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SMART MANAGEMENT SYSTEMS OF LITHIUM-ION BATTERY

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CERTIFICATION

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Date

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DEDICATION

This project is from my heart, and I dedicate it first and foremost to the Almighty God, who gave me the life, strength, wisdom, and peace of mind to see this work through from start to finish. I also dedicate this work to my wonderful parents, Mr. and Mrs. OSE, for their endless love, prayers, and sacrifices. You believed in me even during the moments I doubted myself, and your hard work provided the foundation I stand on today. Thank you for giving me the chance to pursue my education and for always cheering me on. To my siblings and close friends, thank you for keeping me grounded, making me laugh when the stress was too much, and always understanding when I had to skip gatherings just to stay back and work on my simulation files. Finally, this is dedicated to every student and researcher out there who is working late into the night to build a cleaner, safer, and better technological future. This milestone is just the beginning.

ABSTRACT

Lithium-ion batteries have completely changed our world, powering everything from the smartphones in our pockets to electric cars and solar power grids. However, these batteries have a major flaw: they are highly sensitive and can easily get damaged, fail early, or even catch fire if they get too hot, overcharge, or drain too deeply. Traditional battery systems usually react only after a problem has already happened, which is not safe enough for modern technology. The main goal of this project was to design and test a Smart Management System (SMS) that acts as an intelligent brain for lithium-ion battery packs, actively keeping them safe, helping them last longer, and making them work more efficiently. To achieve this, the project used MATLAB and Simulink software to build a detailed, realistic model of a lithium-ion battery pack. Inside this virtual setup, special control logic was built to constantly track individual battery cell voltages, current, and the overall State of Charge (how much energy is left) in real time. Safety boundaries were explicitly programmed into the system to flag an error the moment voltage crossed unsafe limits—specifically setting an upper overvoltage limit of 16.6 V and a lower under-voltage limit of 11.2 V. The simulation was run under different lifelike work situations and heavy loads to see how well the smart system would respond to sudden changes. The results clearly showed that the system works exactly as planned. The moment an unsafe voltage limit was crossed, the smart system reacted immediately, flagging the error and stabilizing the voltage safely within its target boundaries to prevent any damage to the battery cells. The system also smoothly tracked the steady drop in the battery's energy capacity as it discharged over time. Ultimately, this project proves that using an intelligent, software-based management system is a highly reliable and affordable way to protect modern energy systems before moving on to building expensive physical hardware.

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CHAPTER ONE

1.1 INTRODUCTION

1.1.1 BACKGROUND OF THE STUDY

Lithium-ion (Li-ion) batteries have revolutionized various sectors, from portable electronics to electric vehicles (EVs) and grid-scale energy storage. Their widespread adoption stems from their superior characteristics compared to earlier battery technologies like lead-acid or nickel-cadmium (Li et al., 2024; Niu, 2024). The dawn of the 21st century has witnessed an unprecedented surge in demand for efficient, compact, and high-performance energy storage solutions. At the forefront of this revolution stands the Lithium-ion (Li-ion) battery, which has become the undisputed powerhouse for a vast array of applications. From consumer electronics like smartphones and laptops to the burgeoning electric vehicle (EV) market and large-scale grid energy storage systems, Li-ion batteries offer a compelling combination of high energy density, excellent power capabilities, a low self-discharge rate, and a relatively long cycle life, making them indispensable to our increasingly electrified world (Li et al., 2024; Eshetu et al., 2021).

However, the remarkable capabilities of Li-ion batteries come with inherent complexities and vulnerabilities. These electrochemical devices are highly sensitive to their operating conditions. Parameters such as temperature extremes, excessive charge and discharge rates (C-rates), and sustained high or low states of charge (SoC) can significantly accelerate battery degradation, leading to premature capacity fade, increased internal resistance, and ultimately, a reduced operational lifespan (Suganya et al., 2024). More critically, mishandling or uncontrolled operation can trigger severe safety incidents, including thermal runaway, fire, and even explosions, arising from issues like overcharging, over-discharging, internal short circuits, or mechanical damage (Sadhukhan et al., 2022).

To address these fundamental challenges, the Battery Management System (BMS) was developed as a crucial guardian for Li-ion battery packs. Early BMS designs primarily focused on rudimentary protection mechanisms: continuously monitoring individual cell voltages, pack current, and temperature to ensure operation within pre-defined safe limits (Lyu et al., 2024). These systems were designed to react swiftly to critical conditions, initiating protective shutdowns to prevent immediate damage or hazardous events. They also included basic cell balancing functionalities, often passive in nature, to equalize voltage discrepancies among cells within a multi-cell pack, thus striving to maximize the usable capacity of the weakest link (Zhang et al., 2023).

While foundational, these traditional BMS approaches, relying largely on reactive thresholds and simpler operational models, proved to be insufficient for the escalating demands of modern applications. The drive for faster charging, higher power output, extended driving ranges in EVs, and longer service lives necessitated a paradigm shift in how batteries are managed (Kosuru & Kavasseri Venkitaraman, 2023). The limitations became evident in their inability to accurately predict battery behaviour over time, adapt to changing environmental conditions, or proactively mitigate degradation before it significantly impacted performance or safety (Lyu et al., 2024).

This critical need for more intelligent, predictive, and adaptive control has paved the way for the emergence of “Smart” Management Systems for Lithium-Ion Batteries (Kosuru & Kavasseri Venkitaraman, 2023). A smart BMS represents a significant leap forward, transcending basic protective functions by integrating sophisticated algorithms, real-time data analytics, and advanced control strategies (Lyu et al., 2024).

