an effective method to maintain cell balance and protect battery packs, provided the control circuits are carefully designed and calibrated [26].

Simulation played a key role during the early design phase to verify circuit performance before hardware implementation. Basic circuit simulation tools were used to test voltage sensing, threshold response, and passive balancing behavior under different cell conditions [31]. Published studies indicate that simulation-driven design reduces the likelihood of component stress or failure and improves overall system reliability, which is especially important for battery systems where errors can damage cells or reduce longevity [35].

Finally, visual monitoring and instrumentation were incorporated to assist in testing and calibration. Cell voltages and balancing operation were verified using simple display modules and digital multimeters. Literature highlights that providing direct and intuitive feedback of battery status improves usability in workshop environments and allows technicians to calibrate and adjust the system efficiently [36]. This combination of EDA design, simulation, hardware testing, and simple analog control ensures a practical, low-cost, and reliable solution for 10S LiFePO₄ battery maintenance in local EV workshops.

2.7 Requirement Specifications

Requirement specifications define the key features and functional goals of the system, ensuring that it addresses the needs of local EV technicians while meeting industry standards. Following the framework suggested by Bahria University, the specification includes an analysis of the current system limitations and the proposed solution.

2.7.1 Existing System

Current EV maintenance practices in local workshops are limited by basic diagnostic tools. Technicians typically measure cell voltages using simple digital multimeters, which is time-consuming and provides only static readings, failing to capture behavior under load. In most locally available electric bikes, BMS units are primarily passive and non-diagnostic [13]. As a result, cell-level issues often go undetected until significant degradation occurs, leading to premature replacement of entire battery packs, increasing costs for consumers [2].

These limitations also impact safety and reliability. Many battery packs lack thermal monitoring and fast overcurrent protection, which increases the risk of overheating, accelerated degradation, or failure under stressed conditions [4].

Passive balancing in current systems is relatively slow and may not adequately

address highly unbalanced cells, contributing to gradual performance loss over time [3]. Literature emphasizes that the lack of transparent diagnostic feedback is a significant barrier to EV adoption in developing regions [1].

Another limitation is the absence of standardized methods to measure usable battery capacity. Workshop technicians often rely on open-circuit voltage measurements, which are poor indicators of energy storage or real-world range [37]. Without controlled discharge tests or monitoring, it is difficult to predict actual pack performance, reducing trust between technicians and EV owners.

Finally, current systems are often non-repairable at the cell level. When individual cells degrade, technicians have no way to identify or replace only the faulty cells. This limits opportunities for cell reuse or recycling and undermines sustainable maintenance practices [22]. These gaps highlight the need for a locally manufacturable, hardware-based solution that offers passive balancing and diagnostic support.

2.7.2 New Proposed Solution

The proposed system is a low-cost, passive balancing and monitoring tool for 10S LiFePO₄ battery packs, designed specifically for workshop environments. It provides cell-level visibility, allowing technicians to observe individual voltages and safely dissipate excess energy from overcharged cells through resistive balancing circuits [6], [12]. This design maintains voltage uniformity across the pack without requiring the complexity of active energy transfer systems.

The system is designed to be cost-effective and repairable, providing a practical alternative to expensive industrial diagnostic equipment. It includes basic safety features, such as over-voltage, under-voltage, and temperature monitoring using simple thermistors and resistor-based hardware circuits [4], [17]. These features improve operational safety during maintenance and balancing operations.

Clear cell-level voltage display allows technicians to quickly identify imbalances. By presenting straightforward, easy-to-interpret measurements, the system avoids the complexity of high-end diagnostic tools while still providing reliable guidance for maintenance decisions [26].

Finally, the system enables improved battery maintenance practices, such as identifying weak or imbalanced cells and supporting selective cell replacement. This approach extends battery life, reduces unnecessary pack replacements, and enhances sustainability by enabling partial pack repair and recycling [38]. By combining simplicity, affordability, and reliability, the proposed system

addresses the critical limitations of current local EV workshop tools while providing practical and safe battery monitoring and passive balancing for 10S LiFePO₄ packs

2.8 System Testing and Evaluation

The final part of the literature review addresses how the system's functionality, reliability, and practical applicability can be demonstrated. For a 10S LiFePO₄ battery pack, the proposed passive NE555-based balancing and diagnostic system must be evaluated using both electrical tests and scenario-based simulations [31]. These evaluations ensure that the device not only functions correctly under ideal conditions but also performs reliably under realistic workshop environments.

2.8.1 System Testing

System testing begins with unit-level verification of each functional block. Voltage sensing is tested by applying known reference voltages to each input

and checking the corresponding outputs to confirm accurate detection of cell voltages. Following this, the passive balancing stages are tested by introducing controlled voltage imbalances. The system is observed to ensure that each resistive channel dissipates excess energy correctly from higher-voltage cells, as designed [5]. Literature highlights that such stress testing is essential to confirm that the system can operate reliably under continuous workshop use without overheating, drift, or component failure [21].

Testing also includes protection logic verification, where fault conditions such as over-voltage, under-voltage, or over-temperature are simulated. The system must respond appropriately by disconnecting or limiting power to affected cells. This type of negative testing is a widely recognized methodology in battery management research for validating the safety-critical functionality of diagnostic and balancing systems [17].

The stability and reliability of voltage sensing are also evaluated under electrically noisy conditions, simulating the real-world environment of a workshop. The tests ensure that the analog measurement circuitry, including the NE555 comparator and buffered voltage dividers, remains stable and does not introduce errors. This ensures that balancing decisions are based on accurate and consistent measurements, avoiding unnecessary energy dissipation or missed imbalances [12].

Finally, durability testing evaluates the long-term reliability of the device. Repeated operation over multiple balancing and measurement cycles simulates heavy workshop use. The thermal performance of the resistors and MOSFETs, as well as the robustness of PCB trace layouts, are verified to ensure the system meets the usability, safety, and reliability requirements for practical deployment [2].

2.8.2 Evaluation Metrics and Diagnostic Logic

Evaluation focuses on the system's ability to correctly detect voltage imbalances and activate the corresponding passive balancing channels. Cells exceeding the preset threshold voltage must reliably trigger the associated resistor paths, validating the NE555-based threshold logic and driver circuitry [11], [19].

Another metric is balancing effectiveness, which measures how quickly the system reduces voltage differences between cells. For example, the reduction of an initial 200 mV imbalance to a lower steady-state voltage demonstrates the capability of the passive system to restore equilibrium in a 10S pack. This evaluation highlights the performance of resistive balancing compared to uncorrected voltage differences [23].

The system is also evaluated for ease of use in workshop conditions. Technicians should be able to interpret voltage readings and system status quickly to make

informed maintenance decisions. A successful evaluation indicates that users with basic electrical knowledge can operate the device effectively, without requiring specialized training or experience.

Finally, a cost-benefit analysis evaluates the economic impact. The cost of the passive diagnostic tool is compared to the expense of replacing entire battery packs. If the system enables identification of faulty or weak cells and prevents unnecessary pack replacement, it demonstrates clear financial and operational value for local EV workshops.

