Faculty of Engineering
Department of Electrical and Electronics Engineering

EE 401 FINAL REPORT

Fall 2024

BATTERY HEALTH AND PERFORMANCE MANAGEMENT SYSTEM FOR LITHIUM-ION BATTERIES

Submitted by

Seyit Kubilay Uluçay
S029261

Atahan Dikeç
S024983

Supervisor

Dr. Hamza Makhamreh

APPROVAL PAGE

Faculty of Engineering
Department of Electrical and Electronics Engineering

EE 401 FINAL REPORT

Fall 2024

Seyit Kubilay Uluçay
Atahan Dikeç

BATTERY HEALTH AND PERFORMANCE MANAGEMENT SYSTEM FOR LITHIUM-ION BATTERIES

Jury Members:

Supervisor	:	**Dr. Hamza Makhamreh**	________________________
Jury Member 1	:	**Asst. Prof. Umut Başaran**	________________________
Jury Member 2	:	**Prof. Dr. Çiğdem Eroğlu Erdem**	________________________

ABSTRACT

This report explores the study and development of a battery management system for lithium-ion batteries, which are widely used in electric vehicles, renewable energy storage, and portable electronics due to their high energy density and efficiency. A battery management system is essential for ensuring the safety, reliability, and performance of these batteries by monitoring critical parameters such as voltage, current, and temperature. It also plays a crucial role in balancing the cells to prevent issues like overcharging, overheating, and capacity loss.

The report reviews key methods for state estimation, including Coulomb Counting, Voltage Monitoring, and Kalman Filtering. These techniques were analyzed to understand their accuracy, complexity, and suitability for dynamic conditions. For cell balancing, both passive and active methods were compared. The proposed system design uses an STM32F409 Discovery Board for prototyping and includes key components like TMP36 temperature sensors, AD8418A current amplifiers, and a multiplexer to handle multiple data inputs. Voltage monitoring is achieved through buck converters that step down the pack voltage for ADC measurement.

While the design is in its early stages and does not yet include complete hardware implementation, it provides a solid base for future work. The next phase will focus on creating detailed circuit diagrams, running simulations, building a prototype, and testing the system under real-world conditions. This report explains the challenges of designing a battery management system and suggests ways to manage lithium-ion batteries effectively.

ACKNOWLEDGMENT

We would like to express our great appreciation to Dr. Hamza Makhamreh for his extensive efforts in making this project a success.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

ADC	Analog to Digital Converter
BMS	Battery Management System
DoD	Depth of Discharge
EKF	Extended Kalman Filterin
EoL	End of Life
EVs	Electric Vehicles
ICs	Integrated Circuits
MUX	Multiplexer
NTC	Negative Temperature Coefficient
OCV	Open Circuit Voltage
PTC	Positive Temperature Coefficient
RTD	Resistance Temperature Detector
SoC	State of Charge
SoH	State of Health

1 INTRODUCTION

As the demand for sustainable energy increases, Li-ion batteries have become essential for a variety of applications due to their high energy density, long lifespan, and efficiency. These batteries are widely used in EVs, renewable energy storage systems, and portable electronics [2,14,15]. However, issues such as overcharging, overheating, over-discharging, and imbalanced cells pose significant challenges, leading to safety risks, inefficiencies, and reduced battery lifespan [3, 15].

A Battery Management System (BMS) is essential for ensuring the safety, efficiency, and long life of Li-ion batteries. The BMS monitors important parameters like State of Charge (SoC) and State of Health (SoH) to improve performance and identify potential issues [16, 17]. It also performs cell balancing to make sure all cells have the same charge level. This can be done using passive methods, which waste extra energy, or active methods, which move energy between cells [1, 16, 18]. These functions are vital for preventing safety risks like thermal runaway, especially in large battery packs [15, 16].

Despite progress in BMS technology, challenges remain. Accurate SoC estimation during dynamic conditions, such as fast charging or high-power discharging, needs strong algorithms. Common methods like Coulomb Counting, Voltage-based approaches, and Kalman Filtering are widely used but have trade-offs in accuracy, complexity, and adaptability. [1, 7, 17].

Modern BMS designs are now including real-time fault detection features to improve system reliability and ensure the safety of EVs and other applications. [17]. Furthermore, advanced monitoring systems for Li-ion battery packs are increasingly recognized as essential for improving operational efficiency and extending battery life [19].

This report examines the challenges and advancements in Battery Management Systems for Li-ion batteries. It provides an in-depth review of voltage, current, and temperature measurement techniques, SoC and SoH estimation methods, cell balancing strategies, and safety mechanisms. Additionally, the report outlines a proposed BMS design, integrating insights from the literature to create a practical and cost-effective solution.

2 BATTERY MANAGEMENT SYSTEM OVERVIEW

Li-ion batteries are widely used today because they are efficient and can store a lot of energy. They are important for EVs, renewable energy systems, and many portable customer electronics. However, these batteries are sensitive to problems like overcharging, overheating, and over-discharging, which can cause safety risks and reduce their lifespan. To solve these problems, battery management systems are needed [2, 14, 15]. A simplified block diagram of a BMS is shown in Figure 1 and 2, showing the key components of BMS and how they interact to battery and manage the battery pack.

A BMS is a system that monitors and controls how the battery works to make sure it is safe and efficient. It checks important values such as voltage, current, and temperature to keep the battery working in safe conditions. The BMS also calculates the battery's SoC, which shows how much energy is left, and its SoH, which tells how much the battery has degraded over time [1, 17]. These functions help prevent dangerous situations like overheating, known as thermal runaway [17, 18].

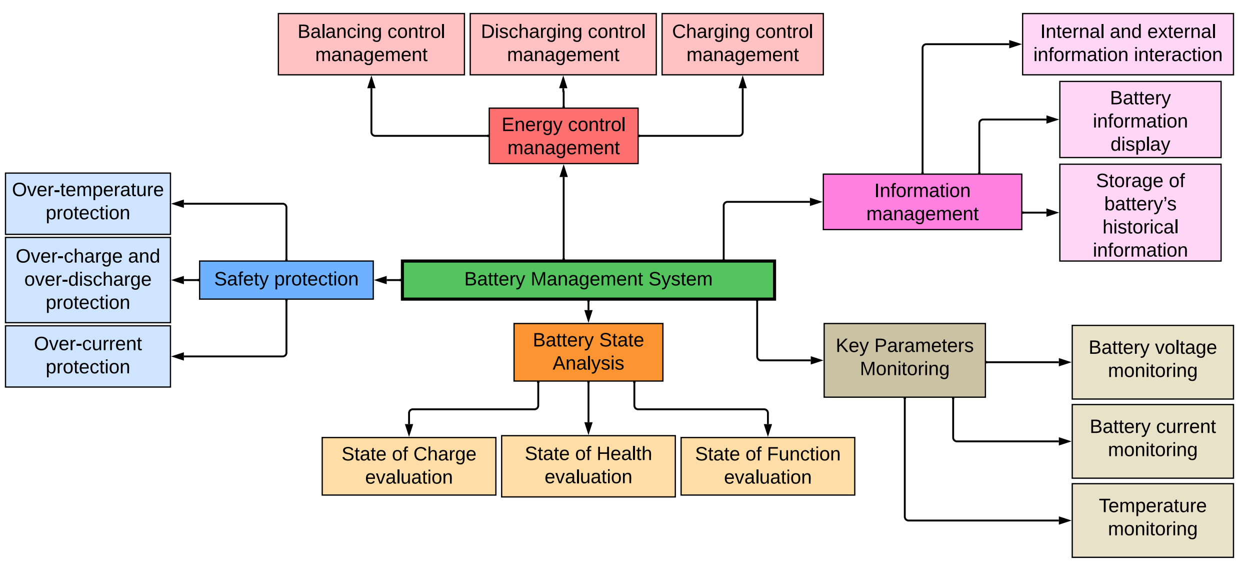


Figure 1: Specification of Battery Management System [1].

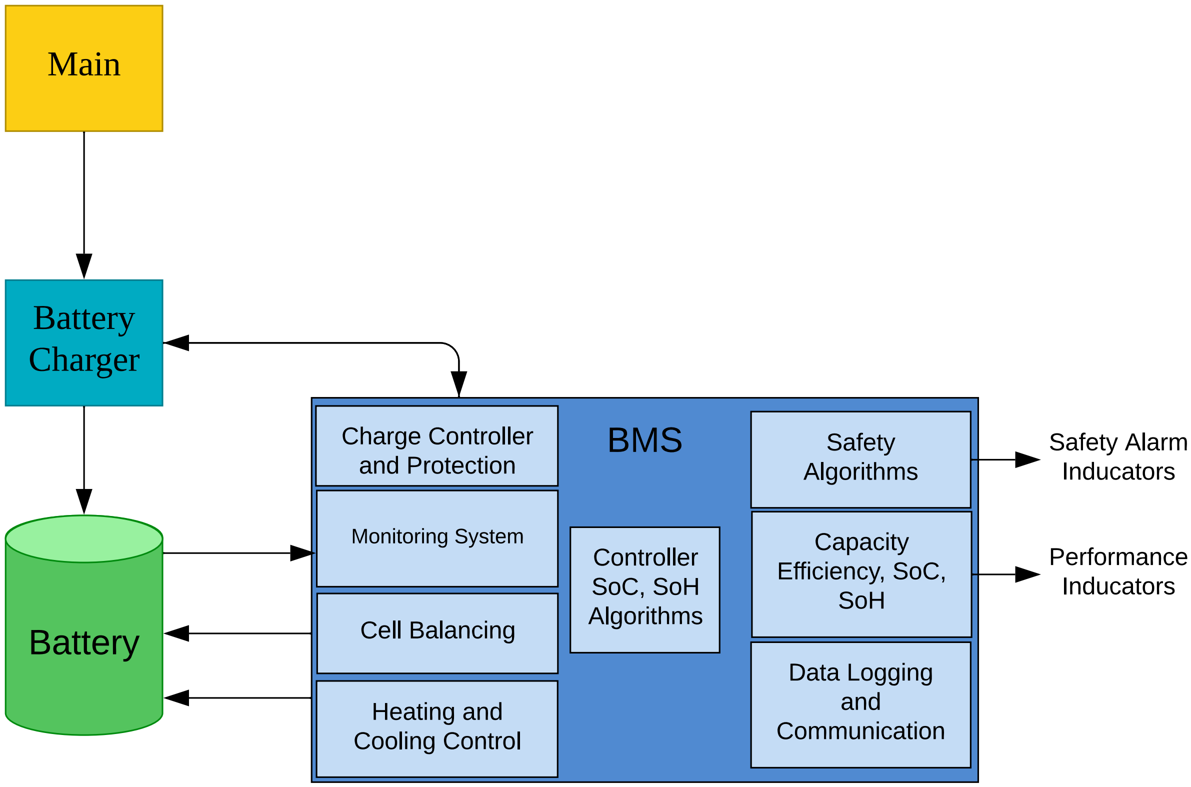


Figure 2: BMS Block Diagram [1].

Another important job of the BMS is to balance the charge between the battery cells. This is needed because some cells may hold more charge than others. Passive cell balancing wastes extra energy as heat, while active cell balancing moves energy from one cell to another to make them equal. Active balancing is often better for larger battery packs because it saves energy and helps the battery last longer [8, 16].

There are three types of BMS. Centralized BMS has all the controls in one place, which is simple and cheap for small systems. Modular BMS divides the battery into smaller units, each with its own control, which works better for bigger systems. Distributed BMS has each battery cell managed separately, giving the best accuracy, but it costs more and is mainly used in complex systems like EVs [20].

3 LITHIUM-ION BATTERIES

3.1 Safety Concerns:

The concept of functional safety is outlined by various standards, such as IEC 61508 and ISO 26262, which is specifically for the automotive industry. Functional safety is defined as "the part of the overall safety of a system or piece of equipment that depends on the system or equipment operating correctly in response to its inputs." A BMS must operate accurately based on its inputs to ensure battery safety [15].

In the context of a battery management system, hazard analysis is the process of identifying potential dangers that could arise from the system's failure to perform its functions correctly.

Common risks in battery management include failing to prevent overcharging, overdischarging, or overcurrent, exposure to very high or low temperatures, incorrect estimates of SoC and SoH, reduced battery capacity, and internal cell defects. All of these issues can harm both safety and performance. [15].

Overcharging of Li-ion cells begins when the cell voltage exceeds a value between 3.75V and 4.2V. Overdischarge refers to discharging a cell beyond 100% Depth of Discharge (DoD). If the overdischarge current is sufficiently high, the cell voltage decreases rapidly and may even reverse. The minimum allowable discharge voltages range from 1.8V to 2.5V per cell.

The lifespan of Li-ion cells varies from 300-800 cycles to tens of thousands of cycles, depending on whether the cells are optimized for high cycle life. Calendar life can range from a few years to 10 to 15 years for some cells.

Exposure to high temperatures not only accelerates cell degradation but may also lead to thermal runaway, a condition in which the activation temperature of various exothermic (heat-generating) chemical reactions inside the cells is reached. This rapid degradation results in a large release of energy, leading to cell venting, a temperature rise, fire, or explosion. The acceptable temperature range for most cells is such that degradation rates increase above 45°C to 55°C, and safety limits are reached between 60°C and 100°C. Most Li-ion cells experience limited performance, especially in charging capability, at low temperatures. Many cells recommend against charging below 0°C, though some permit low-rate charging down to -10°C [7].

Standard hazards in battery management can be categorized as follows:

- **Manufacturing Issues:** Microscopic metal particles can cause internal short circuits, leading to thermal runaway.
- **Design Limitations:** Ultra-thin separators in high-energy cells are more prone to defects and overheating.
- **Stress Events:** Overcharging, freezing temperatures, or vibrations can increase the likelihood of failure.
- **External Factors:** Incorrect handling, such as charging at extreme temperatures or storing fully discharged cells, increases the risks.