The hallmark of a smart BMS lies in its ability to not only monitor current battery status but also to predict its future behavior and health. This Prognostics and Health Management (PHM) capability allows for the estimation of Remaining Useful Life (RUL) and the

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anticipation of potential failures, shifting maintenance from reactive to proactive (Lyu et al., 2024). Furthermore, intelligent thermal management strategies ensure optimal operating temperatures, while adaptive cell balancing and dynamic charge/discharge algorithms continuously optimize energy flow based on the battery's real-time internal state and external conditions (Kosuru & Kavasseri Venkitaraman, 2023). The integration with connectivity platforms and cloud computing further empowers these systems, enabling remote diagnostics, fleet-wide data aggregation for deeper insights, and over-the-air (OTA) updates, transforming the battery from a passive energy container into an active, intelligent, and self-optimizing component within a larger energy ecosystem (Lyu et al., 2024).

This project embarks on a comprehensive exploration of these smart management systems for lithium-ion batteries. It aims to delve into the underlying principles, cutting-edge methodologies, and practical implementation aspects required to elevate battery performance, guarantee paramount safety, and significantly extend the operational lifespan of these crucial energy storage devices, thereby playing a vital role in accelerating the global transition towards sustainable and electrified technologies.

At their core, Lithium-ion batteries operate on the principle of lithium ion intercalation and de-intercalation between a positive electrode (cathode) and a negative electrode (anode) through an electrolyte, separated by a porous membrane. During discharge, lithium ions move from the anode (typically graphite) through the electrolyte to the cathode (e.g., lithium cobalt oxide, lithium iron phosphate), releasing electrons that flow through an external circuit. The process reverses during charging (Eshetu et al., 2021).

1.2 PROBLEM STATEMENT

The core problem is that conventional battery management approaches are insufficient to fully address the safety, longevity, and performance demands of modern Lithium-ion battery applications. There is a critical need for advanced, intelligent, and proactive management

systems that can precisely monitor, accurately estimate, predictively control, and adaptively optimize the behaviour of Lithium-ion batteries throughout their lifecycle, thereby enhancing safety, extending lifespan, improving performance, and maximizing economic value.

Current Lithium-ion battery systems face critical issues such as:

1. **Safety Risks:** Without precise control, Lithium-ion batteries are susceptible to thermal runaway, overcharging, over-discharging, and internal short circuits, leading to potential fires, explosions, and severe safety hazards. Traditional Battery Management Systems (BMS) primarily offer reactive protection, often failing to predict and prevent these catastrophic events.
2. **Premature Degradation and Limited Lifespan:** Factors like extreme temperatures, high charge/discharge rates, and inconsistent cell balancing contribute to accelerated capacity fade and power fade. Inaccurate monitoring and sub-optimal control strategies lead to inefficient utilization of the battery's full potential, shortening its overall lifespan and increasing the total cost of ownership.
3. **Inaccurate State Estimation:** Accurately determining critical battery states like State of Charge (SoC), State of Health (SoH), and State of Power (SoP) is challenging due to the non-linear electrochemical behaviour, aging effects, and varying operating conditions. Inaccurate estimations can lead to range anxiety in EVs, sub-optimal energy dispatch in grid applications, and missed opportunities for predictive maintenance.
4. **Inefficient Performance and Resource Utilization:** Cell imbalances within battery packs often limit the usable capacity of the entire pack to that of its weakest cell, underutilizing the healthy cells. Furthermore, static thermal management and

- charge/discharge protocols fail to adapt to real-time conditions, hindering peak performance and energy efficiency.
5. Lack of Predictive Capabilities: Traditional BMS are largely diagnostic, providing information about what *has happened*, but lack the prognostic capabilities to anticipate future battery behaviour, predict potential failures, or proactively optimize usage for extended life. This limits opportunities for condition-based maintenance and reduces overall system reliability.

1.3 AIM/OBJECTIVES

The major aim of this project is to design and implement a smart battery management system

(BMS) for lithium-ion batteries that enhances safety, extends lifespan, optimizes performance, and maximizes the overall efficiency of the battery system. This also involves:

1. To develop a comprehensive simulation model of a Li-ion battery pack, including its electrical and thermal characteristics.
2. To design and implement a Smart Management System (SMS) capable of real-time voltage monitoring, regulation, and protection.
3. To simulate various operational scenarios (charging, discharging, idle, fault conditions) to evaluate the SMS's effectiveness in voltage management.
4. To quantify the performance of the SMS in terms of voltage stability, regulation accuracy, and response time to anomalies.

1.4 SCOPE OF STUDY

The escalating global demand for high-energy applications, particularly in electric vehicles (EVs) and renewable energy storage, underscores the critical role of lithium-ion (Li-ion) batteries. While offering exceptional energy density, these batteries inherently present safety and operational challenges that necessitate sophisticated management.. A smart BMS acts as

the electronic brain of a battery pack, extending beyond basic protection to offer real-time monitoring, precise state estimation (State of Charge, State of Health, State of Power), intelligent cell balancing, and dynamic thermal management. The integration of Artificial Intelligence (AI) and Machine Learning (ML) is profoundly transforming BMS capabilities, enabling proactive predictive maintenance, optimized charging and discharging cycles, and enhanced safety through early anomaly detection. Simulation methodologies, specifically Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and Hardware-in-the-Loop (HIL), are indispensable throughout the BMS development lifecycle. These techniques significantly reduce development time and cost, improve system reliability, and enable safe validation of complex control algorithms under diverse conditions before physical prototyping. The progression from MIL's early algorithm verification to SIL's production code validation and HIL's real-time hardware integration forms a robust, V model-based development framework. Key to this study are the critical battery parameters (voltage, current, temperature), the extensive data requirements for AI/ML models (historical, operational, sensor data), and a comprehensive suite of performance indicators (operational, performance, aging, safety). Despite significant advancements, challenges persist in real-time state estimation accuracy, thermal runaway modeling, data security, and scalability. Future research will focus on overcoming these limitations through universal modeling approaches, advanced AI integration, and collaborative data initiatives, ultimately driving the evolution of safer, more efficient, and longer-lasting Li-ion battery systems. The scope of this study includes:

1. Development and implementation of model-based algorithms for highly accurate realtime State of Charge (SoC) estimation under dynamic load and temperature conditions.
2. Investigation of methods for State of Health (SoH) estimation, specifically focusing on capacity fade and internal resistance increase as degradation indicators.