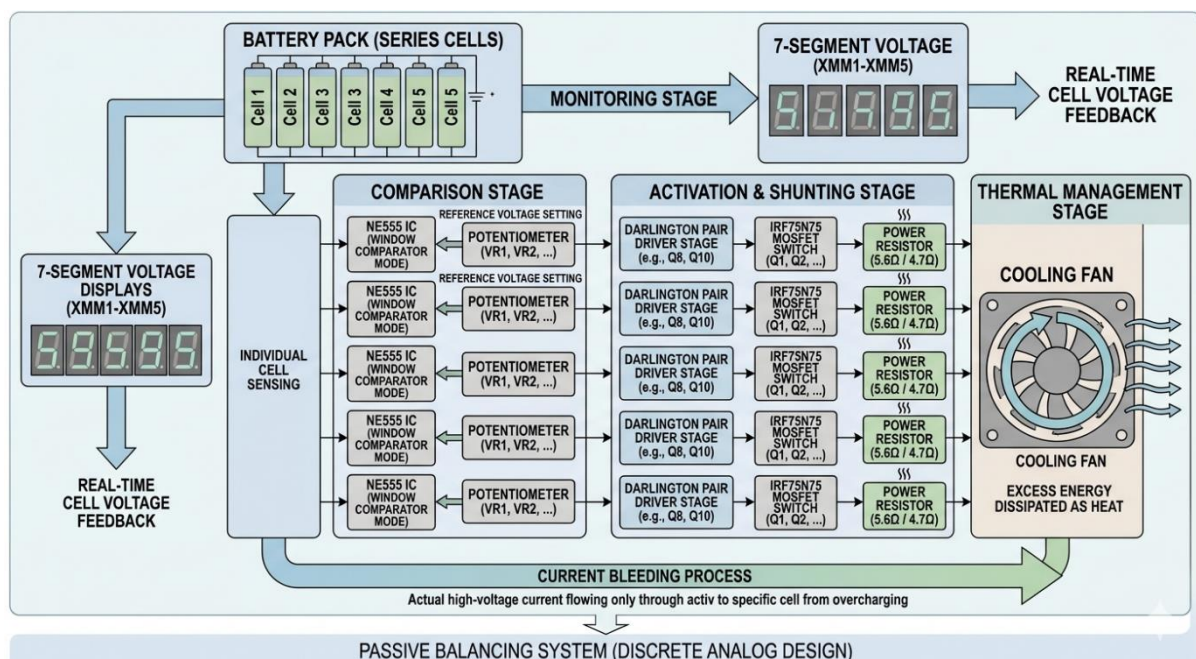
2.8.3 Goals of Evaluation

The primary goals of evaluation are accuracy, reliability, and practical usability. Success is defined by the system's ability to reduce voltage imbalances within acceptable limits using passive balancing, ensuring uniform cell voltages without generating excessive heat or over-stressing components.

Another goal is robust detection of unsafe conditions, such as over-voltage or over-temperature events. Using NE555-based threshold sensing and thermal monitoring, the system must consistently respond to unsafe conditions to prevent further cell stress or damage to the battery pack [4], [17].

Evaluation also confirms that the system is suitable for local manufacturing and maintenance, relying on widely available components and a modular design that can be repaired or replicated in workshop settings. This ensures sustainability and accessibility for the target market.

Finally, the evaluation includes a critical assessment of system limitations, such as the maximum supported cell count, resistor wattage, thermal constraints, and overall balancing current capacity. Identifying these limitations provides clear guidance for future improvements and establishes the practical operational boundaries of the passive balancing system [2], [23]. By documenting these aspects, the project not only demonstrates technical viability but also sets a foundation for future enhancements in low-cost EV battery maintenance tools.



Chapter 3

Requirement Specifications

3. System Requirements and Proposed Design

This chapter defines the functional and non-functional requirements for the proposed passive balancing and monitoring system. It begins by analyzing existing practices in local electric bike workshops and highlights their limitations. Based on this, clear requirements are established for the hardware-based system, ensuring that the final design addresses the safety, reliability, and maintenance challenges associated with 10S LiFePO₄ battery packs [1], [2].

3.1 Existing System

Current battery management practices for 10S lithium battery packs in local electric bicycle repair workshops are primarily manual and non-transparent [2]. Technicians measure individual cell voltages using digital multimeters, which requires partial disassembly of the pack and manual probing of each cell. This approach is time-consuming and only provides a static snapshot of cell conditions, failing to capture real-time performance under load. Consequently, many battery issues remain undetected until severe degradation occurs, often leading to premature replacement of the entire pack and increased costs.

Additionally, most commercially available Battery Management Systems (BMS) for these e-bikes employ passive balancing techniques [3], [13]. These systems dissipate excess energy from overcharged cells through resistors when the cell voltage exceeds a set threshold. While simple and cost-effective, this method generates heat, which can accelerate chemical degradation in high-temperature environments such as those found in Pakistan [4]. Moreover, basic COTS BMS designs generally lack communication interfaces, preventing technicians or users from monitoring individual cell performance or imbalance conditions in real time.

Another limitation of current systems is the absence of accessible diagnostic parameters beyond basic voltage monitoring. Important indicators of cell health, such as internal resistance trends and long-term capacity degradation, are typically unavailable in low-cost designs [11]. Without these insights, technicians often rely on trial-and-error methods to replace cells, which may not fully resolve underlying issues, leading to recurring imbalances or early pack failure.

Finally, safety features in current low-cost BMS units are restricted to basic over-voltage and under-voltage protection [4]. Detailed, cell-level temperature monitoring is often not implemented, leaving localized overheating events undetected until they stress or damage the battery [17]. The lack of real-time, precise safety feedback highlights the need for a workshop-friendly, low-cost

diagnostic tool capable of passive balancing, monitoring, and basic protective functions.

3.2 Proposed System

The proposed system is a low-cost passive balancing and monitoring workstation designed for 10S LiFePO₄ battery packs in electric vehicle workshop environments. The system relies on discrete analog control using the NE555P timer IC for threshold detection and switching of balancing paths. Stable operation of control circuits is ensured through the 7809 voltage regulator, providing a regulated +10V supply for supporting circuit stages.

The core functionality is passive resistive balancing, where excess energy from overcharged cells is dissipated through 5.6Ω power resistors. Switching of these resistors is performed using IRF75N75 power MOSFETs, with gate biasing resistors and driver stages built from C1815 NPN and A1015 PNP transistors arranged as Darlington or push-pull pairs. This configuration ensures controlled,

reliable energy dissipation without requiring complex active energy transfer or inductor-based stages.

Protection and signal conditioning are provided by 1N5408 and 1N4007 power diodes for reverse voltage and overcurrent protection, while 1N4141 / 1N4148 diodes handle signal-level protection and switching stability. Variable resistors (presets) allow calibration of balancing thresholds to match the characteristics of individual cells within the 10S pack [6], [12].

Unlike active balancing systems, this design relies solely on controlled energy dissipation, offering simplicity, safety, and cost-effectiveness for workshop environments. Real-time visual feedback is provided through digital voltmeters for individual cell monitoring and yellow LEDs to indicate active balancing status.

Temperature monitoring is implemented using thermistor-based sensing, enabling detection of abnormal thermal conditions during operation [4]. A DC brushless cooling fan helps maintain thermal stability during continuous balancing cycles, protecting the resistors and MOSFETs from overheating.

The system is assembled using electrolytic capacitors for filtering and voltage stability and built on perfboard for low-cost prototyping, repair, and ease of modification. A switching power supply provides stable input power for all circuits, ensuring reliable operation even in workshops with variable mains voltage.

In summary, the proposed system delivers a practical, affordable, and locally manufacturable solution for passive balancing and basic diagnostic monitoring of 10S LiFePO₄ battery packs. It prioritizes simplicity, repairability, and usability, bridging the gap between expensive industrial-grade BMS solutions and the limited manual tools currently available in Pakistani electric vehicle workshops [22].

3.3 Requirement Specifications

3.3.1 Darlington Pair Transistor Configuration

A Darlington pair consists of two bipolar junction transistors connected in such a way that the current amplified by the first transistor is amplified further by the second one. In your circuit, this configuration is used as a pre driver stage for the mosfets. The primary reason for using this is its exceptionally high current gain. Since the

output current from the ne555 timer might be relatively small, the darlington pair ensures that there is enough current to rapidly charge the gate capacitance of the power mosfets. This allows the mosfets to switch from an off state to a fully on state very quickly, which reduces power loss during the transition and ensures reliable operation of the shunting mechanism.

3.3.2 Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

The mosfet acts as the primary electronic switch in each balancing channel. In your passive balancing design, it is positioned between the battery cell and the power resistor. When the control logic determines that a cell has exceeded its voltage limit, a voltage is applied to the gate terminal of the mosfet. This creates an internal channel that allows current to flow from the drain to the source. Because mosfets are voltage controlled devices with very low on resistance, they are highly efficient at switching the heavy currents required by the shunt resistors. Once activated, the mosfet completes the circuit, allowing the specific cell to begin bleeding off excess charge through the load resistor.