Guidelines for safely using Li-ion batteries include the following:

1. A malfunctioning Li-ion battery may start to hiss, swell, and leak electrolyte.
2. The electrolyte, consisting of Li salt in an organic solvent (lithium hexafluorophosphate), is highly flammable. Burning electrolyte can ignite nearby combustible materials.
3. Use water or a regular fire extinguisher to extinguish a Li-ion battery fire. However, a Class D fire extinguisher should be used specifically for lithium-metal fires, as water can react with lithium. (Li-ion batteries contain only a small amount of lithium metal that reacts with water).
4. If a Class D extinguisher is not available, use water to contain a lithium-metal fire and prevent it from spreading.
5. To achieve the best results in extinguishing a Li-ion fire, use a foam extinguisher, CO2, ABC dry chemical, powdered graphite, copper powder, or soda (sodium carbonate). These are used similarly to extinguish other types of combustible fires. Class D extinguishers should be kept for lithium-metal fires only.
6. If it is impossible to extinguish a burning Li-ion battery, allow the pack to burn in a safe and controlled environment.

7. Be aware of cell propagation, as each cell may catch fire at different intervals when exposed to heat. Keep a seemingly extinguished pack outdoors for a period to ensure complete safety [15].

3.2 Charging/Discharging States

In the case of Li-ion batteries being charged over time; the voltage and current changes in the battery cells in the constant current charge, saturation charge, ready and standby stages can be seen in the table below.

In the Figure 3 and in the first stage, the voltage value increases in direct proportion to time, while the current is seen to be constant one ampere until the saturation stage. During the saturation process, the voltage has peaked and the current decreases inversely proportional to time. In the charge terminates stage, where there is no current, the voltage is seen to drop slightly and then increase again.

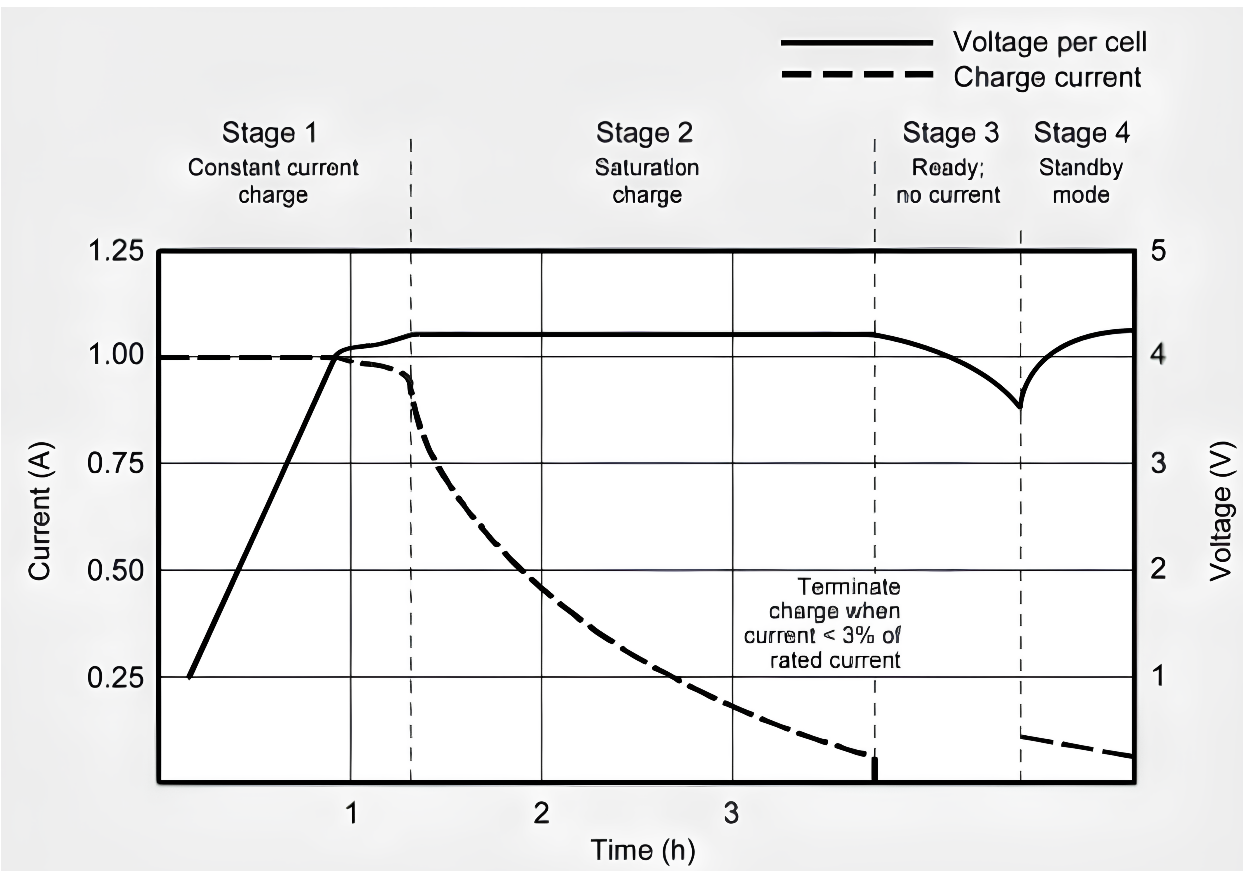


Figure 3: Charge Stages of Li-ion [2].

In the Figure 4 below, how the current and voltage changes behave when the battery is being charged can be seen with 1C charge rate. In addition, how the battery's charge capacity changes and the change in charge current are observed as a percentage.

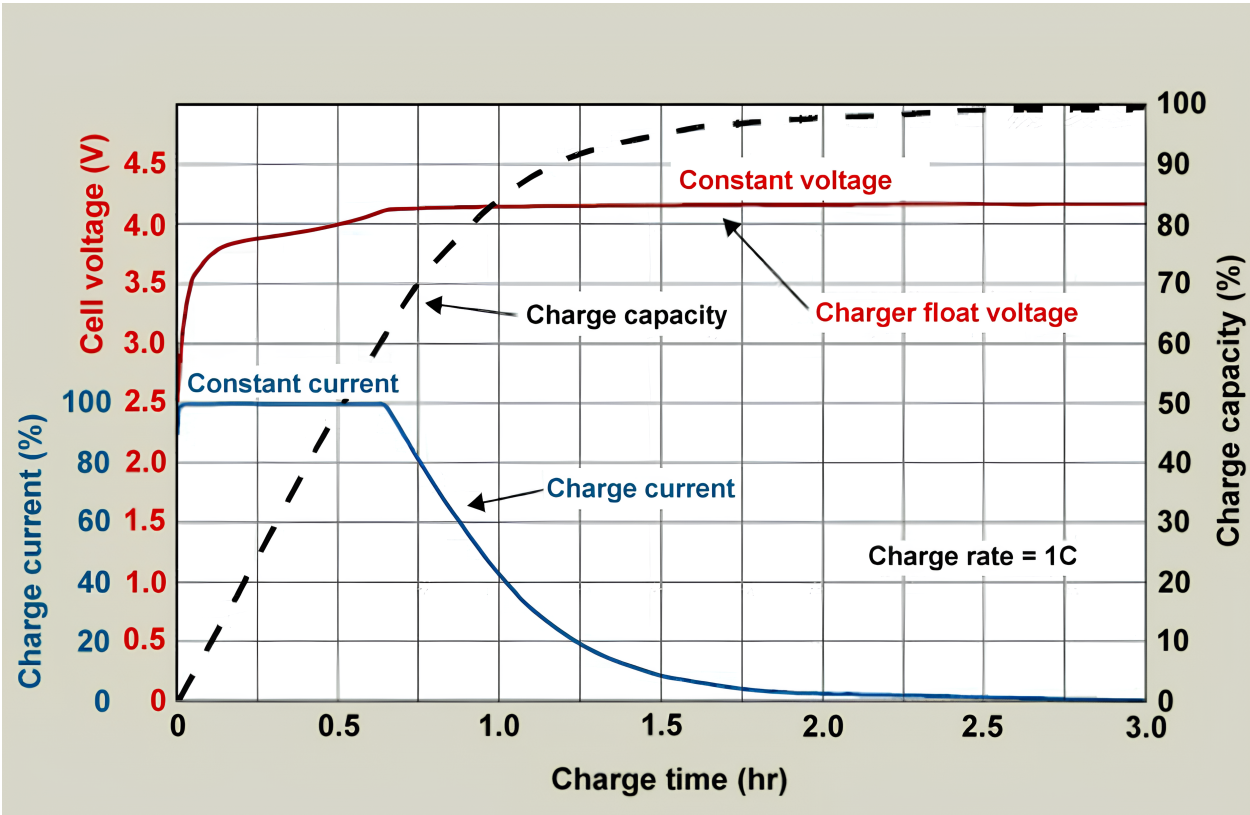


Figure 4: Volts/Capacity vs. time when charging the battery [2].

Sample Guidelines for Discharging Batteries:

1. Heat increases battery performance but reduces its lifespan by half for every 10°C rise above 25–30°C (18°F above 77–86°F). Therefore, always aim to keep the battery cool.
2. Avoid over-discharging, as cell reversal can lead to electrical failure.
3. To reduce stress on the battery during high-load and repetitive full discharges, opt for a larger battery.
4. A moderate DC discharge is preferable for battery health compared to pulse or heavy instantaneous loads.
5. When discharging at high frequencies, a battery behaves like a capacitor, allowing for higher peak currents than would be possible with a DC load.

6. Nickel and lithium-based batteries exhibit fast chemical reactions, while lead-acid batteries are slower and need a few seconds to recover between heavy loads.

7. All batteries experience stress when pushed to their maximum allowable limits [3].

3.3 Energy Cell and Power Cell

Early Li-ion batteries were once seen as fragile and not suitable for high-demand applications. However, this view has changed over time, and today lithium-based systems are as reliable as the stronger nickel and lead-based batteries. Two main types of Li-ion batteries have been developed: the Energy Cell and the Power Cell.

The performance of these two types is determined by their energy storage capacity, often referred to as capacity, and their ability to deliver current, also known as loading or power.

The Li-ion Energy Cell is designed to provide maximum capacity, offering extended runtimes. A notable example is the Panasonic NCR1865B Energy Cell, which has a high capacity but is less durable when discharged at 2C. At a discharge cutoff of 3.0V per cell, the 2C discharge yields approximately 2.3Ah, which is lower than the specified 3.2Ah. This type of cell is ideal for light applications like portable computing. For instance, the 3,200mAh Energy Cell is tested at discharge rates of 0.2C, 0.5C, 1C, and 2C. The circle at the 3.0V per cell line represents the end-of-discharge point at 2C [3].

Discharge characteristics (mAh) of Li-ion energy cell is shown in the Figure 5.

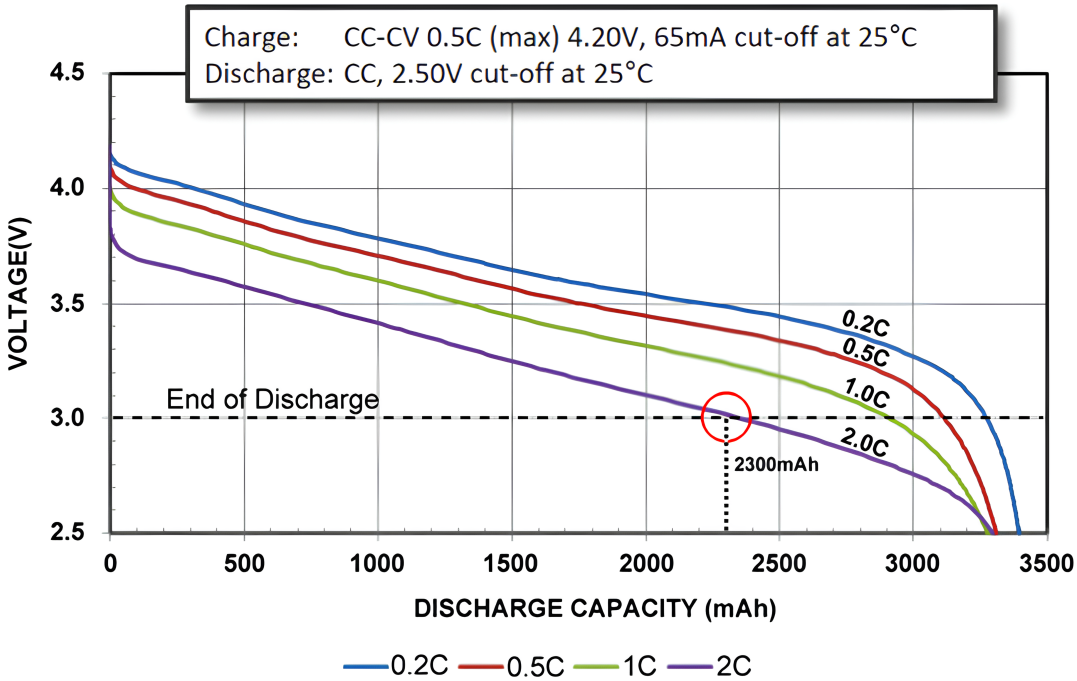


Figure 5: Discharge characteristics of energy cell [3].

The Panasonic UR18650RX Power Cell, shown in Figure 6, serves as an example of a cell with moderate capacity but outstanding load-handling capabilities. A 10A (5C) discharge shows minimal capacity loss at the 3.0V cutoff voltage. This cell performs well in applications that require heavy load currents, such as power tools.