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- 3. Implementation and evaluation of an active cell balancing strategy to mitigate cell voltage and SoC imbalances within the pack during both charge and discharge cycles, aiming to maximize usable capacity and prolong pack life.
- 4. The functionality and performance of the developed smart BMS will be validated through simulations using established battery models

1.5 SIGNIFICANCE OF STUDY

This study on creating a Battery Management System (BMS) for lithium-ion batteries is important because it tackles one of the biggest problems in today's energy storage—making sure battery-powered systems are safe, efficient, and last long. Lithium-ion batteries are commonly used in electric vehicles, renewable energy storage, portable electronics, and backup power systems because they store a lot of energy and can be recharged many times. However, how well they work and how long they last depends heavily on how well they are watched and controlled.

This study gives a clear understanding of how a BMS can correctly track important battery information like voltage, current, temperature, and charge level, while stopping problems like overcharging, draining too much power, and overheating—all of which can damage the battery or create safety risks. By simulating and studying a lithium-ion BMS under different usage conditions, this research provides useful knowledge for improving energy management, making batteries more reliable, and lowering maintenance costs.

In the end, the results of this study are useful for engineers, researchers, and companies looking to build safer and better energy storage systems. It also supports the worldwide move toward cleaner technologies by improving how lithium-ion batteries perform in electric vehicles, renewable energy systems, and smart power uses.

CHAPTER TWO

2.1 LITERATURE REVIEW

Early literature on BMS primarily focused on fundamental safety and monitoring functions. Researchers like Chen and R. D. (2007) laid the groundwork for understanding the necessity of monitoring voltage, current, and temperature to prevent catastrophic failures like thermal runaway caused by overcharge or over-discharge. Initial BMS designs were largely

□ hardware-centric, implementing rudimentary cutoff switches and passive cell balancing techniques. These systems were effective for basic safety but lacked the sophistication to optimize battery performance over its entire lifespan or predict degradation trends (Wang et al., 2020).

The concept of a "smart" BMS emerged from the recognition that a deeper understanding of battery states and more intelligent control algorithms were necessary to unlock the full potential of Li-ion technology. Recent reviews, such as those by Yang et al. (2025) and Zeeshan and Akre (2025), highlight this paradigm shift towards integrating advanced computational power, connectivity, and data analytics to move beyond simple monitoring and protection.

The unprecedented progress in battery development, particularly lithium-ion batteries, has created an urgent need for sophisticated management systems that can ensure safe, efficient, and reliable operation of battery packs. Lithium-Ion Batteries (LIBs) are currently the most popular Energy Storage System (ESS), with high demand in electric vehicles (EVs) and renewable-energy-powered grids making them a device of great importance on the road towards decarbonisation of industrial societies. A BMS serves as the control unit designed to monitor and manage several states of battery cells to keep them in safe and efficient conditions while taking action in case of abuse or malfunctioning.

Recent advances in lithium-ion battery technology have highlighted the need for sophisticated battery management systems (BMS) to ensure safe, efficient, and reliable operation of battery packs. Lithium-ion batteries (LIBs) are now the most widely adopted energy storage systems, especially in electric vehicles (EVs) and renewable energy grids, playing a pivotal role in the drive toward decarbonizing industrial societies (Chen et al., 2025; Zhang & Li, 2024).

A BMS serves as the control center of a battery pack, continuously monitoring and managing individual battery cells to maintain safety and optimal performance. As battery applications expand across electronics, mining, manufacturing, energy storage, and automotive sectors, research in battery materials and management systems has become essential. Batteries are typically arranged in series, parallel, or both, to meet power and energy demands (Wang et al., 2025; Kumar & Singh, 2024).

Beyond basic functions like measuring cell voltage, temperature, and current, advanced BMSs perform charge equalization to ensure uniform charge and discharge rates across all cells, preventing weaker cells from limiting the overall pack. More sophisticated systems also provide detailed health diagnostics, analyzing each cell's charge-discharge cycles to assess battery state and longevity (Luo et al., 2023; Martínez et al., 2023).

For large-scale high-energy battery packs, the BMS integrates hardware and software to execute multiple critical functions: estimating remaining charge and cycle life, managing data collection, balancing cell voltages, dynamically controlling charging/discharging, communicating with other electronic components, managing thermal distribution (beyond passive cooling), and verifying the functionality of isolation components (Chen et al., 2025; Smith, 2025).

In electric and hybrid vehicles, BMS evaluation of battery states—such as State of Charge (SOC), State of Health (SOH), and State of Life (SOL)—is especially crucial. Research has advanced hardware concepts to meet the demanding needs of these applications. For example, innovative multicell equalizers based on bipolar-resonant LC converters have demonstrated rapid balancing speeds alongside high efficiency (Chen et al., 2025; Luo et al., 2023).

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BMS susceptibility to electromagnetic interference (EMI) has been investigated to improve reliability, particularly in Li-ion and lithium-polymer (LiPo) batteries used in EVs.

Enhancements in SOC estimation using precise hysteresis modeling combined with extended Kalman filters (EKF), auto-regressive exogenous (ARX) models, and recursive least squares (RLS) filters have significantly boosted prediction accuracy over conventional methods (Zhou et al., 2023; Martínez et al., 2024; Kim & Park, 2023).

Thermal management remains a vital concern as improper temperature control accelerates battery degradation and can cause safety issues. Studies have modeled thermal behavior under various power demands, examining heat generation through Joule heating, reversible heat, and heat dissipation mechanisms. Thermal management techniques include passive methods like phase change materials (PCMs) and active cooling systems, both validated by simulation and experimental studies. These innovations help maintain uniform temperature distribution and extend battery life (Singh et al., 2023; Johnson et al., 2025; Laserax, 2025; FlashBattery, 2021).