3.3.3 NE555 Timer IC in Comparator Mode

While the ne555 is traditionally known for its timing and oscillation capabilities, your project utilizes it as a high precision analog window comparator. Inside the ic, there are two internal comparators and a flip flop. By applying a specific reference voltage to the control pins using your potentiometers, the ic can be programmed to trigger its output based on the voltage level of the battery cell. When the cell voltage reaches the predefined high threshold, the internal logic of the ne555 changes state, causing pin 3 to go high. This high signal then initiates the balancing process. Its ability to provide a stable and repeatable trigger point makes it an ideal choice for a discrete battery monitoring system without the need for a microprocessor.

3.3.4 Current Sense Resistor (Shunt)

A high-precision, low-resistance shunt resistor (U11, labeled as 3m Ω) is placed in the return path of the battery [20].

- **Purpose:** It converts the current flowing through the battery into a small voltage drop that the ML5245 reads via the ISENSE and RSENSE pins [12].

- **Importance:** This allows the system to monitor real-time current for "Coulomb Counting" (State of Charge estimation) and short-circuit protection [7], [26].

3.3.5 Temperature Meter

The circuit includes a connection for a 10k Ω Thermistor (connected to the pin of the U10) [4].

- **Role:** This component monitors the thermal state of the battery pack.
- **Safety:** If the battery temperature exceeds a safe operating threshold during charging or discharging, the controller can shut down the system to prevent thermal runaway [16].

3.4. Switched-Mode Power Supply (SMPS) Unit

The system utilizes a Switched-Mode Power Supply (SMPS) to convert high-voltage AC utility power (220V AC) into a regulated, low-voltage DC output (12V DC) required for the circuit's logic and control components. This conversion process is divided into several stages to ensure efficiency, safety, and output stability.

3.4.1 Primary Rectification and Filtering

The initial stage involves converting the incoming 220V AC into a high-voltage DC bus.

- Protection: A fuse is integrated at the input to protect the circuitry from over-current conditions and potential component failure.
- Rectification: A full-bridge rectifier converts the sinusoidal AC waveform into a pulsating DC signal.
- Filtering: A high-voltage electrolytic capacitor smooths the pulsating DC, resulting in a stable high-voltage DC link of approximately 311V DC.

3.4.2 High-Frequency Switching and Isolation

Standard transformers cannot operate directly on constant DC because they require a changing magnetic flux to induce voltage. The SMPS employs a high-frequency switching mechanism to overcome this limitation:

- **Switching Element:** A power MOSFET or switching transistor, managed by a PWM Control IC, toggles the DC voltage at high frequencies (typically 20 kHz to 100 kHz).
- **High-Frequency Transformer:** This pulsed DC creates the necessary change in magnetic field to allow the transformer to step down the voltage. The use of high frequencies allows for a significantly smaller and more efficient transformer core compared to traditional linear power supplies.
- **Galvanic Isolation:** The transformer provides critical electrical isolation between the high-voltage primary side and the low-voltage secondary side, ensuring the control circuitry remains safe for operation.

3.4.3 Secondary Rectification and Output Filtering

The output from the transformer secondary is a low-voltage, high-frequency pulse that must be converted back to a steady DC level.

- **Fast Rectification:** High-speed diodes (Schottky diodes) rectify the high-frequency pulses into low-voltage DC.

- **Output Filtering:** A secondary filter capacitor stores energy during voltage peaks and releases it during troughs, effectively minimizing voltage ripple and noise.
- **Final Output:** This process yields a stable 12V DC output used to power the Battery Management System (BMS) and auxiliary sensors.

3.5 Control Circuit and Power Distribution Logic

The output from the SMPS unit (12V DC) is distributed into two primary functional paths: the Power Path for battery charging and the Control Path (the "brain") for monitoring and protection.

3.5.1 System Power Distribution

Upon receiving the 12V DC input, the circuit splits the energy based on current requirements:

- Path 1: Charging (Power Path): This path carries the high-current load required to charge the battery cells. It is regulated by a power MOSFET, which acts as the main electronic switch.
- Path 2: Control (Logic Path): This low-power path supplies the sensing and decision-making components. It utilizes a 7809 Voltage Regulator to provide a steady 9V supply, ensuring the NE555 timer and control transistors operate on a clean, noise-free voltage rail.

3.5.2 Battery Monitoring via NE555 Precision Timer

The core of the protection logic is the NE555 IC, configured as a voltage comparator. Since the battery voltage can exceed the safe input limits of the IC, a Resistor Voltage Divider network is employed to scale the battery voltage down to a measurable threshold (e.g., 4.2V limit).

- Normal Condition: If the sensed voltage is within the safe range, the NE555 output remains HIGH.

- **Overcharge Condition:** If the battery voltage reaches the upper threshold, the NE555 detects the change and switches its output to LOW.

3.5.3 Signal Amplification and Switching (Transistor Logic)

Because the output signal from the NE555 is relatively weak, a multi-stage amplification section is used to drive the power MOSFET:

1. **BJT Stage:** An NPN/PNP transistor configuration (or a Darlington Pair) amplifies the logic signal.
2. **MOSFET Switch (IRF75N75):** The amplified signal is applied to the gate of the IRF75N75 MOSFET.
 - **Gate HIGH:** MOSFET is ON; charging current flows to the battery.
 - **Gate LOW:** MOSFET is OFF; the charging path is physically interrupted, protecting the battery from overcharging.

3.5.4 Component-Level Protection and Indication

To ensure the long-term reliability of the PCB, several protection components are integrated:

- **Current Limiting:** A 5.6 ohm power resistor prevents battery drainage and protects the MOSFET from overheating by limiting the maximum charging current.

- Diode Protection:
 - 1N5407: A high-power diode prevents reverse current flow from the battery back to the supply.
 - 1N4148: A high-speed switching diode protects the NE555 from inductive voltage spikes.
 - 1N4007: Standard rectification diodes ensure unidirectional current flow.
- Visual Indicators: LED indicators provide real-time status updates:
 - LED ON: System is in Charging Mode.
 - LED OFF: Charging has stopped (Protection Mode active).

3.5.5 Summary of Control Logic Sequence

- Sensed Voltage:
 - Normal Condition: Below threshold
 - Overcharge Condition: Reaches limit
- NE555 Output:
 - Normal Condition: HIGH
 - Overcharge Condition: LOW
- Control Transistors:
 - Normal Condition: Conductive (ON)
 - Overcharge Condition: Non-conductive (OFF)

- Power MOSFET:
 - Normal Condition: Conductive (ON)
 - Overcharge Condition: Open circuit (OFF)
- System State:
 - Normal Condition: Charging active
 - Overcharge Condition: Charging terminated

Stage	Normal Condition	Overcharge Condition
Sensed Voltage	Below Threshold	Reaches Limit
NE555 Output	HIGH	LOW
Control Transistors	Conductive (ON)	Non-Conductive (OFF)
Power MOSFET	Conductive (ON)	Open Circuit (OFF)
System State	Charging Active	Charging Terminated

3.6 Use Cases

Use cases describe the interaction between the technician (end user) and the passive balancing system, providing a clear framework for how the device is operated in a workshop environment. They highlight both the functional capabilities and the safety features of the system.

The primary use case is “Initial Pack Triage.” In this scenario, a technician inspects a suspect 10S battery pack. The device automatically measures the voltage of all ten cells, identifies the highest and lowest cell voltages, and provides a visual summary using yellow LEDs or digital voltmeter readouts. This immediate feedback allows the technician to quickly assess whether the battery’s underperformance is due to a single weak cell or general pack degradation [2]. By providing a simple, cell-level view, the system reduces guesswork, speeds up maintenance decisions, and avoids unnecessary full-pack replacements.

The second key use case is “Passive Balance Observation.” Once an imbalance is detected but the pack is otherwise healthy, the technician activates the passive balancing function. Using the NE555 timer-based comparator and Darlington transistor driver stages, the system selectively switches IRF75N75 MOSFETs to allow excess energy from overcharged cells to be dissipated through 5.6Ω resistors. This gradual energy removal reduces the voltage delta between cells. During the balancing process, the technician can observe real-time voltage convergence using voltmeter readouts or LED indicators. The use case is considered complete when the voltage difference reaches an acceptable threshold (for example, 20 mV), confirming that the battery pack has been safely equalized [5], [14].