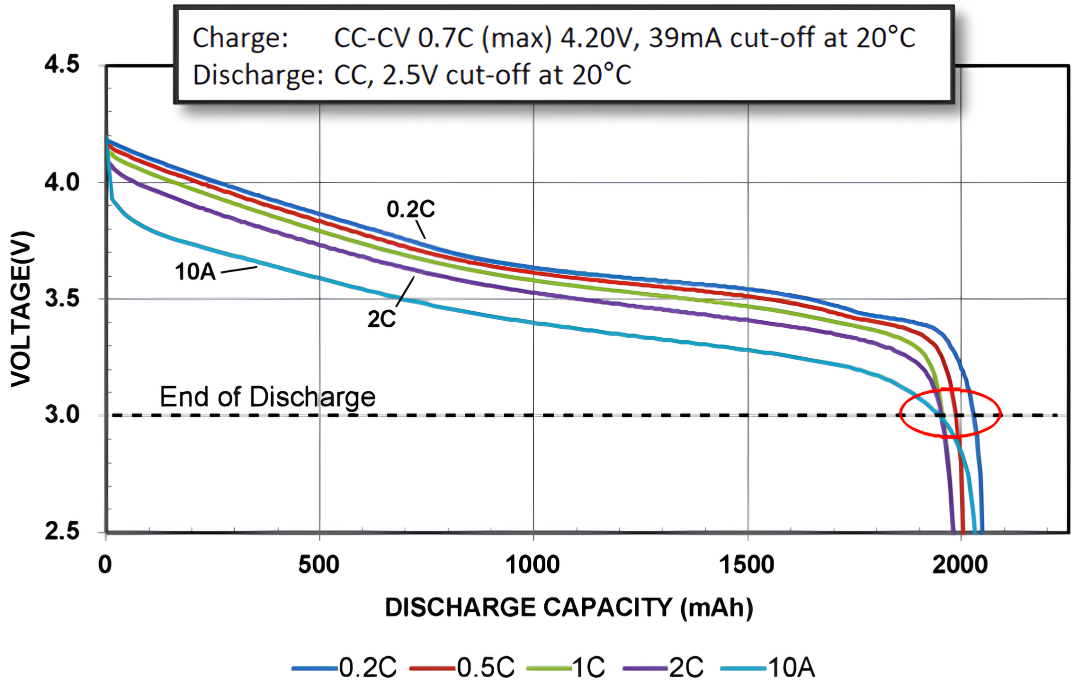


Figure 6: Discharge characteristics of energy cell [3].

The 1950mAh Power Cell is tested at discharge rates of 0.2C, 0.5C, 1C, 2C, and 10A, and all tests reach the 3.0V per cell cutoff point at around 2000mAh. The Power Cell, while having a moderate capacity, is capable of delivering high current.

The Figure 7 below examines the number of full cycles a Li-ion Energy Cell can endure when discharged at different C-rates. At a 2C discharge, the battery exhibits far higher stress than at 1C, limiting the cycle count to about 450 before the capacity drops to half the level [3].

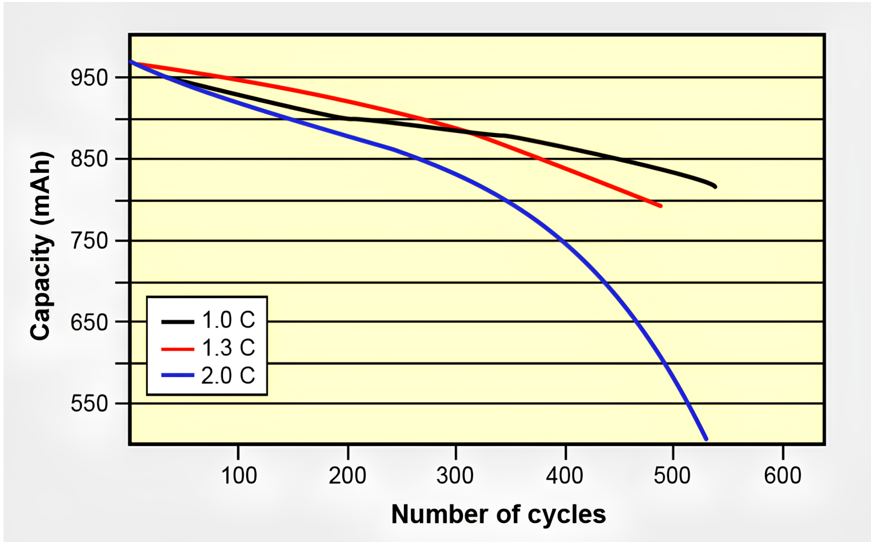


Figure 7: Cycle life of Li-ion energy cell at varying discharge levels [3].

3.4 Battery Capacity and Backup Safety

Spare capacity refers to the portion of a battery's total capacity that remains unused during normal operation. This reserved capacity is crucial for extending battery life, improving system reliability, and providing a buffer for emergency situations. By limiting full charge and discharge cycles, spare capacity reduces battery stress and slows degradation over time.

Spare capacity should be calculated based on worst-case scenarios. As demonstrated in Figure 8, the allowable capacity range is typically 80-100 percent, with a recommended spare capacity of 20 percent for critical applications. More reserve capacity should be allocated when operating at cold temperatures [4].

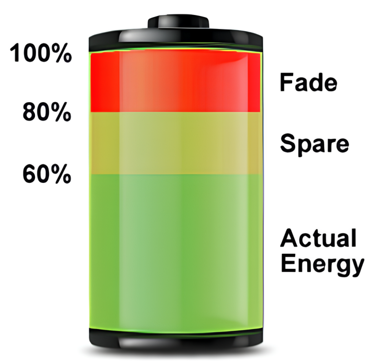


Figure 8: Calculating spare battery [4].

4 METRIC MEASUREMENTS

The BMS is very important for keeping Li-ion batteries safe, efficient, and long-lasting. This section explains the main tasks of a BMS, such as monitoring key values like voltage, current, and temperature. These values are used to estimate important states like the SoC, balance the cells, and detect faults. Each of these tasks is important to make sure the battery works well and stays reliable.

4.1 Monitoring Voltage

Voltage monitoring is one of the most important tasks of a BMS. It helps keep the battery pack safe by checking for problems like overcharging, over-discharging, and differences in voltage between cells. If these problems are not detected, they can cause the battery to perform poorly, overheat, or even fail completely.

There are two main types of voltage measurement in a BMS: individual cell and pack-level. Both types play important roles in ensuring the safety and performance of Li-ion batteries. [1, 7]

- **Cell-Level Voltage Measurement:**
  Individual cell voltage measurement is important for maintaining cell balance and identifying weak or faulty cells. Wires connect each cell to a multiplexer, which sends the voltage data to an ADC as shown in the Figure 9. The ADC converts the analog voltage into digital data that the BMS can read.

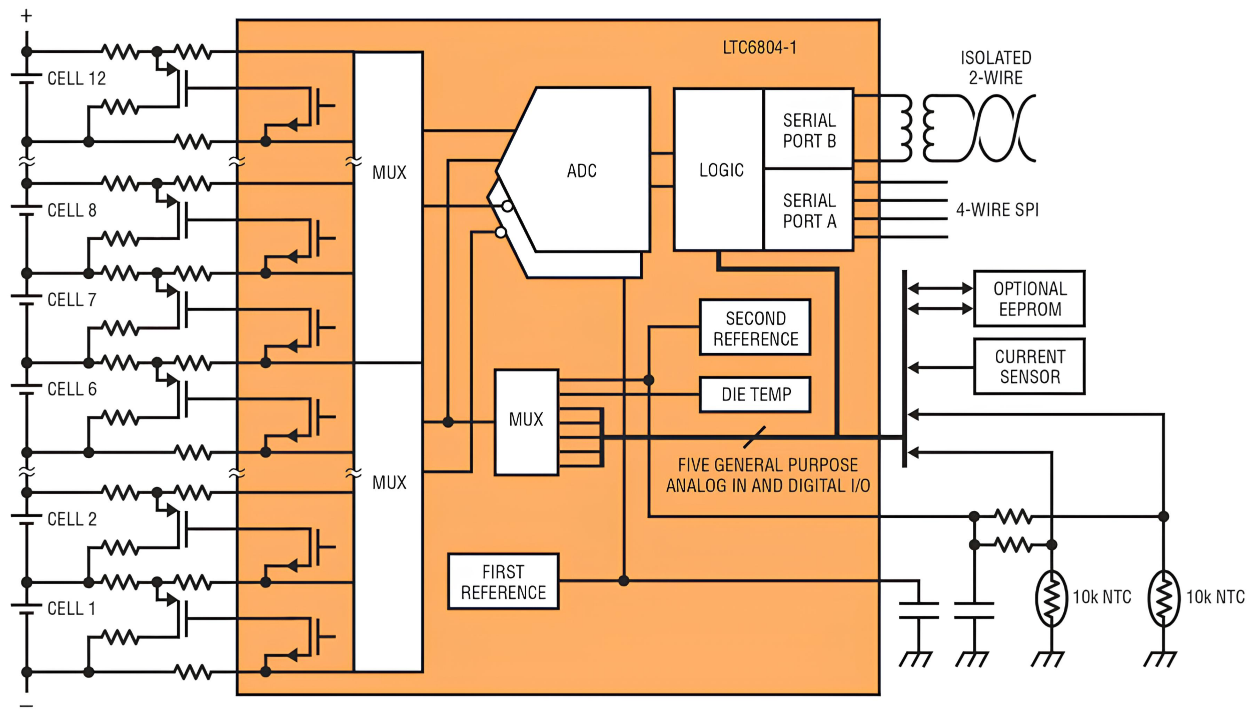


Figure 9: Cell Connection to Multiplexer. [5].

- **Pack-Level Voltage Measurement:**

  Pack-level measurement focuses on the total voltage across the entire battery pack. While this method is simpler and less costly, it does not provide detailed information about individual cells, making it suitable for small or less critical systems [7, 17]

4.2 Methods for Measuring Voltage

Different methods for measuring voltage in a BMS are designed to ensure accurate and reliable monitoring of the battery pack.

- **Analog-to-Digital Converters:** ADCs are most commonly used for digitizing voltage data. They provide high-speed and accurate measurements essential for real-time monitoring [1], one of the example is shown in Figure 9.

- **Differential Operational Amplifiers:** Differential amplifiers can measure the voltage difference between two points while ignoring common noise, making them ideal for applications with series-connected cells and high common-mode voltages [1].

- **Integrated Circuits:** Specialized ICs, such as LTC6804, are designed for high-precision voltage monitoring. They integrate multiple features, including voltage, temperature, or current detection all in one while reducing the complexity of the circuit [21].

Table 1 compares voltage measurement methods based on accuracy, cost, complexity, ease of use, and their application scenarios. The comparison includes the methods previously explained, highlighting their strengths and limitations in different contexts.

Table 1: Comparison of Voltage Measurement Methods.

Method	**Accuracy**	**Cost**	**Complexity**	**Ease of Use**	**Applications**
Analog-to-Digital Converters (ADCs)	High	Moderate	Moderate	High	Real-time monitoring
Differential Operational Amplifiers	Very High	High	High	Moderate	Series-connected cells
Integrated Circuits (ICs)	Very High	Variable	Low	High	High-precision systems

4.3 Monitoring Current

Monitoring current is just as important as monitoring voltage because it tracks the energy moving into and out of the battery pack. This information is crucial for calculating the SoC and detecting unusual situations, like overcurrent or short circuits [1, 7].

4.4 Methods for Measuring Current

There are different types of current measurement methods used in a BMS, each designed for specific applications. These methods ensure accurate and reliable monitoring, which is essential for managing the battery's performance and safety.

- **Shunt Resistors:**
  Shunt resistors are a common method for measuring current. Works by measuring the voltage drop across a small resistor placed in series with the current path. This method is accurate and affordable but generates heat, especially in high-current systems. Shunt resistor diagram is shown in the Figure 10 [6, 7]

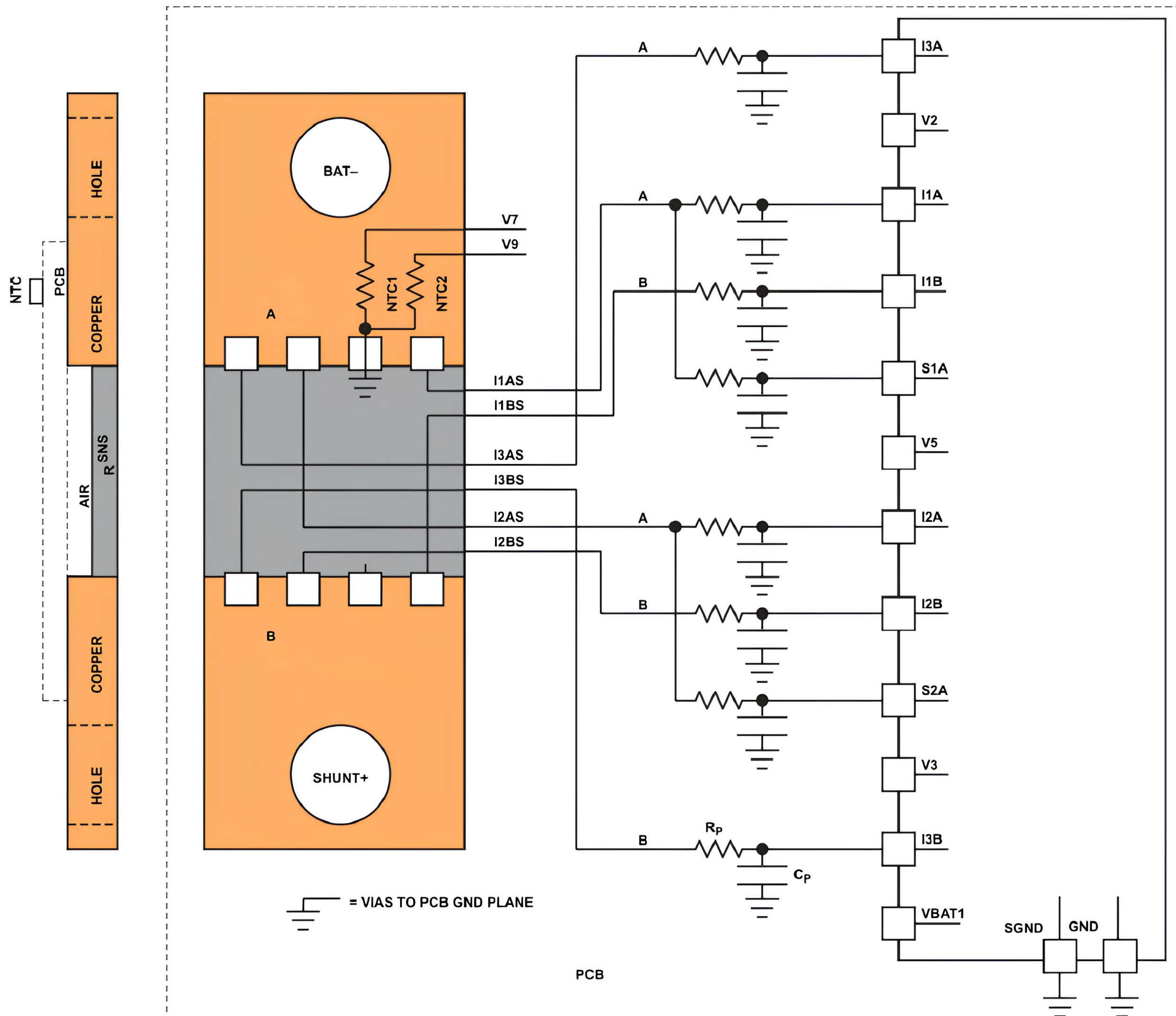


Figure 10: Shunt Resistor Diagram [6].