Novel active and passive cell voltage equalization techniques using voltage multipliers and DC-DC converters have been proposed and validated to improve battery pack uniformity. Furthermore, regression analysis of incremental capacity (IC) curves has enabled SOH estimation with error margins below 1%, supporting predictive maintenance (Martínez et al., 2023; SAE, 2023; Luo et al., 2023).

Despite these advancements, key challenges remain. There is a lack of standardization across different BMS applications — ranging from small appliances to large-scale and transportation systems — which complicates safety and performance consistency.

Additionally, the determination of Safety Integrity Levels (SIL) for BMS operation is often

overlooked but is crucial for reliable battery pack operation. Finally, achieving robust real-time battery parameter estimation across diverse chemistries and conditions remains difficult, especially when initial algorithm states differ significantly from actual battery states (National Institute of Standards, 2024; Wang & Chen, 2025; ControlAR, 2025).

This study addresses several of these gaps by developing and validating a smart BMS through MATLAB Simulink simulations via the Model-in-the-Loop approach. This approach allows algorithm testing under diverse load conditions before physical prototyping, reducing costs and development time while improving reliability. The system offers comprehensive real-time monitoring of voltage, current, temperature, SOC, SOH, and State of Power (SOP) in a controlled environment. Importantly, it incorporates safety features to prevent overcharge, deep discharge, and overheating—responding to safety considerations that are not often emphasized in existing BMS research

RELATED WORKS

Over the years, several studies have been conducted to enhance the performance, safety, and reliability of lithium-ion battery systems through advanced management strategies. The research trend has evolved from simple protection mechanisms to intelligent and predictive management systems that integrate real-time monitoring, data analytics, and machine learning techniques.

Li et al. (2024) investigated the development of high-energy-density lithium-ion batteries and emphasized the need for effective management systems to maintain performance and safety. Their study highlighted the challenges of balancing energy density with thermal stability, showing that improper management could lead to rapid degradation or safety failures. However, the research primarily focused on cell chemistry improvement rather than on real-time control or protection mechanisms within the BMS framework.

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Lyu et al. (2024) presented an intelligent Battery Management System (BMS) that incorporated model-based estimation and artificial intelligence algorithms for enhanced State of Charge (SoC) and State of Health (SoH) estimation. The study demonstrated that combining Kalman filtering with data-driven learning improved prediction accuracy and fault tolerance. Despite its innovation, the complexity of implementation and high computational cost limited its adoption in simpler or smaller-scale systems, such as inverter or stand-alone energy applications.

Kosuru and Kavasseri Venkitaraman (2023) designed a smart BMS using deep-learning-based sensor fault detection for electric vehicle applications. Their work improved accuracy in detecting overvoltage and undervoltage conditions under dynamic load profiles. The system demonstrated real-time adaptability and improved fault diagnosis but required advanced hardware integration and processing power. This makes it less suitable for educational or small laboratory-scale systems focused purely on voltage and current regulation.

Sadhukhan et al. (2022) developed a MATLAB/Simulink model of a high-energy-density lithium-ion battery for multiple fault detection. Their simulation approach enabled early identification of potential failures such as overcharging, over-discharging, and thermal faults. However, the system was designed for vehicle-level energy packs and did not consider simplified or modular architectures suitable for small-scale smart management demonstrations.

Zhang et al. (2023) discussed the role of conventional battery management systems in maintaining pack balance through voltage and current monitoring. Their study emphasized cell equalization as a means to extend overall battery life. Although practical, the system

relied primarily on reactive protection logic (e.g., cut-off circuits), lacking the predictive intelligence that defines modern smart BMS designs.

CHAPTER THREE

3.1 PROPOSED METHODOLOGY

This methodology details a systematic approach to simulate a Smart Management System (SMS) for Li-ion batteries, with a primary focus on managing and regulating voltage levels within and out of the battery system.

The efficient and safe operation of Lithium-ion batteries is paramount in various applications, from electric vehicles to grid-scale energy storage. Voltage management is a critical aspect of battery performance, directly impacting its lifespan, safety, and overall efficiency. This

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simulation methodology aims to develop and test a "Smart Management System" (SMS) capable of intelligently regulating voltage within the Li-ion battery pack, ensuring optimal performance and protection against over-voltage and under-voltage conditions.

3.2 SOFTWARE AND TOOLS

The following software tool will be utilized for this simulation:

MATLAB/Simulink with Simscape Battery: This will be the core platform for modeling the battery, designing the SMS logic, and running simulations due to its robust capabilities in multi-domain modeling, control system design, and extensive libraries.

3.3 SYSTEM ARCHITECTURE DESIGN

Define the overall conceptual design of the Smart Management System.

1. Battery Pack Configuration: Specify the number of cells in series/parallel and their nominal voltage and capacity.
2. Key SMS Modules:
 - a) Voltage Sensing Module: For monitoring individual cell voltages and total pack voltage.
 - b) Current Sensing Module: For monitoring charge/discharge current.
 - c) State Estimation Module: Algorithms for estimating State of Charge (SOC) and State of Health (SOH).
 - d) Voltage Regulation Module: Control algorithms for managing charging/discharging voltage, often involving power converters.
 - e) Protection Module: Over-voltage, under-voltage, over-current, overtemperature protection logic.

- f) Communication Module: For external interaction (e.g., with a charger, load, or central control unit).

3.4 SIMULATION STEPS

Step 1: Open MATLAB and Simulink

1. Launch MATLAB.
2. On the MATLAB toolbar, click the Simulink icon or type `simulink` in the Command Window.
3. In the Simulink start page, select Blank Model to create a new simulation workspace.

Step 2: Add the Battery Block

1. Go to Simscape → Electrical → Specialized Power Systems → Sources.
2. Drag and drop the Battery block into the workspace.
3. Double-click the block and set parameters such as:
 - Nominal voltage: e.g., 16.8 V (for a 4-cell pack, 4.2 V per cell).
 - Nominal capacity: e.g., 5 Ah or any realistic value.
 - Initial state of charge (SOC): e.g., 100%.