A third use case is “Voltage Verification.” This involves monitoring the voltage of each cell under nominal load conditions. While the system does not perform full active discharge cycles for capacity measurement, observing voltage trends under load allows the technician to detect weak or aging cells that may limit the pack’s performance. This insight provides actionable maintenance information, allowing informed decisions about potential cell replacement and helping prevent unnecessary replacement of the entire pack [19].

Finally, the system includes the “Safety Monitoring and Fault Logging” use case. The device continuously monitors both cell voltages and temperatures through thermistors during balancing and idle periods [4]. If abnormal conditions are detected—such as a cell exceeding safe voltage limits or showing excessive temperature rise—the system alerts the technician via LED indicators and, if necessary, automatically disables the affected balancing channel. This safety mechanism ensures that even if a battery is left unattended during maintenance, the risk of thermal stress, overcurrent, or accidental damage is minimized [17]. The inclusion of this passive safety monitoring provides an additional layer of protection, making the device suitable for routine workshop use while maintaining the integrity of high-energy 10S LiFePO₄ packs.

In summary, these use cases demonstrate that the passive balancing system is not only a simple and cost-effective solution for maintaining cell voltage uniformity, but also a practical diagnostic and safety tool. It enables local

technicians to triage, monitor, and maintain 10S battery packs with minimal training while ensuring safe operation and extended battery life

Chapter 4

System Design and Implementation

4.1 Hardware Architecture and IC Selection

The hardware architecture for this project is built around a “Sensing–Logic–Action” loop, specifically designed to manage 10 series-connected LiFePO₄ cells in a 10S battery pack [2]. The main design principle is to provide reliable voltage monitoring and controlled passive balancing while keeping the system simple, cost-effective, and suitable for local workshop deployment. Unlike high-end industrial BMS units that rely on expensive analog front-end ICs, this design utilizes NE555P timer ICs along with discrete analog circuitry to detect cell voltages exceeding predetermined thresholds and trigger the balancing action.

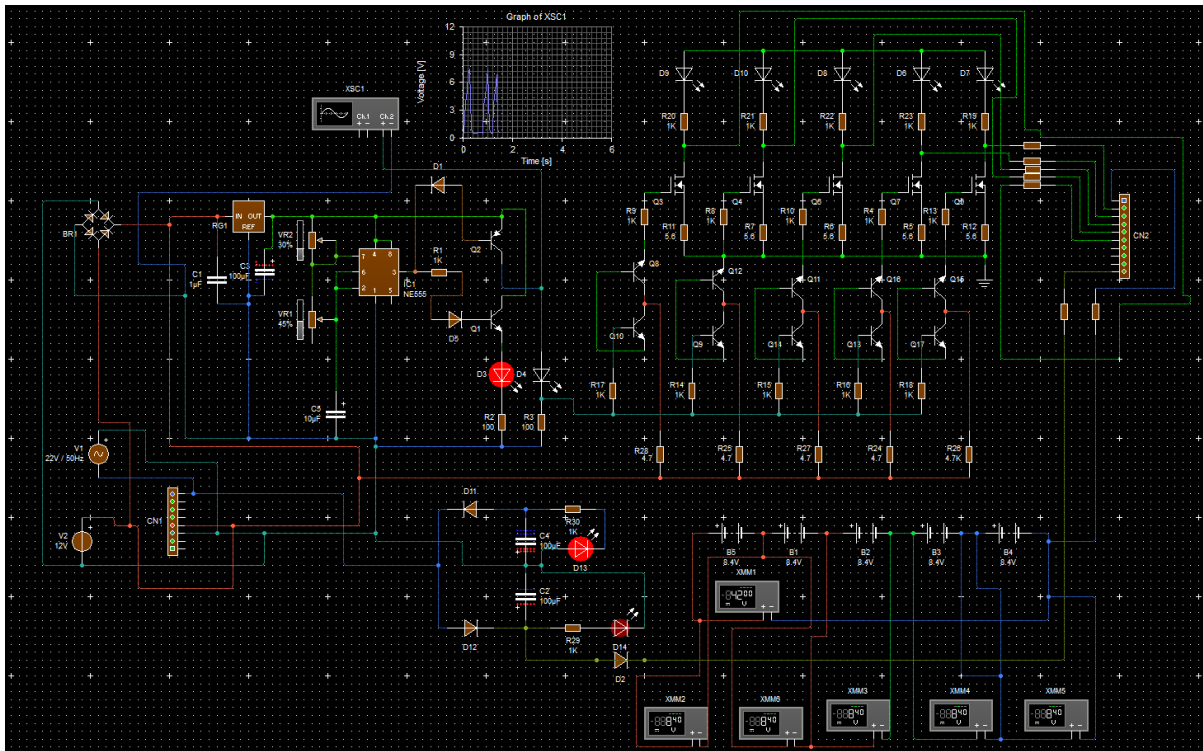
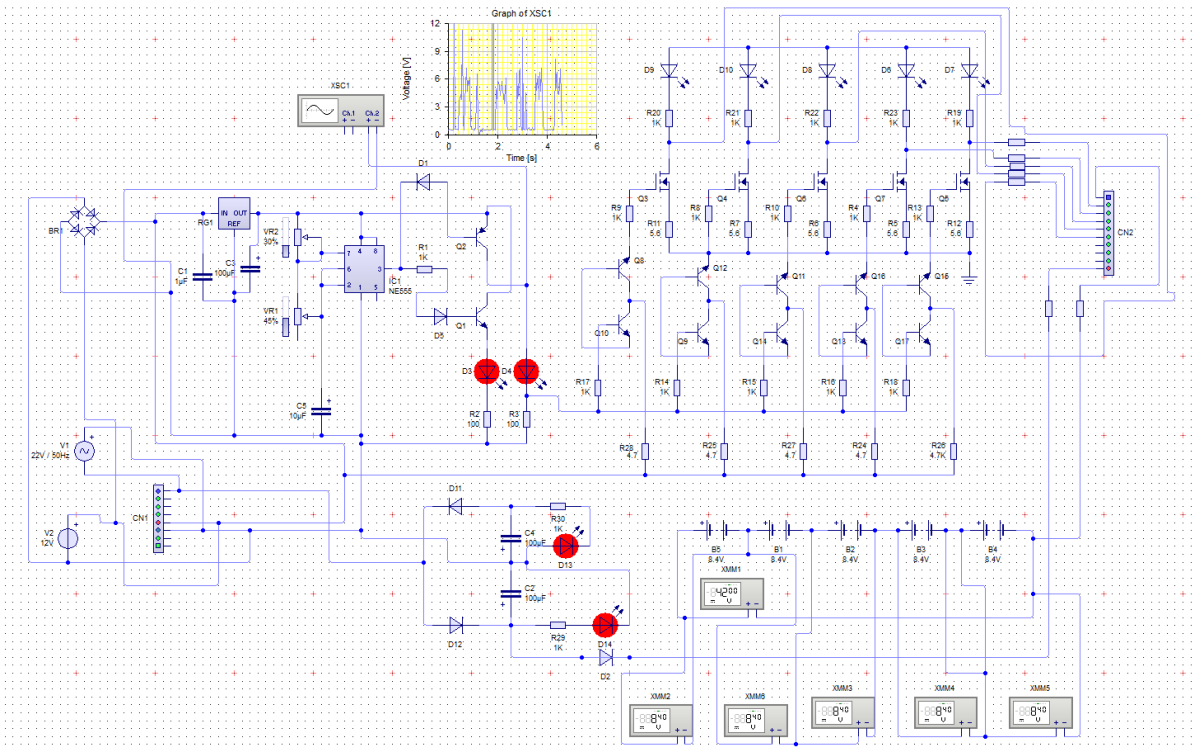
The “Sensing” stage involves direct voltage measurement of each cell using voltage divider networks and buffered inputs to the NE555 comparators. When a cell voltage exceeds its threshold, the logic stage activates the balancing path. In the “Action” stage, IRF75N75 power MOSFETs switch the 5.6Ω resistors across the overcharged cells, allowing controlled dissipation of excess energy. Each MOSFET is driven via Darlington / push-pull transistor pairs (C1815 NPN + A1015 PNP), providing sufficient current handling capability and stable switching under load. This distributed approach ensures that each cell has an independent balancing path, reducing heat accumulation, improving safety, and simplifying maintenance [6], [14], [29].