Amplifiers enhance weak signals from the shunt resistor or Hall-effect sensor, allowing the ADC to process the data more effectively [7].

- **Hall-Effect Sensors:**
  Hall-effect sensors work by measuring the magnetic field produced by an electric current and turning it into a voltage signal that matches the current level. These sensors are non-invasive, meaning they don't interfere with the current flow, which makes them a great choice for high-current systems. However, they tend to be a bit less precise and more costly compared to shunt resistors. [7].

To improve accuracy, current measurement systems often use filters to reduce electrical noise. This method ensures that the signals reaching the ADC are cleaner and more reliable, allowing for precise current measurements even in noisy environments [1, 7, 17].

Table 2 compares current measurement methods based on accuracy, cost, complexity, ease of use, and their application scenarios. The comparison includes the methods previously explained, highlighting their strengths and limitations in different contexts.

Table 2: Comparison of Current Measurement Methods.

Method	**Accuracy**	**Cost**	**Complexity**	**Ease of Use**	**Applications**
Shunt Resistors	High	Low	Low	High	Low-to-medium current systems
Hall-Effect Sensors	Moderate	Moderate	Moderate	High	High-current applications

4.5 Monitoring Temperature

Monitoring temperature is one of the most important tasks in a BMS because Li-ion batteries are highly sensitive to temperature changes. Excessive heat can cause thermal runaway, a dangerous condition where the battery overheats uncontrollably, potentially leading to fires. Low temperatures, on the other hand, reduce the efficiency and capacity of the battery and performance [1].
By tracking temperature, the BMS can ensure the battery operates in safe range, which is typically between -0°C and -10°C on the low end and +45°C to +65°C on the high end. The measured data helps the BMS manage cooling and heating systems to prevent overheating or freezing. Additionally, temperature data can be used to adjust charging and discharging rates, ensuring optimal performance and extending the battery's lifespan [5, 7].

4.6 Methods for Measuring Temperature

There are several methods to monitor temperature in Li-ion batteries, each using different types of sensors that are chosen based on accuracy, cost, and application.

- **Thermistors:**
  These are temperature-sensitive resistors widely used in BMS designs for monitoring temperature. Thermistors change their resistance as the temperature changes, allowing precise measurements. There are two main types of thermistors: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC) [22].

- **NTC Thermistors:** NTC Thermistors have a resistance that decreases as the temperature increases, as shown in the Figure 11. NTC thermistors are commonly used in BMS systems due to their high sensitivity and wide operating temperature range. They are ideal for applications requiring precise temperature control, such as preventing battery overheating.
- **PTC Thermistors**: PTC Thermistors have a resistance that increases as the temperature rises, a complete reverse version of NTC. PTC thermistors are often used for overcurrent protection or as temperature sensors in applications where a rapid response to temperature increase is needed.

Both types of thermistors are compact, cost-effective, and easy to integrate into BMS systems, making them a popular choice for temperature monitoring [7, 22].

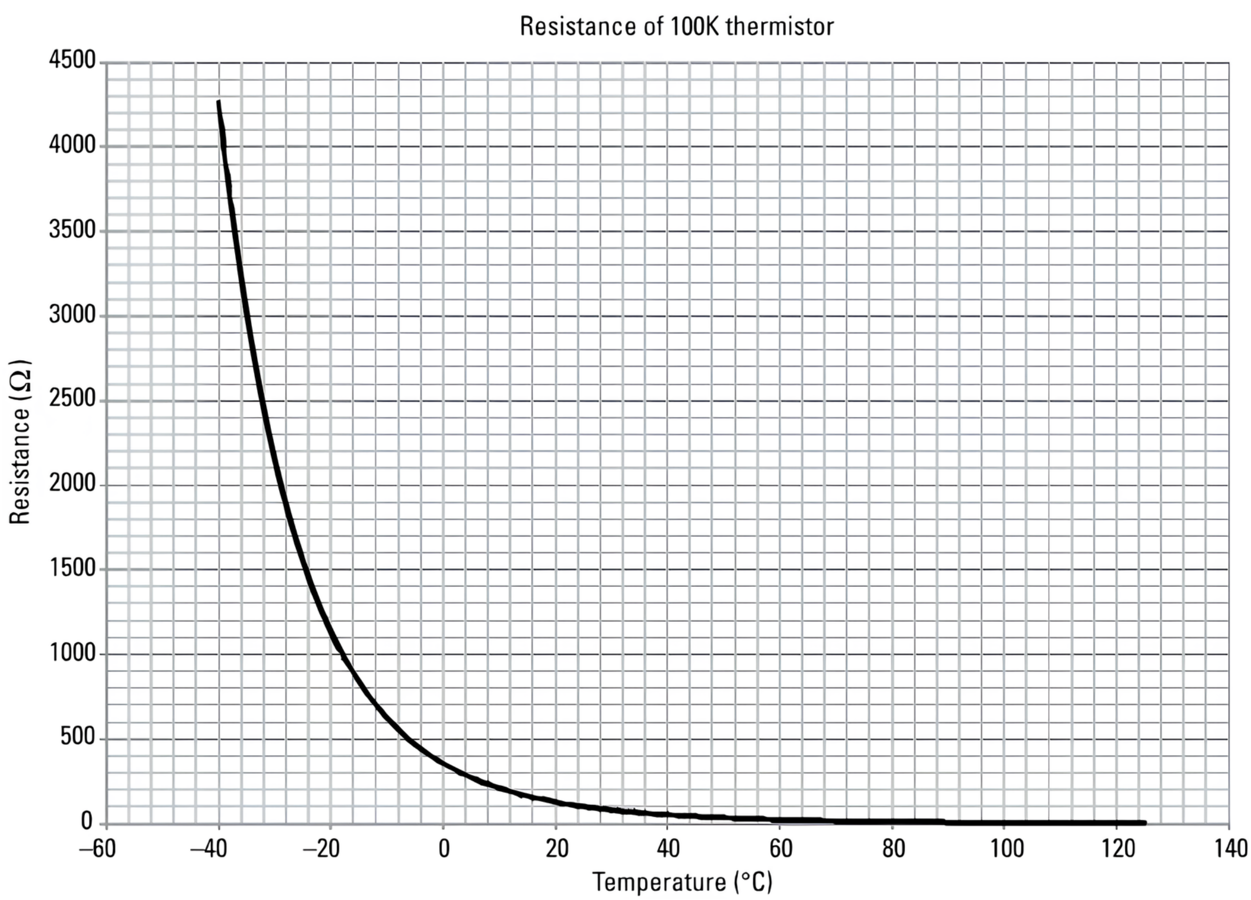


Figure 11: Thermistors vs. Temperature Relation [7].

- **Resistance Temperature Detectors:**

RTDs measure temperature by changing resistance in response to temperature changes. Even though both RTDs and thermistors operate by this principle, there are important differences between the two methods. RTDs are made of pure metals, such as platinum, which provide higher accuracy and stability over a wide temperature range, typically from -200°C to 850°C. This makes them more suitable for high-end applications like EVs. However, RTDs are more expensive and require additional circuits, such as amplifiers, to process their signals effectively. Despite these challenges, their reliability and precision make them valuable in systems needing high accuracy. [23].

- **Infrared Sensors:**

  Infrared sensors measure surface temperature without physical contact, making them ideal for sealed battery packs. However, they are more expensive and can be sensitive to environmental interference [24].

Table 3 compares temperature measurement methods based on accuracy, cost, complexity, ease of use, and their application scenarios. The comparison includes the methods previously explained, highlighting their strengths and limitations in different contexts.

Table 3: Comparison of Temperature Measurement Methods.

Method	**Accuracy**	**Cost**	**Complexity**	**Ease of Use**	**Applications**
Thermistors	Moderate	Low	Low	High	General BMS systems
RTDs (Resistance Temperature Detectors)	High	High	Moderate	Moderate	High-end applications
Infrared Sensors	High	High	Moderate	High	Sealed or hard-to-access packs

Monitoring voltage, current, and temperature is very important for a BMS. These measurements show the battery's condition and help it work safely and efficiently. Using sensors and methods, the BMS protects the battery, improves its performance, and makes it last longer. This is essential for modern systems like EVs, renewable energy storage, and customer electronics [7].

5 State Estimation

State estimation is one of the most important functions of a BMS as it provides important information about the battery's condition and performance. Understanding these metrics helps prevent damage caused by overcharging, deep discharging, self discharging and excessive cycling, which can lead to reduced efficiency and capacity loss. This section discusses the main state estimation metrics, such as SoC, SoH, DoD, and EoL, with the methods used to determine them. Accurate state estimation is important in applications like EVs and renewable energy systems, where variations in load and temperature significantly affect battery performance and lifespan [7, 25].

5.1 State of Charge

The SoC represents the amount of energy remaining in a battery as a percentage of its total capacity. SoC is important for managing the charging and discharging processes to prevent overcharging and over-discharging, both of which can lead to battery damage and reduced lifespan. It is a critical parameter in energy management systems for EVs, renewable energy storage, and portable electronics [1, 7]. SoC is formulated in various forms in different publications, depending on the application and the estimation methods used.

One common method for estimating SoC is Coulomb Counting, which calculates the state of charge by integrating the current entering and leaving the battery over time [26, 27].

5.2 Coulomb Counting Method

The Coulomb Counting Method is a widely used technique for estimating the SoC of a battery. It calculates the SoC by integrating the current flowing in and out of the battery over time, providing real-time insights into the remaining capacity. This method is valued for its simplicity and compatibility with various applications, such as EVs and renewable energy systems [27].

5.2.1 Cumulative Capacity Change

The cumulative capacity change between two time points, t_1 and t_2, is calculated using the Equation 1 [1]:

$$Q_{t_1}^{t_2} = \int_{t_1}^{t_2} i(\tau)\, d\tau \tag{1}$$

Here:

- $Q_{t_1}^{t_2}$: Cumulative capacity change from t_1 to t_2,
- $i(\tau)$: Current at time τ,
- τ: Time variable.

The current, $i(\tau)$, determines whether the battery is charging or discharging:

- $i(\tau) > 0$: The battery is discharging.
- $i(\tau) < 0$: The battery is charging.

Cumulative Capacity Change is important for the Coulomb Counting Method as it calculates the energy exchange during a specific interval, forming the base for SoC updates [1].

5.2.2 SoC Update

Using the cumulative capacity change, the SoC at time t_2 is updated as in Equation 2 [1]:

$$Q_{t_2} = Q_{t_1} - Q_{t_1}^{t_2} \tag{2}$$

Here:

- Q_{t_2}: SoC at time t_2,
- Q_{t_1}: SoC at time t_1.

Equation 2 adjusts the SoC by accounting for the net energy flow:

- If $Q_{t_1}^{t_2} > 0$: The battery has discharged more energy than it has charged, reducing SoC.
- If $Q_{t_1}^{t_2} < 0$: The battery has charged more energy than it has discharged, increasing SoC.

SoC update ensures that the SoC shows the current energy state of the battery in real time [1].

5.2.3 Proportional SoC Calculation

Proportional SoC calculation expresses the SoC as a percentage of the total capacity, the Equation 3 is used [7]:

$$SoC = \frac{Q_{\text{current}}}{C} \times 100 \tag{3}$$

Here:

- Q_{current}: Remaining capacity of the battery,
- C: Nominal total capacity of the battery.

This Equation simplifies communication of the battery's state. For example, an SoC of 80% indicates that 80% of the battery's total capacity remains available [27].

Coulomb Counting method is simple and works well for real-time SoC monitoring, but it has some problems, like needing accurate starting values and errors that build up over time. These issues are often fixed by adding other methods, like using Open Circuit Voltage recalibration or adjusting for temperature [1, 7].

5.3 Voltage Method

The Voltage Method is a straightforward approach to estimate the SoC of a battery. It involves measuring the battery's voltage and comparing it to a pre-determined curve that shows how the voltage changes with the SoC. This curve is developed through controlled tests and is specific to the type of battery being used. By matching the measured voltage to the curve, the remaining charge in the battery can be estimated [26].

However, the accuracy of this method can be affected by factors like the current flowing through the battery and the temperature. For example, when a battery is charging or discharging, its voltage can shift due to internal resistance. To address this, corrections are made based on the current. Additionally, the impact of temperature is accounted for by using a reference table that shows how the battery's open-circuit voltage (OCV) varies with temperature. These adjustments help improve the method's accuracy, especially under different operating conditions [18, 26].