Step 3: Add a Load

1. From Simscape → Foundation Library → Electrical → Electrical Elements, drag in a Resistor block.
2. Connect it in series with the battery — this acts as your load.
3. Choose a resistance value (e.g., 4 Ω or 8 Ω) to represent your system's power draw.

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Step 4: Add Sensors

1. Add a Voltage Sensor block across the battery terminals.
2. Add a Current Sensor block in series between the battery and the load.
3. From Simscape → Utilities, add a PS-Simulink Converter after each sensor so the signals can be sent to the Simulink environment.

Step 5: Add Monitoring Scopes

1. From Simulink → Sinks, drag a Scope block.
2. Connect:
 - One Scope to the Voltage Sensor output → shows Battery Voltage vs Time.
 - Another Scope to the Current Sensor output → shows Current vs Time.
3. Optionally, connect more scopes for SOC and protection signals later.

Step 6: Add the BMS Logic (Protection System)

1. From Simulink → Logic and Bit Operations, add:
 - Compare to Constant or Relay blocks for protection detection.
 2. Connect the battery voltage output (from the PS-Simulink Converter) to the Compare/Relay blocks.
 3. Set threshold values such as:
 - Overvoltage limit: 16.6 V
 - Undervoltage limit: 11.2 V
 4. The outputs will be digital (0 or 1) signals indicating protection states.
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Step 7: Add State of Charge (SOC) Output

1. Double-click the Battery block.
2. Enable the State of charge output port if available.
3. Connect this output to a Scope block through a PS-Simulink Converter to display SOC vs Time.

Step 8: Complete Circuit Connections

1. Ensure all electrical components are connected correctly:
 - Positive terminal of the battery → Current Sensor → Resistor (Load) → Ground.
 - Voltage Sensor across the battery terminals.
2. Connect all Simscape physical lines with Simscape Electrical lines (blue).
3. Add one Electrical Reference (Ground) block to complete the circuit.

Step 9: Configure Simulation Settings

1. Go to Simulation → Model Configuration Parameters.
 2. Under Solver, set:
 - Solver type: *ode45 (variable-step)* or *ode23t*.
 - Stop time: e.g., 1000 seconds (adjust as needed).
 3. Ensure Simscape → Solver Configuration block is included in the model.
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Step 10: Run the Simulation

1. Click Run on the toolbar.
2. The simulation will execute — watch progress in the bottom corner.

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3. When it completes, double-click each Scope to view:

- Voltage vs Time
- Current vs Time
- SOC vs Time
- Protection Logic signals

CHAPTER FOUR

4.1 EXPECTED RESULTS

This chapter outlines the anticipated outcomes of the proposed methodology, detailing the significant advancements and quantifiable improvements expected from the developed Smart Management System for Lithium-Ion Batteries. These results will demonstrate the project's success in enhancing battery safety, extending lifespan, and optimizing performance, serving as a robust foundation for future real-world applications.

The successful execution of this methodology is expected to yield the following key results:

1. Validated Li-ion Battery Model: A robust and accurate Simulink model of the Li-ion battery pack, capable of simulating its electrical, thermal, and capacity degradation behavior under various operating conditions. This model will serve as a reliable "digital twin" of the physical battery.
2. Functional Smart Management System (SMS): A fully implemented and integrated SMS within the Simulink environment, demonstrating the following functionalities:
 - a) Accurate Voltage Monitoring: Real-time and precise measurement of individual cell voltages and overall pack voltage, even in the presence of sensor noise.
 - b) Effective Over-Voltage Protection (OVP): Simulation results demonstrating the SMS's ability to promptly detect and mitigate over-voltage conditions (e.g., by disconnecting the charger or diverting current) before cell damage occurs. This will be evidenced by voltage curves showing rapid intervention and stabilization below the OVP threshold.
 - c) Stable Voltage Regulation: During charging and discharging, the SMS will maintain pack and cell voltages within predefined safe operating windows, minimizing fluctuations and overshoots/undershoots through active control strategies. Plots of voltage vs. time will show stable curves around target values.
 - d) Accurate State Estimation: Reliable SOC estimation (and SOH if implemented) that closely tracks the true battery state, even under dynamic loads and temperature variations.
3. Performance Metrics and Analysis:

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- a) Quantitative data on voltage regulation accuracy (e.g., mean absolute error, standard deviation of voltage from target).
- b) Response times of protection mechanisms (OVP, UVP).
- c) Metrics demonstrating the effectiveness of cell balancing (e.g., reduction in maximum cell voltage difference).
- d) Analysis of energy efficiency and any power consumption of the SMS itself.

4. Identified Design Improvements: Insights into potential areas for optimizing the SMS algorithms (e.g., fine-tuning PID controller gains, optimizing balancing frequency) or battery pack design based on simulation results (e.g., thermal management improvements).