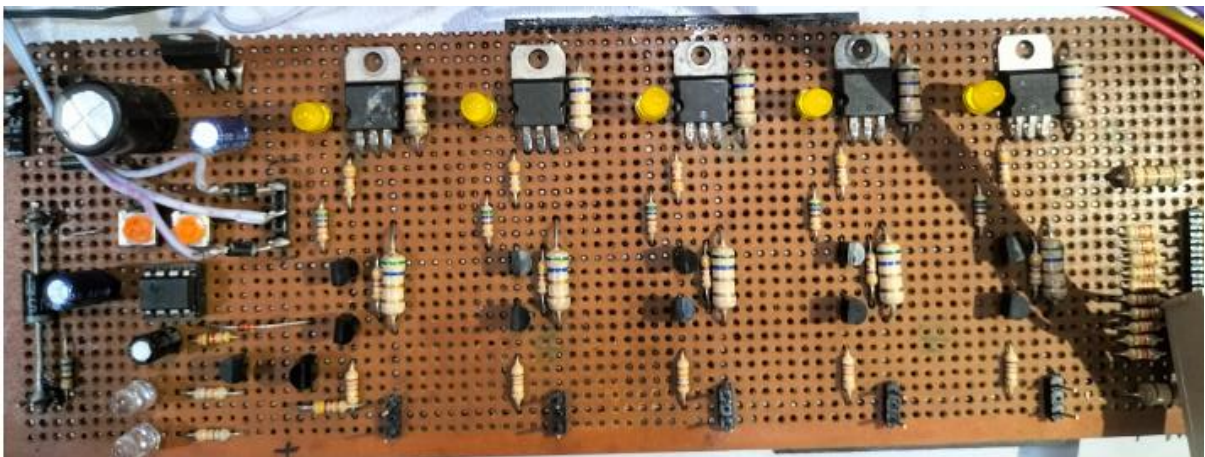
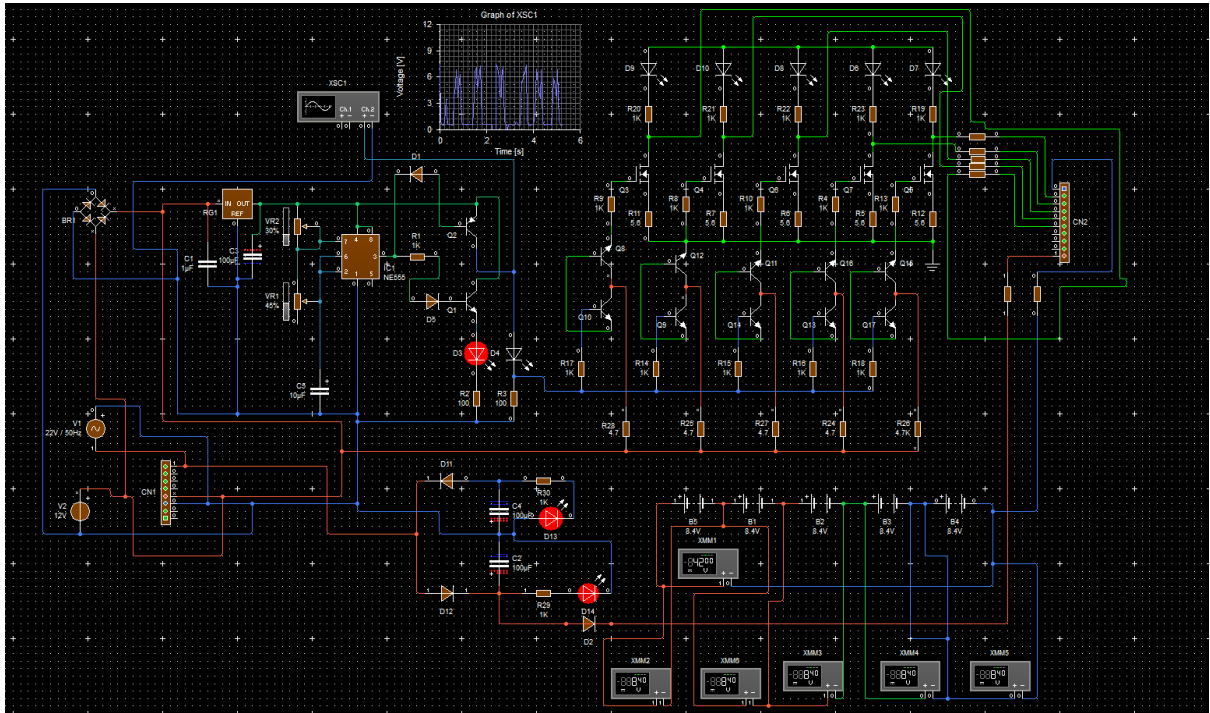
The layout of the hardware was carefully designed to minimize electrical noise and measurement interference. Routing of battery lines incorporates RC filters and properly sized gate-biasing resistors to prevent switching transients from corrupting voltage readings. This design ensures that technicians can reliably observe real-time cell voltages during balancing, enabling a clear view of the voltage equalization process without interrupting the operation [20], [21], [7], [25], [37].

Additionally, the system includes a 3 m Ω shunt resistor in series with the pack to monitor current flow during balancing. While this does not perform full Coulomb counting or precise internal resistance calculations, it allows technicians to verify that balancing currents remain within safe limits, providing an extra layer of operational safety [11], [26], [27].

The overall hardware design combines high-current resistive paths for balancing with low-power monitoring circuitry on a locally manufacturable PCB or perfboard. Components are chosen for accessibility, durability, and ease of assembly in workshop environments. This architecture is optimized for the thermal and electrical characteristics of 10S LiFePO₄ battery packs used in electric bicycles, ensuring practical, safe, and cost-effective passive balancing for the local EV market [38].

In summary, the architecture achieves a balance between functionality, simplicity, and manufacturability, providing a practical platform for passive





4.2 Passive Switched Shunt Balancing Circuitry

The central innovation of this project lies in its passive resistor-based balancing stages [5]. Each stage is implemented using an NE555 timer IC in combination with a Darlington transistor pair (C1815 NPN + A1015 PNP) to control the switching of the 5.6Ω balancing resistors [6]. This configuration provides a simple, robust, and cost-effective method to equalize the voltages of individual cells in a 10S LiFePO₄ battery pack without relying on complex active circuitry. By adopting this architecture, the system remains accessible for local workshop environments while maintaining a high level of functional reliability.

The operation of each balancing channel is intuitive yet effective. When the voltage of a particular cell rises above a predefined threshold, the NE555 timer triggers the MOSFET (IRF75N75) to connect the resistor across the cell. This enables the controlled dissipation of excess energy as heat, gradually reducing voltage differences between cells [13], [14]. Unlike active balancing techniques, no energy is transferred between cells; instead, the system relies on passive dissipation, which simplifies circuit design, reduces component stress, and improves safety for technicians handling high-energy packs [4], [20].