Despite its simplicity, the Voltage Method has some limitations. One key issue is that voltage can change rapidly with current and temperature, making it difficult to obtain stable readings in

real-time systems, such as EVs. Another drawback is that this method often requires a controlled discharge and recharge process, which is time-consuming and interrupts normal operation. This makes it unsuitable for applications that need continuous monitoring [1,26].
Due to these challenges, the Voltage Method is not widely used in dynamic systems. Instead, it is typically employed during battery testing to create discharge curves or in backup systems where the battery operates under steady conditions. While it is not ideal for real-time applications, it remains a useful tool for understanding basic battery behavior and can be combined with other techniques, such as Coulomb Counting, to enhance accuracy [1].

5.4 Kalman Filtering for SoC Estimation

Kalman Filtering is a mathematical technique developed in 1960 by Rudolf E. Kálmán to estimate the state of a dynamic system from noisy and incomplete measurements. It provides an optimal solution to the problem of predicting, updating, and correcting the state of a system in real-time. Originally designed for aerospace applications like navigation and control systems, it has since been adapted for various fields, including robotics, economics, and BMS [7].
Kalman Filtering was created to overcome the challenges of traditional estimation methods, which often had difficulty dealing with uncertainties and noise in real-time systems. Kalman Filtering provides several advantages:

- **Dynamic State Estimation:** Tracks changing variables over time.
- **Noise Management:** Handles uncertainties in both the system model and sensor measurements.
- **Real-Time Operation:** Processes data sequentially, making it suitable for systems like EVs and drones.

5.4.1 Formulation

Kalman Filtering consists of two main steps, prediction and update. In each step, specific equations are used to estimate the system's state, such as the SoC, and improve the estimate over time as new measurements are collected. This process allows the filter to continuously to adjust and provide more accurate results.

- **Prediction:** Uses a system model to predict the next state of the system.

- **Update:** Includes new measurements to correct the prediction and minimizing error.

This process runs iteratively, adjusting the state estimate as more data becomes available.

5.4.2 Prediction Step

The prediction step calculates the next state ($\hat{x}_k^-$) and its associated uncertainty (P_k^-) based on the previous state and system dynamics [7].

Predicted State

$$\hat{x}_k^- = A \cdot \hat{x}_{k-1} + B \cdot u_k \tag{4}$$

- $\hat{x}_k^-$: Predicted state (SoC) at time k,
- A: State transition matrix, representing the system dynamics,
- $\hat{x}_{k-1}$: Previous state (SoC) at time $k-1$,
- B: Input control matrix, linking the input u_k to the state,
- u_k: Input, such as current flowing in or out of the battery.

This Equation calculates the next state using the system model and external inputs, giving a starting point for adjustments.

Predicted Error Covariance

$$P_k^- = A \cdot P_{k-1} \cdot A^T + Q \tag{5}$$

- P_k^-: Predicted error covariance, representing the uncertainty in the prediction,
- P_{k-1}: Error covariance from the previous step,
- A: State transition matrix, propagating uncertainty forward,
- Q: Process noise covariance matrix, accounting for inaccuracies in the model.

This equation calculates the uncertainty in the predicted state by considering the previous uncertainty and process noise.

5.4.3 Update Step

makes the prediction better by real-time sensor measurements (z_k), correcting both the state estimate and the error covariance [7].

Kalman Gain

$$K_k = \frac{P_k^- \cdot H^T}{H \cdot P_k^- \cdot H^T + R} \tag{6}$$

- K_k: Kalman Gain, determining the weight of the predicted state vs. the measured value,
- P_k^-: Predicted error covariance,
- H: Measurement matrix, linking the predicted state to the measurement,
- R: Measurement noise covariance, accounting for sensor inaccuracies.

This equation improves the state estimate by adjusting the prediction using the measurement and the difference between the measurement and the prediction

Updated State

$$\hat{x}_k = \hat{x}_k^- + K_k \cdot (z_k - H \cdot \hat{x}_k^-) \tag{7}$$

- $\hat{x}_k$: Updated state estimate at time k,
- z_k: Measured value (e.g., voltage),
- H: Measurement matrix, mapping the predicted state to the observed measurement space,
- K_k: Kalman Gain,
- $z_k - H \cdot \hat{x}_k^-$: Residual, the difference between the measured and predicted values.

This equation updates the state by correcting the prediction based on the measurement and the residual.

Updated Error Covariance

$$P_k = (I - K_k \cdot H) \cdot P_k^- \tag{8}$$

- P_k: Updated error covariance, representing the uncertainty in the refined state estimate,
- I: Identity matrix, ensuring consistent dimensions,

- $K_k \cdot H$: Correction term, reducing uncertainty using the measurement.

This equation updates the error covariance to show the improved state estimate after adding the measurement.

The prediction step calculates the next state and its uncertainty using the system model. The update step improves these estimates using real-time measurements. Together, these steps allow Kalman Filtering to estimate states like SoC accurately, even in noisy and changing environments [7].

5.5 Extended Kalman Filtering (EKF)

The standard Kalman Filter works well for linear systems, but battery systems often have non-linear relationships between variables like voltage, current, and SoC. The EKF solves this problem by using a first-order approximation to linearize the system around the current state.

5.5.1 Key Changes in EKF

- **Linearization:** Instead of using fixed matrices A and H, the EKF calculates Jacobian matrices:
  - A: Represents the linearized system model.
  - H: Represents the linearized measurement model.
- **State Update:** The state prediction and update equations are similar to the standard Kalman Filter but use the linearized models:

$$\hat{x}_k^- = f(\hat{x}_{k-1}) + B \cdot u_k \quad (9)$$

$$z_k = h(\hat{x}_k^-) + \text{noise} \quad (10)$$

  Where:
  - $f(\hat{x}_{k-1})$: Non-linear system model.
  - $h(\hat{x}_k^-)$: Non-linear measurement model.
- **Impact on Results:** By accounting for non-linearities, the EKF improves SoC estimation accuracy, especially in situations like:
  - Large changes in load or voltage.

- Complex battery behaviors, such as polarization and hysteresis effects.

These advanced filtering techniques are essential for reliable battery management because they:

- **Improve System Safety:** Accurate SoC estimates prevent dangerous conditions like overcharging or deep discharging, which can damage the battery or cause safety hazards.
- **Enhance Performance:** Reliable state estimation ensures the battery is used efficiently, extending its lifespan and improving overall performance.
- **Adapt to Complex Conditions:** Advanced methods like EKF handle non-linear systems, making them ideal for unstable environments like EVs or renewable energy systems.

Kalman Filtering and its extended version (EKF) are powerful tools for estimating the State of Charge in battery management systems. While the standard Kalman Filter works well for linear systems, the EKF is better suited for non-linear systems, providing more accurate and reliable results. These methods help ensure safe, efficient, and reliable battery operation, even in challenging and changing environments.

5.6 State of Health

The SoH shows the overall condition of a battery compared to its condition when it was new. It is usually given as a percentage of the battery's original performance. For example, a battery with 80% SoH can still hold 80% of its initial capacity. Keeping track of SoH is important because it helps predict how long the battery will last and when it might need maintenance or replacement. [1, 17].

5.6.1 State of Health Calculation

- **Capacity Fade**: The ratio of the battery's current capacity to its rated capacity is a primary indicator:

$$SoH = \frac{C_{\text{current}}}{C_{\text{rated}}} \times 100 \tag{9}$$

  Where:

  - C_{current}: Current capacity of the battery.
  - C_{rated}: Rated capacity of the new battery.

- **Internal Resistance**: As batteries age, their internal resistance increases. This can be expressed as:

$$SoH = \frac{R_{\text{EOL}} - R_{\text{current}}}{R_{\text{EOL}} - R_{\text{new}}} \times 100 \tag{10}$$

  Where:

  - R_{EOL}: Resistance at end of life.
  - R_{new}: Resistance when the battery was new.
  - R_{current}: Current internal resistance.

- **Cycle Count**: The number of charge-discharge cycles completed by a battery is used to estimate its remaining life, especially in applications like EVs and renewable storage systems.

5.6.2 Methods for SoH Estimation

- **Capacity Fade Monitoring**: Measures how the battery's capacity decreases over time through regular charge-discharge tests.
- **Internal Resistance Measurement**: Tracks changes in resistance using voltage and current measurements.
- **Data-Driven Methods**: Uses machine learning models trained on historical data to predict SoH based on real-time measurements.

In Table 4 comparison of three different SoH estimation methods are compared, Capacity Fade Monitoring, Internal Resistance Measurement, and Data-Driven Techniques. The table evaluates these methods based on ease of use, cost, effectiveness, and typical applications.

Table 4: Comparison of SoH Estimation Methods.

Method	**Ease of Use**	**Cost**	**Effectiveness**	**Applications**
Capacity Fade Monitoring	Moderate	Low	High	General SoH estimation in small and medium battery systems.
Internal Resistance Measurement	Moderate	Moderate	High	Diagnostics in EVs and renewable energy systems.
Data-Driven Techniques	Low	High	Very High	Advanced predictive maintenance for EVs and large-scale applications.

5.6.3 Applications

SoH is used in predictive maintenance to determine when a battery needs replacement. For example, in EVs, a battery may be considered at the End of Life (EoL) the battery when the SoH drops below 80% [15, 28].

5.7 Depth of Discharge

The DoD measures how much of a battery's total capacity has been used during a single discharge cycle. It is shown as a percentage of the battery's full capacity. For instance, a DoD of 80% means that 80% of the battery's capacity has been drained in one cycle. Controlling DoD is important because discharging a battery too deeply can greatly reduce its lifespan and make it less efficient over time. [1, 3].

When a battery is discharging, the DoD is defined as the percentage of the capacity that has been discharged relative to the rated capacity [26]:

$$DoD = \frac{C_{\text{released}}}{C_{\text{rated}}} \times 100\% \tag{11}$$

Here:

- C_{released}: The capacity discharged by any amount of current.
- C_{rated}: The rated capacity of the battery.

This Equation highlights the percentage of energy that has been used in relation to the battery's total capacity.

5.7.1 Relationship Between DoD and SoC

DoD and SoC are closely related and complementary metrics:

$$DoD = 100\% - SoC \tag{12}$$

This equation illustrates that when a battery has a higher DoD, its SoC is correspondingly lower. For instance:

- If the battery's SoC is 80%, the DoD is 20%, indicating that 20% of the battery's total capacity has been used.

- If the battery's SoC is 30%, the DoD is 70%, reflecting more significant energy utilization.

Both metrics are essential for understanding the battery's energy state. SoC helps monitor available energy, while DoD is used to analyze performance and cycle life [26].

5.7.2 Importance of DoD

- **Battery Lifespan**: Regularly discharging a battery deeply (using high DoD values) speeds up its aging process because it puts more stress on the electrodes. Most lithium-ion batteries work best when used within a moderate DoD range, usually between 20%–80% [26].

- **Performance Optimization**: Controlling DoD helps find a balance between using the battery's capacity and extending its cycle life. This is especially important for applications like EVs and renewable energy systems [26].

5.8 End of Life

The EoL of a battery is the point where its performance falls below acceptable levels for its intended use. This usually happens when the SoH decreases to less than 80% of its original capacity. Determining EoL is important because it helps plan for battery replacement and ensures the reliability of the system [18].

5.8.1 Methods for Estimating EoL

- **Threshold-Based Estimation:** Specific limits for capacity, internal resistance, or energy retention are predefined to mark the EoL [17].

- **Cycle Life Prediction:** Cycle life data is analyzed to estimate when the battery will reach its EoL based on usage patterns and operating conditions [17].

- **Data-Driven Models:** Machine learning or statistical approaches predict EoL using historical and real-time performance data [17].

EoL estimation ensures safety and cost-effectiveness by preventing the overuse of degraded batteries, which could lead to failures or safety risks.

5.9 Other Metrics

Beyond SoC, SoH, DoD, and EoL, additional metrics are used in specific applications to provide further insights into battery performance [7].:

- **State of Power (SoP):** Indicates the battery's ability to deliver power under specific conditions. It helps evaluate performance during peak loads, such as acceleration in EVs.
- **Internal Resistance:** Measures the battery's resistance to current flow. Higher internal resistance correlates with aging and reduced efficiency.
- **Temperature Sensitivity:** Tracks how temperature variations impact battery performance, as extreme conditions can accelerate degradation.

These metrics work alongside the main parameters, providing a more complete picture of how batteries perform in challenging environments, such as renewable energy systems and EVs.

6 CELL BALANCING

Cell balancing ensures that all cells in a battery pack have the same charge level. This process is important because it helps maximize the battery's capacity, prevents safety issues like overcharging, and extends the overall lifespan of the battery pack. [1, 16].

Imbalances in cell charge levels occur because of variations in cell chemistry, aging, and operational conditions. These imbalances can cause [8, 17]:

- **Reduced Capacity Utilization:** The overall capacity of the battery pack is limited by its weakest cell.
- **Safety Risks:** Overcharging or over-discharging individual cells can lead to thermal runaway.
- **Increased Heat Generation:** Uneven charge distribution increases the risk of local overheating.

6.1 Methods of Cell Balancing

Cell balancing is a process used in battery packs to ensure all cells have the same charge level. This helps improve the battery's performance, safety, and lifespan. There are two main methods of cell balancing: passive balancing and active balancing. Each method is chosen based on the system's needs and size [7].

6.1.1 Passive Balancing

Passive balancing dissipates excess energy from higher-charged cells as heat through resistors as shown in Figure 12. This method is simple and cost-effective, making it suitable for smaller systems or those with low energy density requirements. However, the energy lost as heat reduces overall efficiency and necessitates careful thermal management [8]. In the representation of Formula 13 below, power is dissipated as heat in terms of current and resistance of the system.

$$P = I^2 R \tag{13}$$

Where:

- P: Power dissipated as heat,
- I: Current through the resistor,
- R: Resistance of the balancing circuit.