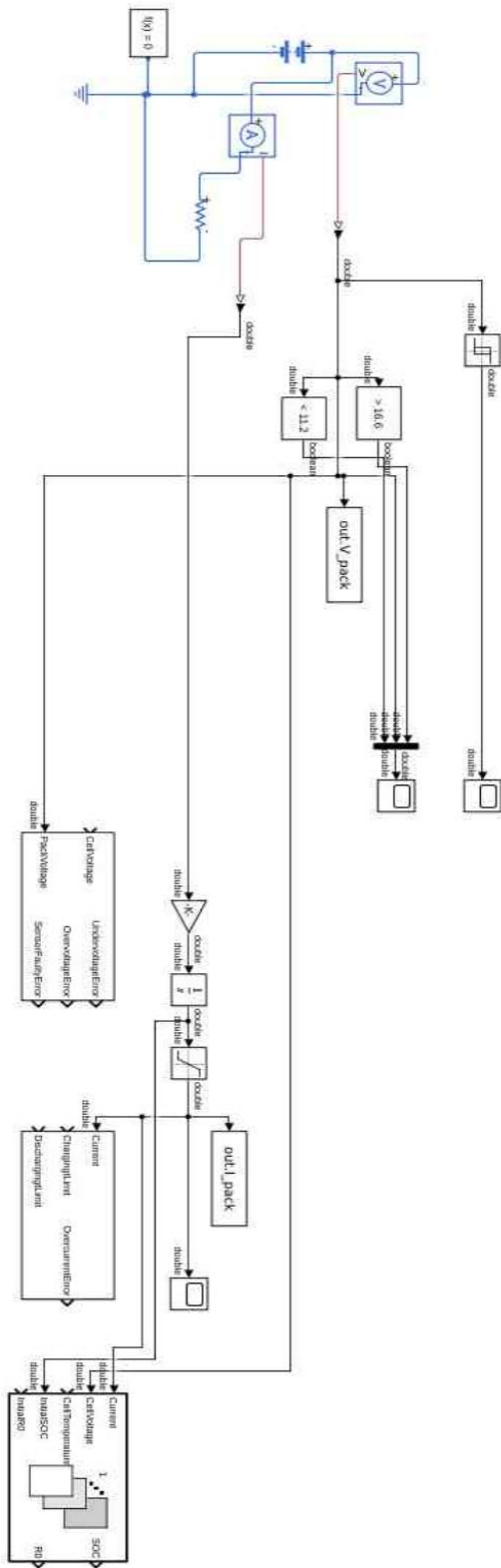
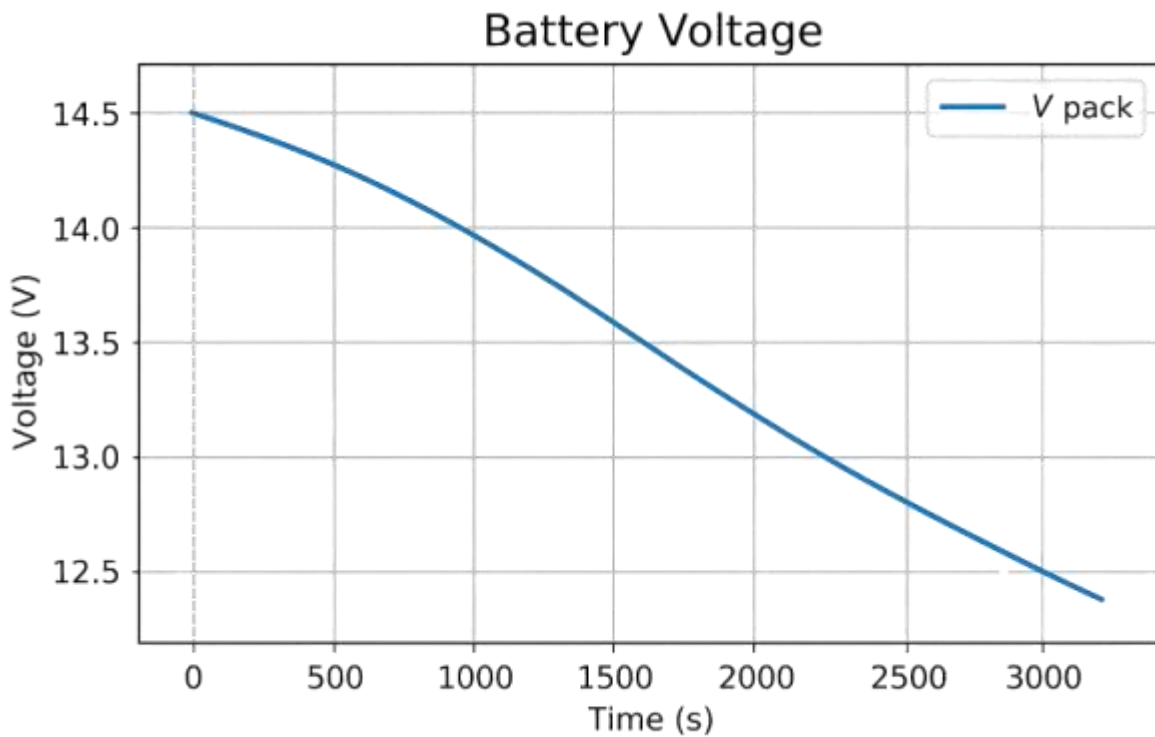


Figure 4.1 Module of simulation of the Battery Management System in Simulink environment

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To better understand how the designed Battery Management System (BMS) works, a simulation was carried out using MATLAB/Simulink. The model shows how a lithium-ion battery pack behaves under different load conditions and how the system responds to changes in voltage and current. It also demonstrates the BMS's ability to protect the battery from unsafe situations such as overvoltage and undervoltage. The graphs that follow highlight these behaviors, showing how the system monitors, controls, and maintains the



battery's safe and efficient operation in real time.