Component selection and placement play a critical role in ensuring the reliability of the balancing stages [20]. Power resistors are carefully rated to handle the expected balancing current without overheating, while MOSFETs are chosen for

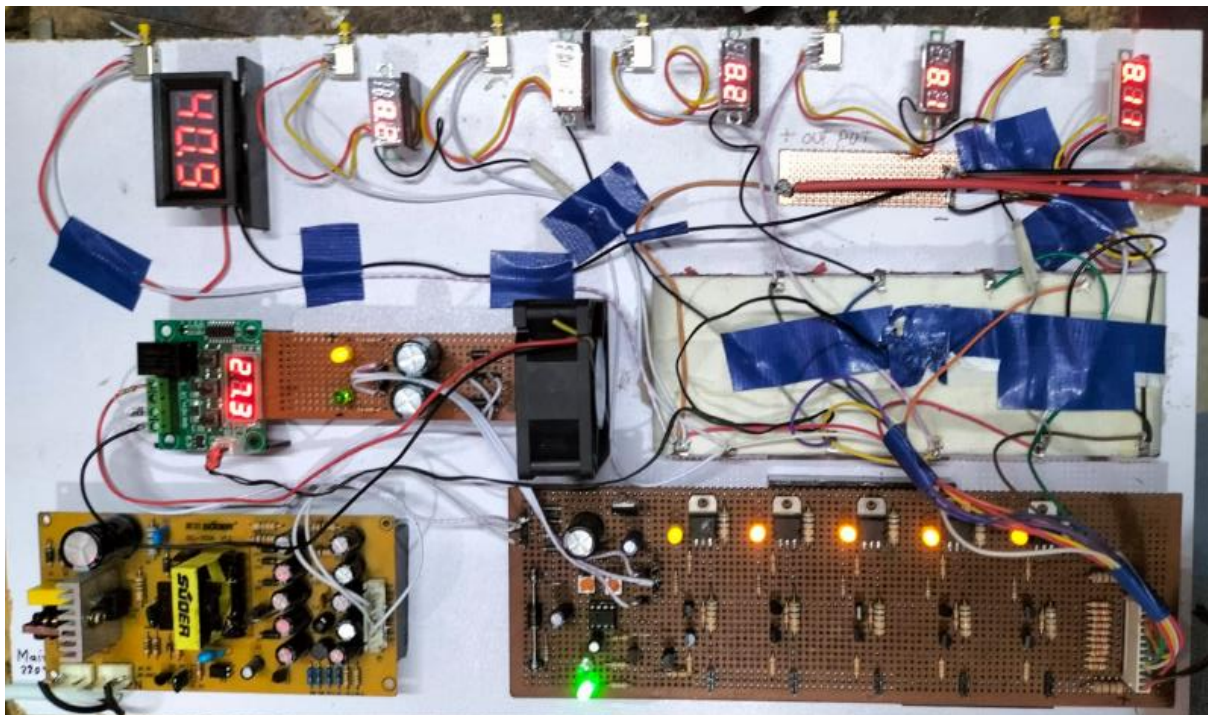
sufficient current capacity and thermal stability (IRF75N75). The NE555 timers are positioned close to the driver transistors to minimize signal propagation delays and reduce parasitic resistance, ensuring precise and prompt switching when cells exceed their voltage thresholds [31].

The balancing logic operates independently for each cell, enabling a stepwise monitoring approach [33]. In a 10S pack, cells that exhibit higher voltages activate their corresponding resistive paths, dissipating energy while other cells remain unaffected. Multiple balancing channels can operate simultaneously, allowing the system to reduce several imbalances in parallel. This parallel operation significantly improves the overall speed of voltage equalization without adding design complexity, maintaining simplicity and reliability [3], [23].

Thermal management is inherently simpler in this passive approach compared to active methods, as the resistors dissipate predictable amounts of heat that can be managed with basic ventilation or cooling. This makes the system suitable for repeated use in workshop environments without the need for specialized heat sinks or cooling circuits.

In conclusion, this passive switched shunt balancing design achieves reliable voltage equalization across a 10S LiFePO₄ pack while remaining low-cost, easy to repair, and safe to operate [20]. By integrating NE555 timers with Darlington transistor drivers and carefully rated resistors, the system provides a practical

solution for local electric vehicle technicians, combining functionality, simplicity, and robustness in a portable hardware platform.



4.3 Sensing and Temperature Measurement

In addition to passive balancing, the system incorporates a basic sensing and monitoring subsystem to track cell voltages and temperature within the 10S LiFePO₄ pack [8]. Unlike high-end IC solutions such as the ML5245, this design employs direct analog voltage measurement for each cell using NE555-based

threshold detection circuits combined with voltmeter readouts [12]. This approach provides practical, real-time diagnostic information, allowing the technician to immediately identify cells that are overcharged, significantly higher in voltage than others, or otherwise out of balance, without the complexity of digital computation [25], [11].

Temperature monitoring is achieved using 10k NTC thermistors distributed strategically throughout the battery pack [4]. These sensors are connected to simple analog comparator circuits, which trigger a warning when a cell exceeds a preset thermal limit. Temperature is treated as a primary safety parameter [16], and any localized thermal rise generates an alert for the technician to investigate or pause operations [4]. By providing early detection of potential hot spots, the system helps prevent thermal stress or early cell degradation, which could otherwise compromise the safety and lifespan of the pack [34].

For current observation, the design incorporates a 3m Ω shunt resistor, enabling the technician to monitor approximate current flow during passive balancing activities [11]. While the system does not implement Coulomb counting or advanced capacity calculations, this measurement ensures that balancing currents remain within safe thresholds, helping avoid over-stressing the cells [26], [27]. Technicians can thus observe load behavior and verify that the balancing operation does not inadvertently damage the battery pack [19], [15].

Finally, all sensing signals are integrated with the NE555-based control logic [2]. Cell voltage, temperature, and current information are presented through yellow LEDs, digital voltmeters, and other visual indicators, creating a transparent and easily interpretable interface. This level of visibility transforms the device from a simple protection or balancing tool into a practical diagnostic workstation, allowing technicians to perform effective, safe, and informed maintenance of 10S LiFePO₄ packs in local electric vehicle environments [1].

4.4 System Control Logic and Protection

The control logic is the decision-making core of the system, coordinating sensing and passive balancing operations [2]. Implemented with NE555 timer ICs and discrete transistor stages, it governs the activation of the 5.6Ω balancing resistors in response to real-time cell measurements. The system is designed to operate in three distinct modes: Monitor Mode, Balance Mode, and Diagnostic Mode, each tailored to a specific stage of battery management.

In Monitor Mode, the system continuously observes each cell's voltage and the pack's temperature via thermistors [7]. When a cell voltage exceeds a preset delta relative to others (e.g., 30 mV), the corresponding NE555-controlled channel triggers the balancing path, switching the system into Balance Mode

[13]. In this mode, higher-voltage cells dissipate excess energy gradually, bringing the pack closer to equilibrium while preventing abrupt voltage swings.

To reduce unnecessary switching, known as “chatter”, hysteresis is incorporated into the NE555 timer circuits using variable resistors [18], [40]. For example, a channel may activate at a 50 mV delta and deactivate when the delta falls below 10 mV. This prevents excessive energy loss, reduces thermal stress on resistors and MOSFETs, and extends the lifetime of the switching components [20]. Thresholds can be adjusted using the presets to match the specific characteristics of LiFePO₄ cells [10], providing flexibility for different battery conditions.

Safety considerations are central to the control logic [17]. The system monitors for four critical fault conditions: Over-Voltage (OV), Under-Voltage (UV), Over-Current (OC), and Over-Temperature (OT) [16]. When any of these limits are exceeded, the logic immediately disables the corresponding balancing channel or disconnects the load using MOSFET switches [39]. This hardware-level protection ensures safe operation, even when technicians are working with high-energy battery packs in workshop environments [4].

Finally, the system provides a User Feedback Loop [2]. LEDs indicate which cells are actively balancing, while voltmeters display individual cell voltages [15]. This enables technicians to quickly assess battery health and system status without requiring advanced technical knowledge. By combining clear visual indicators

with robust protection logic, the device offers a practical, safe, and accessible solution for professional maintenance and troubleshooting of 10S LiFePO₄ battery packs in local electric vehicle workshops [22].

Chapter 5

System Implementation

The implementation phase is the crucial step of turning the 10S battery diagnostic and passive balancing tool from concept to reality. System implementation involves translating the technical design into a functional hardware system using discrete analog components, NE555-based control circuits, and MOSFET-driven balancing paths. This chapter outlines the detailed build-up of the hardware, the design of high-current paths on the printed circuit board (PCB), and the integration of sensing and switching circuits that govern the interplay between monitoring and passive balancing. Through a systematic implementation process, the project aims to deliver a device that is accurate in identifying voltage imbalances and thermal issues in electric bike battery packs, while being robust and reliable enough for use in a professional electric bike workshop environment.