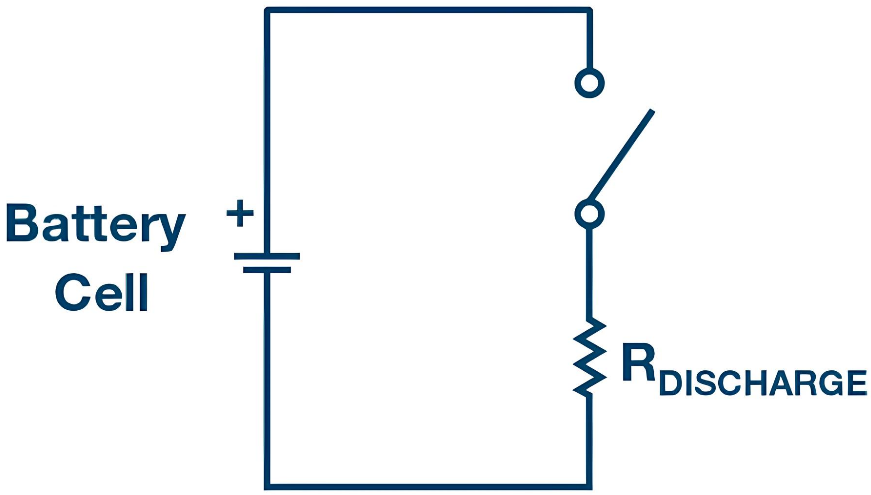


Figure 12: Passive Balancing Curcit [8].

6.1.2 Active Balancing

Active balancing redistributes energy from higher-charged cells to lower-charged cells, improving efficiency by minimizing energy loss. Several techniques are used [1, 16]:

Capacitor-Based Balancing: Energy is temporarily stored in capacitors and redistributed to lower-charged cells as shown in Figure 13.

- **Advantages:** Low cost and simplicity.
- **Limitations:** Limited energy transfer per cycle.

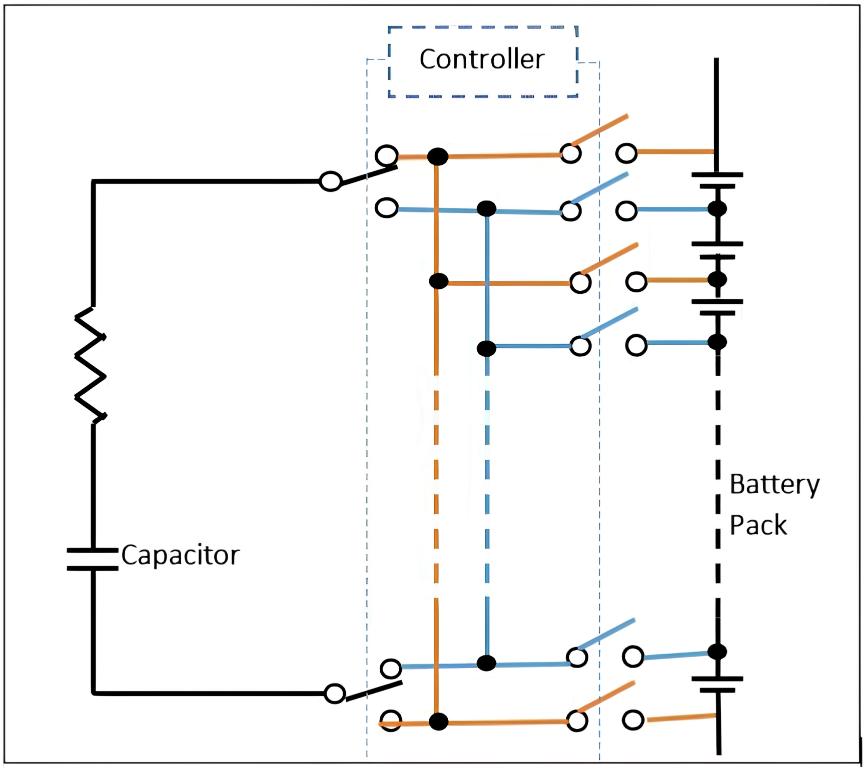


Figure 13: Capacitor based active balancing [9].

Inductor-Based Balancing: Inductors create magnetic fields to transfer energy between cells. This method is highly efficient for large systems like EVs.

- **Advantages:** High energy transfer efficiency.
- **Limitations:** Increased circuit complexity.

Converter-Based Balancing: DC-DC converters directly transfer energy between cells or modules, enabling precise balancing for large and high-performance systems. A DC-DC converter transfers extra energy from cells that are overcharged to those that are undercharged. In more advanced systems, energy can also be moved between different modules to ensure balance.

- **Benefits for Li-ion Batteries:**
  - Efficiency: Minimizes energy loss compared to passive balancing.
  - Precision: Provides accurate energy redistribution, critical for Li-ion systems sensitive to overcharging and thermal runaway.
  - Scalability: Suitable for large systems like electric vehicles and renewable energy storage.

- **Challenges:** Higher cost, increased design complexity, and the need for proper thermal management.

6.2 Comparison of Balancing Methods

Cell balancing techniques are generally divided into two main types: passive balancing and active balancing. Each method is designed for specific applications and use cases.

Table 5: Comparison of Passive vs. Active Balancing.

Aspect	Passive Balancing	Active Balancing
Efficiency	Low; energy is dissipated as heat	High; energy is redistributed between cells
Complexity	Low; simple resistor-based circuits	High; requires complex circuits
Cost	Low; inexpensive to implement	High; advanced hardware increases cost
Heat Generation	High; significant energy is wasted as heat	Low; minimizes heat generation
Applications	Small systems, cost-sensitive designs	High-performance systems

As shown in Table 5, passive balancing is simple and affordable, making it a good choice for small, low-power systems where efficiency is not a concern. However, it wastes energy by converting it into heat, which can impact the overall performance of the system. On the other hand, active balancing is much more efficient because it transfers energy between cells instead of wasting it. Although active balancing is more complex and costly, it is necessary for high-performance systems like EVs and renewable energy applications, where efficiency and safety are extremely important. [1, 16].

6.3 Comparison of Active Balancing Methods

Active balancing can be implemented using various techniques, each with its own strengths and weaknesses.

Table 6: Comparison of Active Balancing Methods.

Method	Advantages	Disadvantages	Applications
Capacitor-Based	Low cost, simple design	Limited energy transfer per cycle	Moderate balancing requirements
Inductor-Based	High efficiency, suitable for large systems	Increased circuit complexity	Electric vehicles, renewable energy systems
Converter-Based	Precise energy redistribution, scalable	High cost, complex design	High-capacity battery packs

As seen in Table 6, active balancing methods differ in how they transfer energy and where they are best used. Capacitor-based balancing is simple and cost-effective. It uses capacitors to store and move energy temporarily, but its energy transfer ability is limited. This makes it suitable for systems with moderate balancing needs [16]. Inductor-based balancing is more efficient and works well for large systems, such as EVs. However, it needs more complex circuits, which makes the design process harder [16]. Converter-based balancing is the most precise and scalable. It allows energy to be moved directly between cells or modules. This method is ideal for large battery packs in applications like grid storage and EVs. However, it is more expensive and complex, so it is less common in smaller systems [1].

6.3.1 Challenges in Cell Balancing

Using active balancing makes the design more complex and expensive, but its advantages are greater in high-performance systems. Passive balancing is still a good choice for smaller or less demanding applications. Both methods are important in modern battery management systems, as they help ensure safety, efficiency, and long-lasting performance. [1, 16].

7 SAFETY MECHANISMS

Ensuring the safety of Li-ion batteries is one of the most important tasks of a BMS. Li-ion batteries have high energy densities, creating risks like thermal runaway, overcharging, over-discharging, and internal short circuits. The safety features in a BMS are designed to monitor, detect, and respond to these conditions to prevent failures and keep the battery performing well. [7].

7.1 Overcharge and Overvoltage Protection

Overcharging and overvoltage conditions can lead to serious damage, such as electrolyte breakdown and thermal runaway. The BMS keeps track of cell voltages and activates protective measures when voltage limits are crossed [7].

Voltage Threshold Monitoring The BMS continuously monitors cell voltages and checks them if they are near to the safety limits. If a cell voltage gets close to the overcharge limit, the system either slows down the charging rate or disconnects the charger [7].

Rate-of-Change Analysis The slope of the OCV to the SoC curve can predict dangerous voltage levels. The following equation 14 determines the maximum safe rate of voltage change as seen in the Figure 14 [7]:

$$\frac{dV}{dt} = C \cdot \frac{dV}{dQ} \cdot I \tag{14}$$

where $\frac{dV}{dt}$ is the voltage change over time, C is the cell capacity, $\frac{dV}{dQ}$ is the slope of the OCV-SoC curve, and I is the current [7].

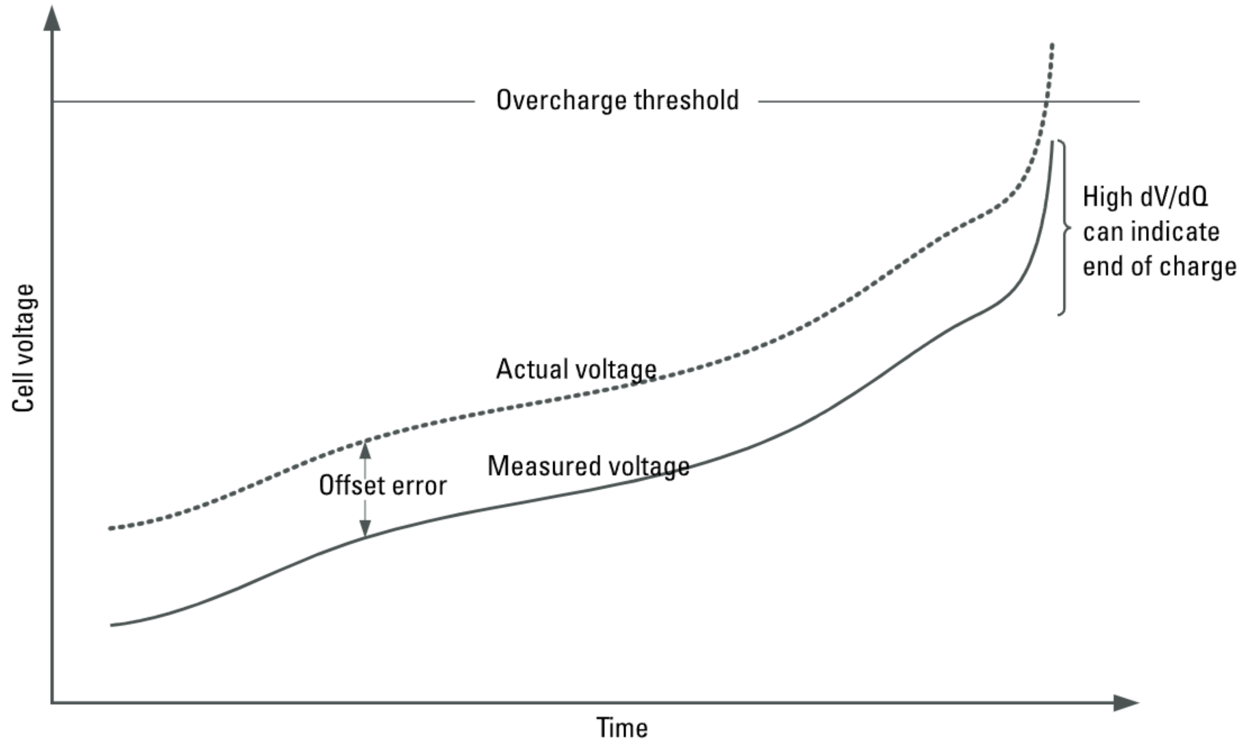


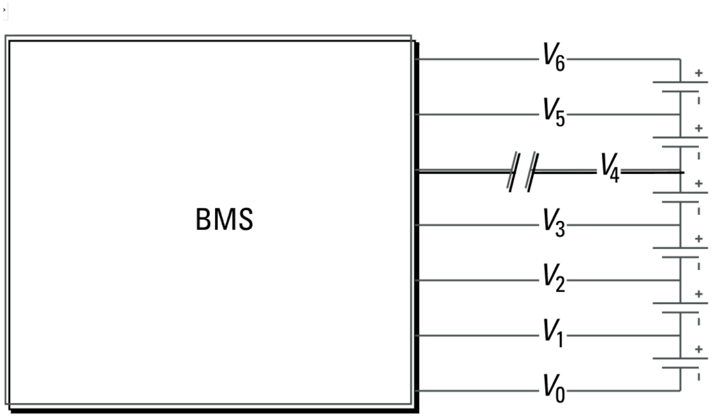
Figure 14: End of charge detection [7].

7.2 Overcurrent Protection

Excessive currents during charging or discharging can overheat the battery and damage components. The BMS uses fuses or circuit breakers as a safety system [7].

Current Monitoring Current sensors track the flow of charge through the battery pack. When currents exceed safe levels, the BMS interrupts the circuit.

Fault Diagnosis The BMS detects blown fuses by measuring voltage on both sides as represented in Figure 15. This ensures the system responds quickly to prevent further damage.



Measurement	Actual	Measured
V_{01}	3.558 V	3.558 V
V_{12}	3.601 V	3.601 V
V_{23}	3.603 V	3.603 V
V_{34}	3.604 V	0.002 V
V_{45}	3.608 V	0.004 V
V_{56}	3.602 V	3.602 V
V_{06}	21.576 V	21.576V

Figure 15: Lost Connection Detection [7].

7.3 Over-Temperature Protection

Temperature monitoring is important for avoiding thermal runaway and ensuring battery efficiency. The BMS uses thermal sensors distributed across the pack to detect unusual temperature rises. Protective measures include [7]:

Thermal Shutoff The BMS disconnects the battery pack if temperatures exceed safety limits.

Plausibility Checks Rapid temperature changes outside the expected range are flagged as sensor errors or faults to avoid false alarms.

Safety features in a BMS use real-time monitoring, fault detection, and protective measures to ensure Li-ion batteries operate safely. By using advanced methods and technologies, the BMS not only reduces risks but also improves the lifespan and performance of battery packs.