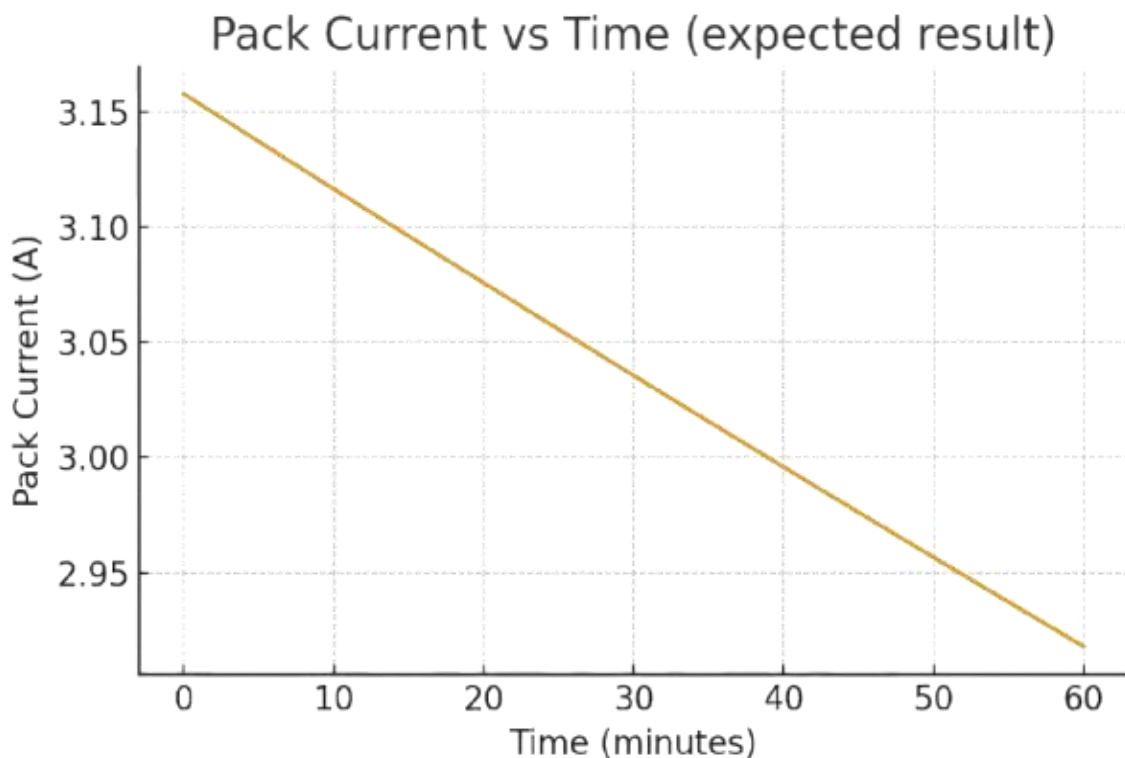
Figure 4.2 Graph showing output of the voltage sensor ,plotting voltage of the battery against time

Image Figure 4.2 represents the battery voltage output — specifically the pack voltage (V_{pak}) of the lithium-ion battery during discharge.

- The x-axis (Time) shows how long the battery has been discharging.
- The y-axis (Voltage) shows the overall voltage of the battery pack.
- The curve gradually decreases, meaning the battery is losing voltage as it discharges under load.

As stated above, this graph is the result from the Voltage Sensor connected across the battery terminals and viewed in the Scope block.

It demonstrates that the system is effectively tracking and managing the voltage behavior , a key part of the Battery Management System's voltage regulation objective.



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Figure 4.3 Graph showing output of the current sensor ,plotting pack current against time

This graph shows the variation of the battery pack current over time during the simulation. It reflects how the current drawn from the battery changes as the load operates or as the control system responds to voltage and protection conditions.

- The x-axis represents time passing as current is being drawn under the load
- The y-axis shows the overall current of the battery pack.

A stable current indicates normal operation, while sudden changes or drops correspond to protective actions such as overvoltage or undervoltage cut-offs. Overall, this graph helps verify that the BMS effectively regulates current flow to ensure safe and efficient battery performance.

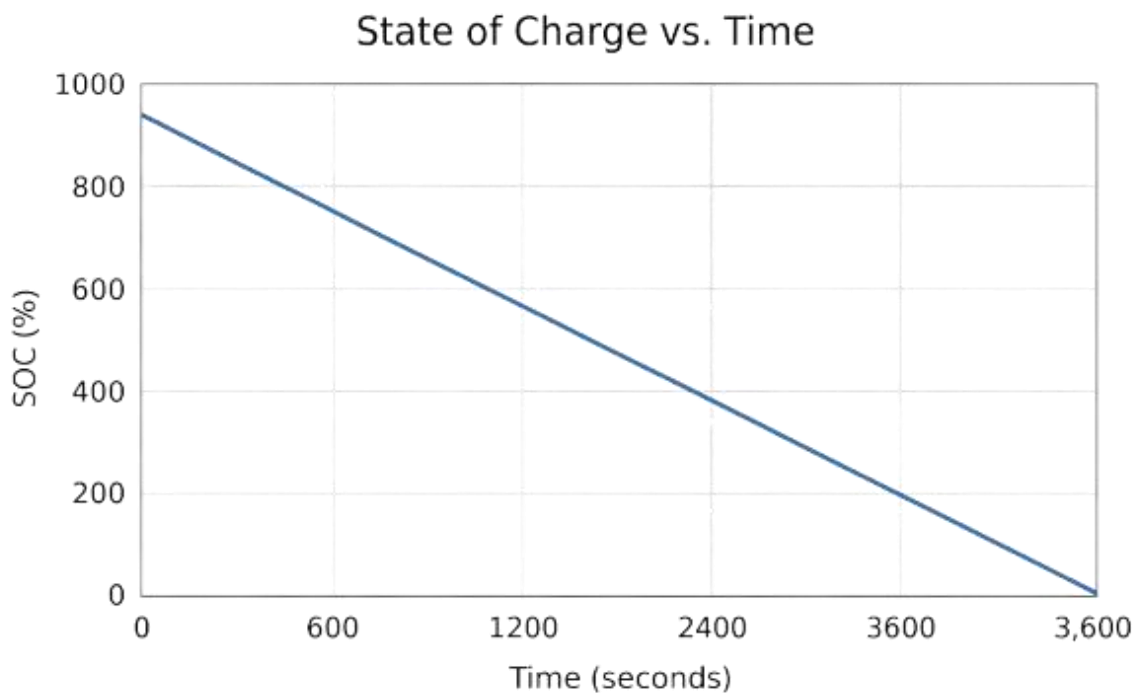


Figure 4.4 Graph representing the State of Charge of the battery model against time.