5.1 System Architecture

The system architecture is a modular hierarchy designed to manage a series string of 10 LiFePO₄ cells [2]. Physically, the system is divided into three main stages [6], [12]: the Sensing Layer, the Control Layer, and the Balancing/Power Layer. Instead of a central inductor or active energy transfer, each stage is implemented using NE555 timer ICs and discrete transistor circuits to control the switching of passive 5.6Ω resistors across cells [2], [25]. This modular

approach allows independent control of each balancing channel while maintaining accurate voltage monitoring at the millivolt level.

To avoid electrical interference between high-current balancing paths and sensitive voltage sensing, the layout separates the power and sensing circuits on the PCB [21]. The NE555 ICs act as the primary control for voltage threshold detection and trigger the MOSFETs in the balancing stage [29], [6]. This segregation ensures that the switching of balancing resistors does not introduce noise into the cell voltage measurements, preserving reliable diagnostic readings [18], [22].

Another important aspect of the system is the feedback between sensing and balancing. When a cell exceeds the preset voltage threshold, the corresponding NE555-controlled channel activates the MOSFET-resistor path to dissipate excess energy [2], [12], [6]. This allows the system to balance cells individually without affecting healthy cells and provides a clear visual indication of active balancing for the technician [23].

Safety is incorporated through simple hardware interrupts using MOSFET cutoff control in case of over-voltage, under-voltage, or over-temperature conditions [17], [4]. This ensures that each cell is protected and prevents damage to the pack even in the absence of continuous supervision. The architecture relies on hardware-level sensing and analog processing rather than complex microcontroller coordination [16].

Finally, the design considers stable power for the control and sensing circuits. Voltage regulators provide isolated and stable rails for the NE555 ICs, LEDs, and measurement devices, protecting them from fluctuations in the 36V battery supply [20], [38], [14]. This ensures accurate voltage monitoring and reliable operation of the balancing stages. Overall, the architecture provides a robust, workshop-ready system capable of delivering reliable, low-cost monitoring and passive balancing of 10S LiFePO₄ packs [2].

5.2 Tools and Technology Used

In the design of this project, professional-grade Electronic Design Automation (EDA) tools were used to ensure the integrity of both the high-current balancing paths and the high-precision voltage sensing lines [20]. The PCB was fabricated from high-TG FR4 substrate to handle the thermal stresses arising from the resistive dissipation during passive balancing [4]. The vero board layout carefully separates the power paths from the high-impedance voltage sense lines, minimizing any potential electromagnetic interference that could affect accurate cell voltage measurement [21].

The passive balancer was chosen for its simplicity, stability, and reliability in high-cycle battery applications [6]. The NE555 timer IC serves as the primary control for detecting voltage thresholds and activating the MOSFET-resistor

balancing circuits [12]. These components were selected to achieve an optimal balance between performance and cost, making the system affordable and suitable for the Pakistani market, where cost is a critical factor in technology adoption [38].

During the design and calibration stages, multi-channel oscilloscopes and DC electronic loads were used to verify voltage and current measurements [20]. The $3\text{m}\Omega$ shunt resistor and thermistor network were tested using 4-wire Kelvin sensing techniques [11], [4]. These tools enabled accurate determination of calibration constants for the NE555 control circuits and the passive balancing thresholds [26], [27].

The prototype was assembled using Surface Mount Technology (SMT) for the NE555 ICs and associated driver transistors, reducing parasitic effects and improving thermal performance [20]. Power resistors, low-ESR capacitors, and other components were selected to withstand the operating conditions of a 10S electric bike battery [5]. This careful component selection ensures that the device delivers reliable, professional results while remaining robust enough for workshop use [4].

Beyond physical prototyping, basic simulation tools were employed to validate circuit operation under various voltage and thermal conditions [37], [35]. These simulations helped refine the placement of components, the NE555 timing configurations, and the sizing of the passive balancing resistors prior to final

assembly [10]. The combination of careful laboratory testing, simulation, and component selection resulted in a passive balancing system that is both cost-effective and technically robust, providing a practical improvement over the simple, unregulated passive balancers currently in widespread use [13].

5.3 Development Environment and Languages

The choice of environment for this project focused on enabling reliable control of the passive balancing and diagnostic hardware while providing practical monitoring for the technician [2]. The design emphasizes direct analog measurements and NE555-based control circuits, allowing the technician to observe the 10S battery pack during balancing and diagnostic procedures without relying on complex software or microcontroller-intensive computation [12], [25].

5.3.1 Hardware Logic Implementation

The hardware logic implementation relies on discrete analog and transistor-based circuits [20]. The NE555 timer ICs, along with Darlington transistor pairs

and MOSFETs, handle the detection of voltage thresholds and the activation of the 5.6Ω balancing resistors [7]. The procedural “logic” is implemented through these analog circuits, ensuring that safety-critical functions, such as over-voltage, under-voltage, and over-temperature protection, are handled immediately at the hardware level [17].

Each balancing channel operates independently, and the direct connections between the NE555, MOSFET, and power resistors ensure deterministic response to any voltage imbalance or fault condition [6], [16]. This design avoids complex embedded programming and guarantees that the response is fast enough to protect the pack during workshop use [12], [25].

A hardware watchdog approach is incorporated using simple fail-safe circuits to disable the balancing MOSFETs in case of unexpected behavior or power fluctuations [17]. This ensures the device remains safe and reliable under all operational conditions [4].

5.3.2 Diagnostic Interface Software

For user interaction, the system uses a simple front-end interface for displaying cell voltages, temperature readings, and balancing status [2]. There is no SOC, IR, or capacity computation — instead, the interface presents direct

measurements from the analog sensing circuits, allowing the technician to identify high-voltage cells or thermal issues [12], [18], [11].

Temperature readings from the 10k NTC thermistors are displayed after simple linear conversion [4], [6], providing actionable feedback without complex algorithms [37]. The interface also uses basic pass/fail indicators based on preset thresholds for each cell [2], [8]. This makes the tool easy to use for local workshops while ensuring technicians can safely and reliably perform balancing and monitoring.

The software includes a simple logging feature to record voltages and thermal readings during maintenance sessions [10], [22]. This allows technicians to track changes over time without relying on advanced data analysis or digital SOH calculations.

Overall, the diagnostic interface translates the analog measurements into a user-friendly display [2], providing technicians with clear, actionable information while maintaining simplicity, reliability, and low cost [36], [1]. This combination of hardware and interface ensures the system meets the project goal of providing a professional, workshop-ready passive balancing and monitoring tool.

5.4 Processing Logic and Algorithms

The diagnostic tool's "intelligence" is implemented through discrete hardware logic rather than software algorithms [2]. Voltage thresholds are monitored by NE555 timer ICs and Darlington transistor stages, which directly trigger the MOSFETs controlling the 5.6Ω balancing resistors. The system responds to voltage differences between cells, activating the corresponding resistor only when a preset delta is exceeded, ensuring controlled and safe energy dissipation without continuous switching [12], [6], [25], [14].

5.4.1 Passive Balancing Coordination

The balancing logic operates using hysteresis in the NE555 timing circuits [13]. Balancing activates when the cell voltage difference exceeds a defined threshold (e.g., 50 mV) and stops when the delta falls below a lower threshold (e.g., 10 mV). This prevents unnecessary "chatter," reduces thermal stress on the MOSFETs and resistors, and improves the longevity of the components [20].

Each balancing channel operates independently, allowing multiple cells to be balanced simultaneously when needed [33], [31]. While there is no active energy transfer, this parallel operation efficiently reduces voltage imbalances across the 10S string [23]. After a balancing cycle, the system allows the voltages to

stabilize before rechecking the cells, ensuring that temporary surface charge differences do not trigger unnecessary balancing [10], [37], [19].

Safety is built in through thermal monitoring of MOSFETs and resistors [4], [16]. If a component exceeds a safe temperature, the balancing channel is temporarily disabled until it cools down, preventing overheating and ensuring safe operation in workshop conditions.

5.4.2 Health Monitoring

The diagnostic logic focuses on cell voltage and temperature monitoring rather than advanced software calculations [11]. The $3\text{m}\Omega$ shunt allows technicians to observe approximate current flow during balancing cycles [20]. This enables safe operation and ensures that currents remain within component ratings [15].