8 METHODOLOGY

The proposed BMS shown in Figure 16 is designed to manage Li-ion battery packs as shown in Figure 17 efficiently, ensuring safety, and reliability. This design is not a fixed or final version; components and methods may change or evolve during the second semester as we refine and optimize the system. Initially, planned to implement the system on an STM32F409 Discovery Board for ease of development. If time permits after successful implementation, the system may migrate the design to a standalone STM32 or any microcontroller for a more compact and cost-effective solution.

8.1 Core Features of the BMS

The BMS is structured around critical components that ensure efficient and safe battery operation.

8.1.1 Active Balancing System

To maintain charge uniformity across cells, the capacitor-based active balancing method has been selected, as it is considered the easiest to implement for this project. In this method, energy is temporarily stored in a capacitor and is then redistributed to undercharged cells. Although it has limitations in energy transfer capacity when compared to inductor or converter-based balancing, its simplicity, low cost, and reduced circuit complexity make it suitable for this project. Capacitor-based balancing ensures that all cells are kept within safe operating limits without significant energy loss or design challenges being introduced.

8.1.2 Voltage Monitoring

Voltage monitoring is essential for understanding the energy state of the battery. The voltage of each cell, which is under 4.2V, can be directly read by the ADC on the STM32F409 Discovery Board. However, the total battery pack voltage of 67.2V is too high for the ADC's input range. Instead of physically dividing the pack, four buck converters are connected to specific cell groups: cells 1–4, 5–8, 9–12, and 13–16. Each converter reduces its group's voltage (maximum 16.8V) to a range of 0–5V, which is suitable for ADC readings. This setup allows efficient monitoring of the pack without changing its physical structure.

8.1.3 Current Sensing

Accurate current measurement can be achieved by using a shunt resistor combined with the Analog Devices AD8418A current sense amplifier. This setup amplifies the voltage drop across the resistor, allowing for precise ADC readings. The AD8418A is selected because it is performs well in low-to-medium current systems and covers our voltage range 2 V to +70 V, continuous operation while ensuring both safety and reliable operation [29].

8.1.4 Temperature Monitoring

The system is going to use Analog Devices TMP36 temperature sensors, which operate over a wide range of $-40°\text{C}$ to $+125°\text{C}$, making it suitable for this project. These sensors monitor cell and system temperatures, allowing steps to be taken to prevent overheating or freezing. The collected data is processed by the STM32 Discovery Board, which activates safety mechanisms when needed [30].

8.1.5 Independent Power Supply:

The BMS is powered by a separate battery, ensuring it operates independently of the main battery pack. This setup allows the system to stay active even during deep discharge conditions, improving reliability.

Multiplexer for Input Expansion: With at least 19 data points, including cell voltages, converter outputs, and temperature sensors, the STM32 Discovery Board's ADC pins are not enough. To address this, a 16:1 multiplexer will be used to expand the input capacity. By reading inputs one after another through the MUX, the system remains scalable and can support additional sensors if needed.

Because of the use of the STM32F409 Discovery Board or any similar board, we are limited by the number of available inputs and outputs. This limitation makes the use of a multiplexer necessary, which creates small delays in data collection. If the initial implementation on the Discovery Board is successful, the system might move to a standalone STM32 or any microcontroller to optimize the system further.

8.2 System Architecture and Flow

The proposed BMS brings together sensors, processing units, and safety features into one complete design.

8.2.1 Data Collection

Individual cell voltages are read directly by the STM32 Discovery Board's ADC. Buck converters reduce the total pack voltage from specific cell groups to make it compatible with the ADC. Current is measured using a shunt resistor and the AD8418A amplifier, while temperature data is collected using TMP36 sensors. These inputs are sent one after another to the microcontroller through the multiplexer.

8.2.2 Processing

The STM32 Discovery Board processes the collected data to calculate key metrics such as SoC and SoH with Kalman filtering. It also monitors safety thresholds and triggers actions to prevent overcharging, over-discharging, or overheating.

8.2.3 Action

Based on the processed data, the system activates balancing circuits, adjusts charge/discharge rates, or disconnects the battery pack to ensure safety. The system also logs data for diagnostics and displays relevant information on a user interface.

8.3 Practicality and Ease of Integration

By starting with the STM32 Discovery Board, we avoid the challenges of designing connections for a standalone microcontroller. This makes the implementation simpler and offers flexibility for prototyping. Additionally, the chosen components, like the AD8418A current amplifier and TMP36 sensors, are affordable and easy to integrate into the system. Active balancing using capacitors minimizes energy loss without adding extra circuit complexity.

8.4 Limitations and Future Improvements

While the system is designed to be reliable and efficient, it has some limitations. Active balancing with capacitors, though simple, may not be as efficient as inductor or converter-based methods for larger systems. The use of multiplexers causes delays in data collection, which could impact performance in fast-changing conditions.

In the future, if time is available, the goal is to improve the design by switching to a standalone STM32 or another microcontroller and testing more advanced balancing techniques, such as converter-based methods, for better precision and efficiency.

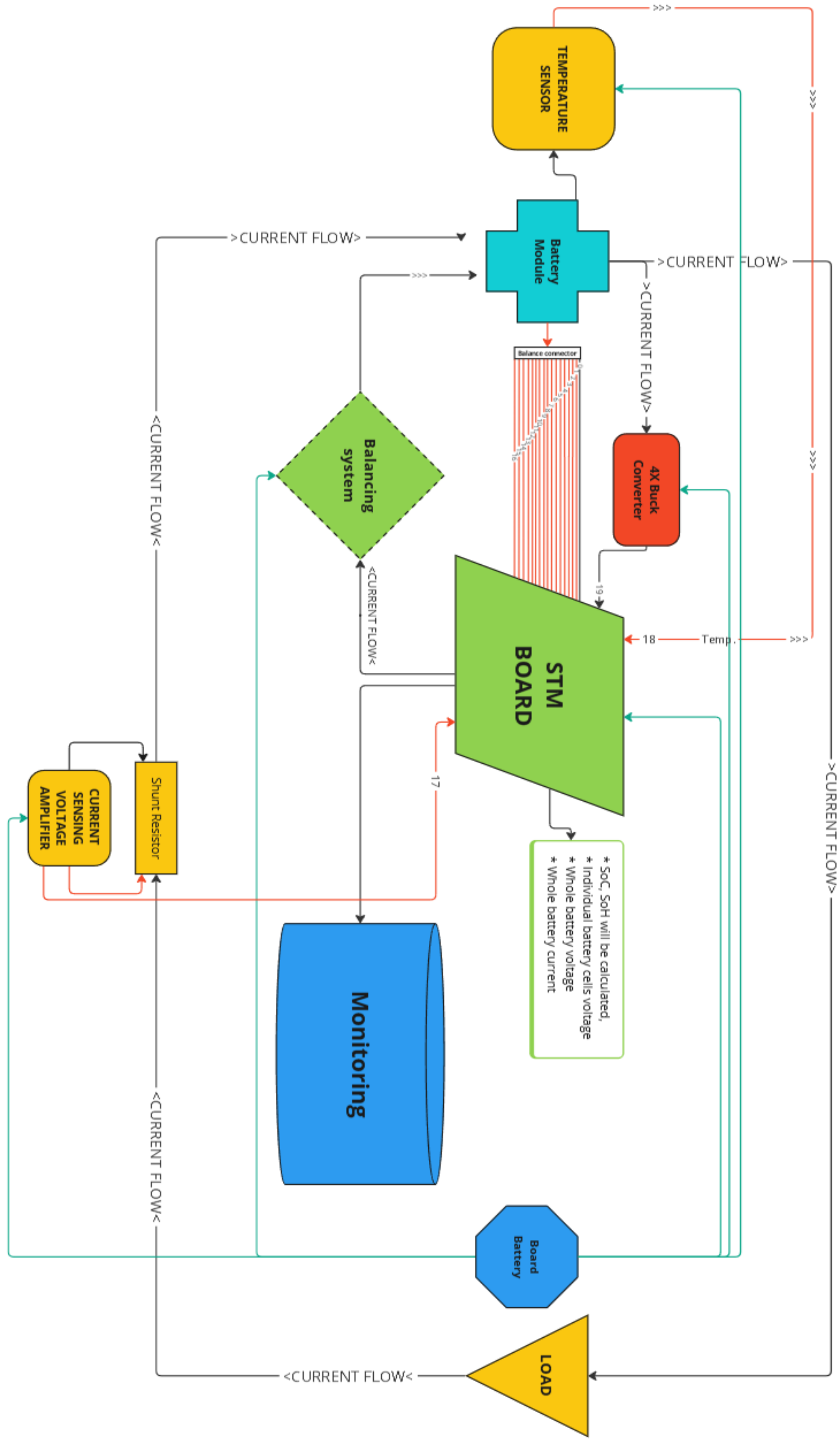


Figure 16: System diagram.

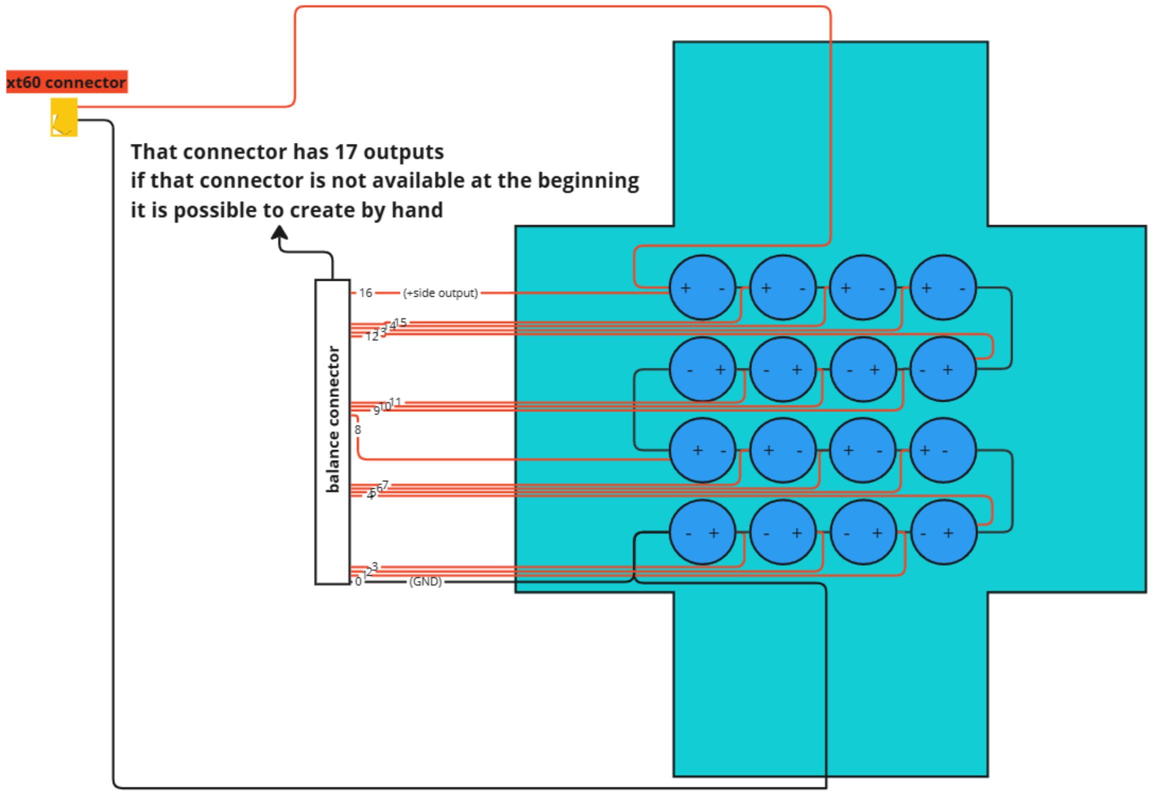


Figure 17: Battery individual cell connection.

9 BMS SIMULATION

This simulation was published by MathWorks on Nov 22, 2019, and was made with using Simulink. The simulation model enables desktop-based testing, allowing for the evaluation of various scenarios without risking damage to the real battery system. This system is designed to represent a battery integrated in an electric vehicle, with the simulation starting under conditions where the battery is charged 75% and the ambient temperature is 15°C. The simulation incorporates three primary operational states: driving, standby, and charging. Additionally, the system features a BMS ECU, which is responsible for monitoring the battery and executing control algorithms. A battery pack is also included within the simulated setup to ensure a comprehensive representation of the actual system. The Figure 18 shows a general look of the simulation in its most general and external form.