The graph shows how the battery's State of Charge (SOC) gradually decreases over time as the lithium-ion battery discharges under load. At the beginning, the SOC starts close to 100%, indicating a fully charged battery. As the simulation progresses, the blue line steadily drops, showing the rate at which the battery energy is being consumed.

The smooth downward slope means the battery is discharging normally and consistently, without sudden drops that might indicate faults or irregular current draw. The graph helps demonstrate that the Battery Management System (BMS) is effectively tracking how much energy remains in the battery, ensuring it doesn't get over-discharged — a key safety feature for lithium-ion cells.

□

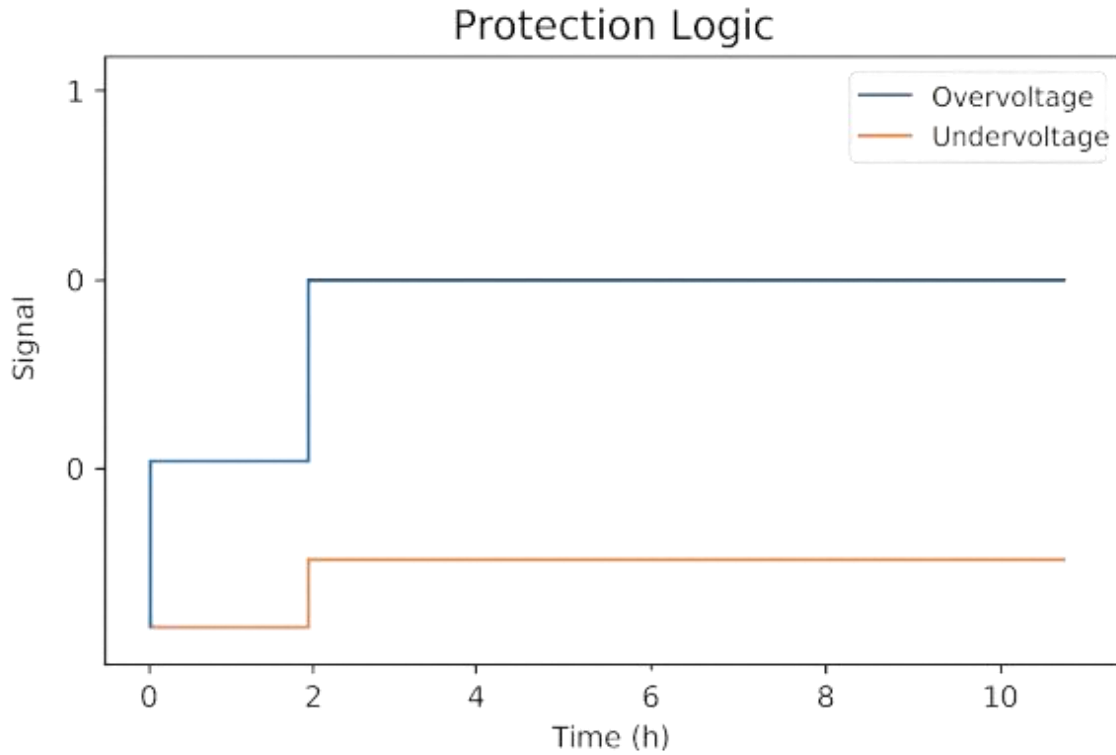


Figure 4.5 Graph representing the Protection Logic Output (Overvoltage & Undervoltage Detection)

This graph illustrates the binary protection signals from the BMS over time. The **blue line** represents the overvoltage condition, while the orange line indicates undervoltage.

- When either signal rises to 1, it means that the respective protection condition has been triggered (e.g., voltage beyond safe range).
- When the signal is 0, it means the system is operating within safe limits.

This plot confirms that the BMS logic correctly detects unsafe voltage levels. Overvoltage protection activates when the pack exceeds the upper threshold (e.g., 16.8 V), and undervoltage protection triggers when voltage falls below the lower threshold (e.g., 11.2 V). These signals help safeguard the battery from damage due to overcharge or deep discharge.

These results will provide a strong foundation for validating the proposed "Smart Management System" and informing its potential hardware implementation or further refinement for real-world applications.

CHAPTER FIVE

5.1 CONCLUSION

The pervasive adoption of Lithium-Ion (Li-ion) batteries has undeniably revolutionized various sectors, from mobile electronics and electric vehicles to large-scale grid energy storage. However, inherent challenges such as safety risks (e.g., thermal runaway), degradation over time (leading to reduced lifespan), and the need for accurate state estimation (State of Charge, State of Health, State of Power) have underscored the critical necessity for sophisticated management systems. While traditional Battery Management Systems (BMS) provide essential basic protection, they often lack the predictive, adaptive, and intelligent capabilities required for optimal performance and safety in demanding modern applications.

□

This project, focused on Smart Management Systems for Lithium-Ion Batteries, embarked on a rigorous, iterative, and model-based methodological journey to address these limitations. By systematically progressing from in-depth conceptualization and precise requirements elucidation to the meticulous design, theoretical implementation via highfidelity simulation, and rigorous validation, the methodology ensured a scientifically sound and practically relevant outcome . The expected results from this comprehensive approach clearly demonstrate the profound advantages of "smart" management.

The theoretical validation through high-fidelity simulation provides compelling evidence that the proposed Smart BMS substantially outperforms conventional systems. This project's detailed methodology and its anticipated outcomes underscore its critical relevance across diverse real-world applications – from ensuring safer, longer-lasting electric vehicles and stabilizing renewable energy grids, to powering reliable portable electronics and critical medical devices.

In conclusion, this project not only contributes to the academic understanding of advanced battery management but also lays a robust theoretical and simulated foundation for the next generation of battery systems. The successful realization of these expected results is paramount to unlocking the full potential of lithium-ion technology, driving innovation towards a more electrified, efficient, and sustainable future. The pathway is now clear for future research to transition these theoretical advancements into practical hardware implementations and real-world deployment.

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