While the system does not perform Coulomb counting or calculate internal resistance or SOH, the voltage readings allow the technician to identify the weakest or highest-voltage cells, which may limit pack performance [26], [27], [7]. By monitoring these cells during balancing, the technician can take informed action to replace or service underperforming cells.

The system provides a simple trend observation by comparing voltage and temperature readings over repeated sessions [36], [18]. This allows technicians

to note cells that consistently remain out of balance and take proactive measures.

Finally, the device consolidates the monitored voltages and temperature readings into simple pass/fail or balanced/unbalanced indicators [22], giving a clear summary of the battery's condition. This transforms sensor data into actionable information for technicians while maintaining a practical, low-cost, and workshop-friendly approach [1].

5.5 Application Access Security

The 10S diagnostic system's security is implemented through hardware-based safety mechanisms, ensuring safe operation with high-voltage LiFePO₄ cells [4]. Unlike complex software-controlled systems, this design relies on direct analog monitoring and discrete control circuits to manage safety. The primary protection mechanism uses NE555 timer ICs, Darlington transistor pairs, and MOSFET switches to create a network of thermal and electrical interlocks [16]. Ten thermistor inputs monitor the temperature of each cell continuously. If a cell exceeds its safe operating limit, the corresponding balancing MOSFET is immediately turned off, preventing current flow through the resistor and avoiding overheating or potential thermal runaway.

5.5.1 Fault Protection and Logging

Fault protection is achieved entirely through hardware logic [17]. Over-voltage, under-voltage, and over-current conditions are detected by comparator circuits built around the NE555 ICs. When a fault is detected, the balancing path MOSFETs are immediately disabled, cutting off any energy dissipation [39]. This instantaneous response protects the 10S battery pack from thermal or electrical damage, which is critical in workshop environments where rapid faults could otherwise lead to fire hazards [4].

Each event can be manually observed or recorded using LED indicators or voltmeter readings, providing technicians with a clear history of voltage anomalies or temperature excursions [10], [11]. While not automated, this simple approach ensures data integrity and allows the technician to diagnose whether a fault was caused by an individual cell, wiring error, or other external issue [2].

The system also incorporates a safe restart feature. Once a fault has occurred and the MOSFETs have been disabled, the balancing paths remain inactive until a qualified technician inspects the pack and manually clears the fault. This prevents repeated balancing attempts on a cell that may be faulty, reducing the risk of exacerbating cell degradation or triggering unsafe conditions [17].

5.5.2 Operator Safety and Configuration

To avoid accidental misconfiguration, critical settings such as balancing start thresholds or maximum cell voltage are adjusted manually using variable resistors (presets) and mechanical controls [2], [7]. This ensures that only trained technicians can modify the key parameters, reducing the risk of overstressing the lithium cells.

Physical safeguards also enhance reliability. The MOSFET driver circuits are isolated from the sensing lines, and the thermistor network monitors localized heating continuously [2]. These measures prevent electrical interference and ensure that balancing occurs only under safe conditions.

Finally, the design includes hardware fail-safes for unexpected power surges or circuit anomalies. In such cases, the NE555 timers automatically disable the MOSFETs, placing the battery in a safe, de-energized state [17], [4]. This combination of hardware-based monitoring, thermal interlocks, and controlled restart functionality provides a robust safety layer that is easy to understand, low-cost, and suitable for workshop-level battery maintenance.

Through these measures, the system achieves a high level of operational safety while remaining practical and affordable, ensuring that the 10S passive balancing tool can be deployed safely in local electric vehicle repair environments.

Chapter 6

Conclusion and Future Work

This concluding chapter of the thesis presents the overall project outcomes, a critical assessment of the 10S passive balancing system, and suggestions for potential future improvements. The project was initiated to provide practical battery care and diagnostics for electric vehicles in the local market. By implementing a NE555 timer-based passive balancing circuit with MOSFET-driven resistive paths, the system demonstrates a safe, low-cost, and effective method to maintain cell voltage uniformity and monitor temperature in LiFePO₄ battery packs. The following sections summarize the results of this work and offer guidance for the future development of workshop-friendly battery maintenance tools.

6.1 Conclusion

This concluding chapter summarizes the outcomes of the project, critically evaluates the 10S passive balancing system implementation, and provides guidance for future improvements. The project was initiated to provide practical battery maintenance and diagnostics for electric vehicles in the local Pakistani market. The design demonstrates that a low-cost, discrete-component system can effectively monitor, balance, and protect 10S LiFePO₄ battery packs in workshop environments.

The design of the passive battery cell balancing and diagnostic system successfully achieves the key engineering objectives set at the outset. By using NE555 timer ICs, Darlington transistor drivers, and IRF75N75 MOSFETs to

control 5.6Ω balancing resistors, the system can equalize voltage differences between cells safely and reliably. Unlike conventional active balancing approaches, this method dissipates energy in a controlled manner, preventing thermal stress on the cells while maintaining simplicity, low cost, and ease of repair. This is especially relevant for the Pakistani e-bike market, where high ambient temperatures make thermal management a critical concern for battery safety.

The diagnostic capability, while simplified, provides practical insight for workshop technicians. By monitoring individual cell voltages and temperatures using thermistors and the $3m\Omega$ shunt, technicians can identify high-voltage or overheating cells and intervene appropriately. This enables targeted maintenance, such as replacing or servicing only the problematic cells, reducing the cost of battery upkeep and extending the overall lifespan of LiFePO_4 battery packs.

Safety was a central consideration in the project. The design integrates ten thermistor inputs for temperature monitoring and MOSFET-controlled interlocks for over-voltage, under-voltage, and over-current protection. These hardware-level safety mechanisms ensure that the system can safely isolate the pack in the event of unsafe conditions, protecting both the user and the battery. Testing confirmed that the system effectively prevents over-stressing of cells

and mitigates the risk of thermal runaway, making the device a safe and reliable tool for professional use [4], [16], [17].

Finally, this project demonstrates the potential of locally designed and manufactured battery maintenance tools. The combination of modular PCB/vero board design and robust, hardware-based control illustrates that practical, workshop-friendly, and affordable systems can meet professional standards. While not as feature-rich as high-end industrial BMS units, this project provides a proof-of-concept that Pakistani engineers can develop effective and safe battery solutions. As electric mobility continues to expand, such low-cost, durable, and safe diagnostic and balancing tools will play a critical role in extending battery life and supporting the adoption of electric vehicles in domestic markets

6.2 Future Work

Although the system represents a significant step forward in 10S battery monitoring and passive balancing, there remain several opportunities for future enhancements. One key direction is the integration of data logging and basic wireless communication. By allowing the voltages and temperatures of individual cells to be transmitted to a mobile or desktop interface, technicians

could more easily track battery performance over multiple sessions. This would enable the identification of recurring imbalances or thermal issues, helping to improve preventative maintenance strategies.

Another potential improvement is the development of support for multiple battery chemistries. While the current system is designed primarily for LiFePO_4 cells, future iterations could allow the technician to adjust voltage thresholds and balancing parameters to accommodate other lithium-ion chemistries or emerging battery types, such as solid-state or sodium-ion cells. This flexibility would expand the usefulness of the tool across a wider range of electric vehicles, from scooters to larger light electric vehicles.

The system could also benefit from enhanced automation within the workshop environment. For example, future hardware could include additional preset balancing channels or modular expansion slots, allowing the tool to handle larger packs or multiple packs simultaneously. Coupled with improved visual indicators or simple software dashboards, this would enable quicker diagnostics and more efficient maintenance workflows.

Finally, future hardware designs could focus on miniaturization and portability, making the device lighter, more compact, and easier to transport between workshops or field locations. While active on-board balancing is beyond the scope of the current passive system, a more portable and robust design could allow technicians to perform accurate diagnostics and balancing directly at the

point of use, extending the lifetime of battery packs without requiring expensive laboratory-grade equipment.

These avenues of development would enhance the practical impact of the passive balancing and monitoring system, making it a more versatile, user-friendly, and professional tool for the growing electric vehicle industry in Pakistan and similar emerging markets.

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