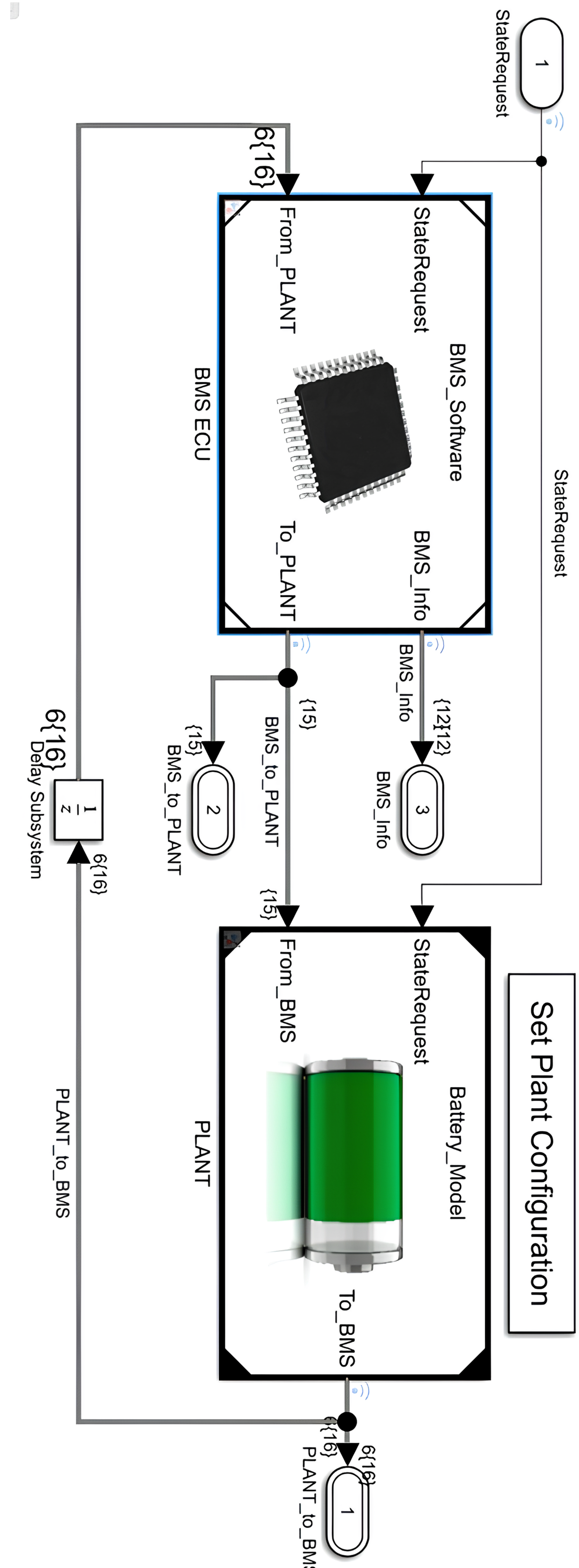


Figure 18: Overview of the simulation on Matlab [10].

9.1 Battery Pack and Cell Module

The simulation model incorporates two configurations of the battery pack: a smaller pack containing 6 cells and a larger pack with 96 cells inside of the battery pack module as shown in the Figure 19. In the smaller pack, the 6 cells are connected in series as shown in the The Figure 20. Electrical connections are represented by blue cables, while thermal connections are represented by orange cables. The cells are designed to exchange heat with each other, although the thermal layout is asymmetric. In particular, the sixth cell at the bottom is thermally isolated to manage heat more effectively [10].

Each individual cell is modeled using an equivalent circuit as shown in the Figure 21, which integrates parameters such as temperature, SOC, and potentially aging dependencies. These parameters provide a more accurate representation of the cell's behavior under varying conditions [10].

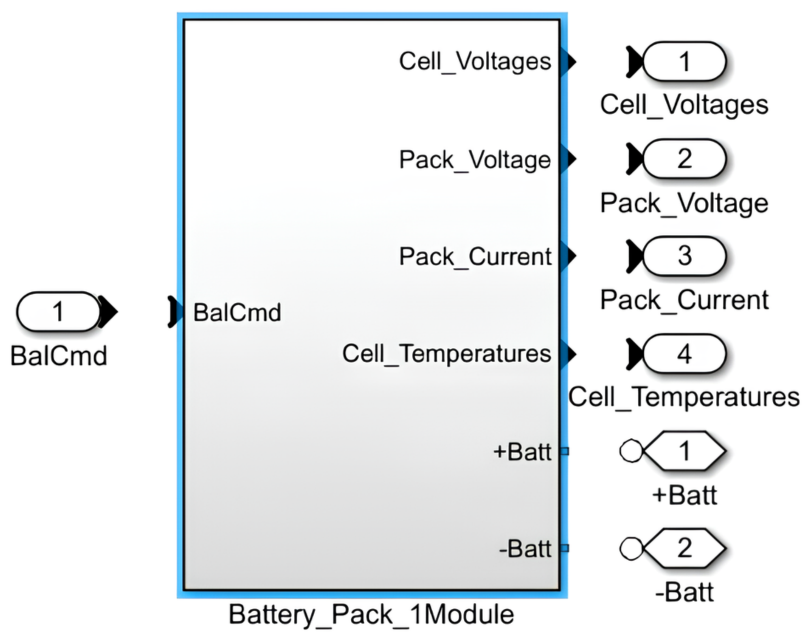


Figure 19: Battery pack module [10].

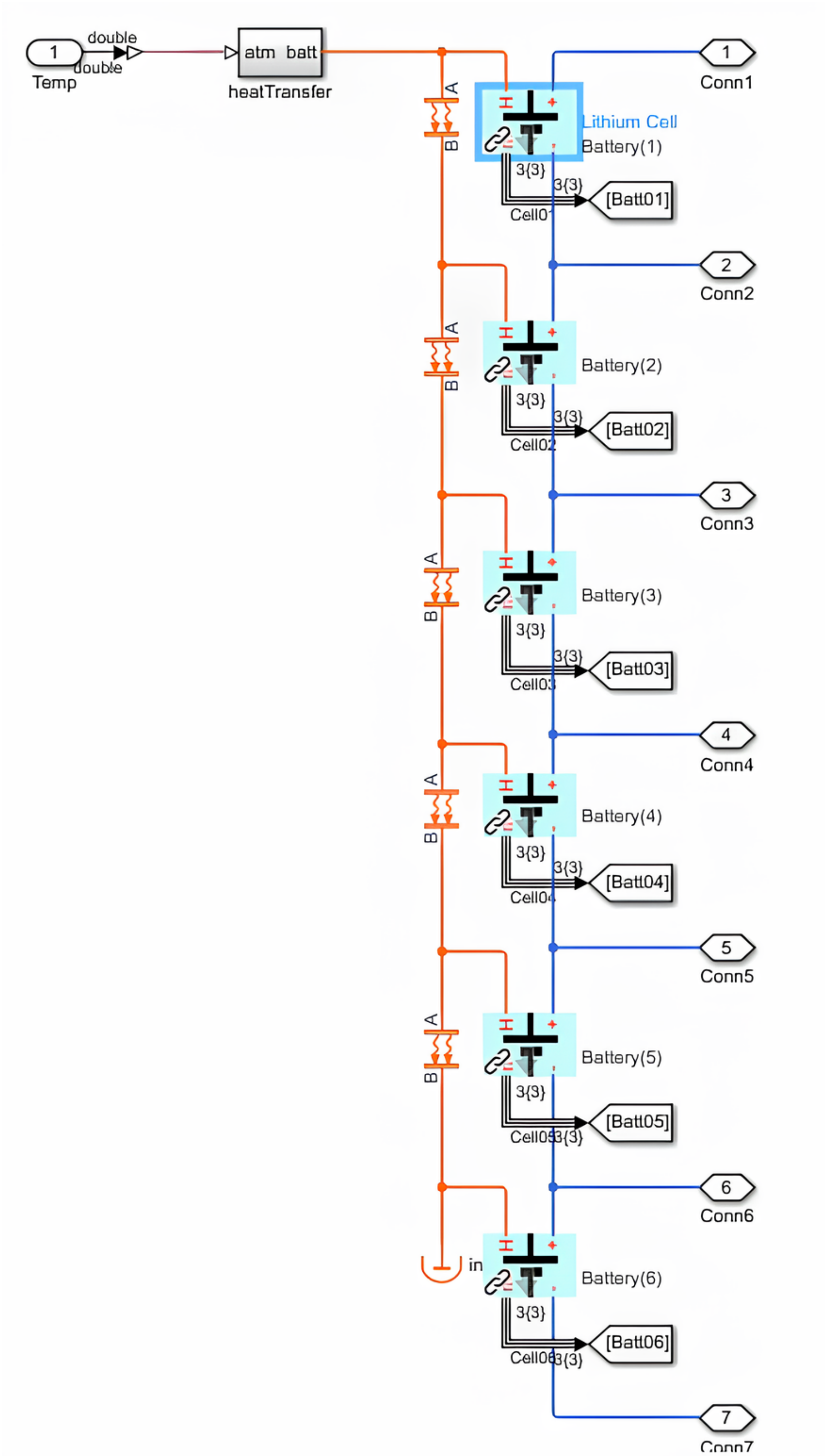


Figure 20: 6 cells connected serial [10].

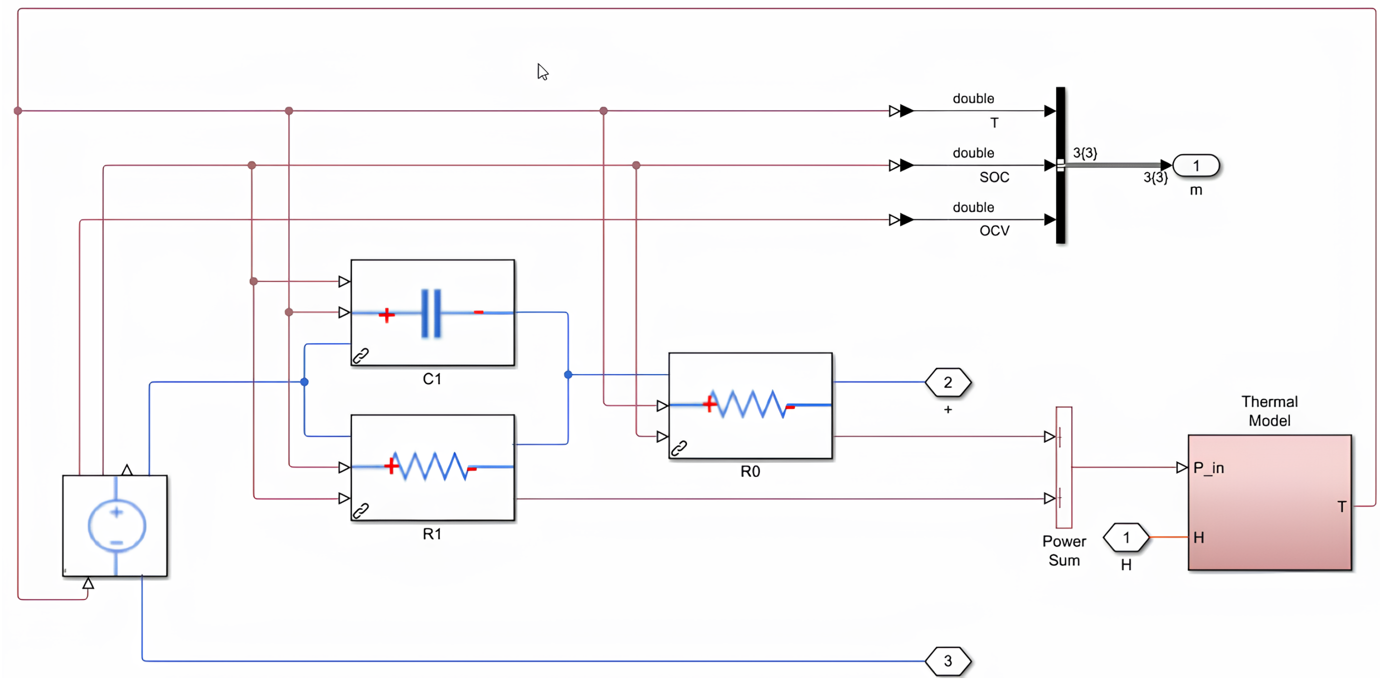


Figure 21: Circuit of a cell [10].

9.2 Cell Monitoring

The cell monitoring unit includes a passive balancing circuit. Based on the balancing logic defined by the BMS algorithm, the switches which are shown in the Figure 22 are selectively closed for cells that require partial discharge to lower their SOC. This ensures that all cells maintain an optimal charge balance [10].

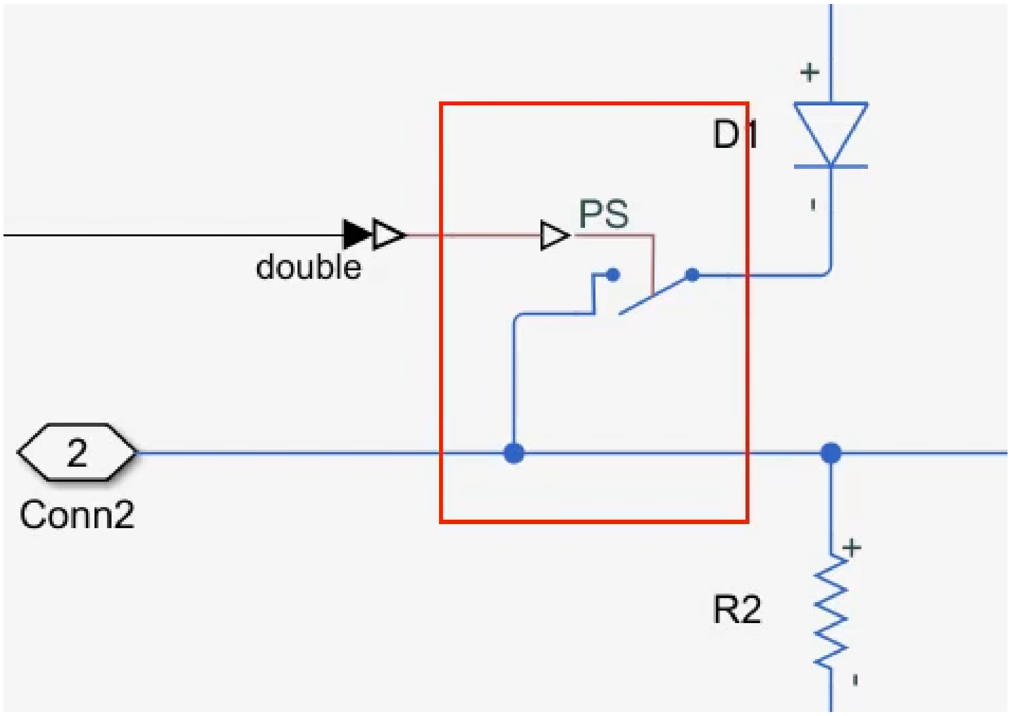


Figure 22: Passive balancing circuit switch [10].

9.3 Precharge

The precharge unit is critical for managing the connection of the charger and inverter. A resistor which is shown in the Figure 23 is preconnected during this process to prevent an excessively high current from rushing into the battery pack, which could cause potential damage [10].

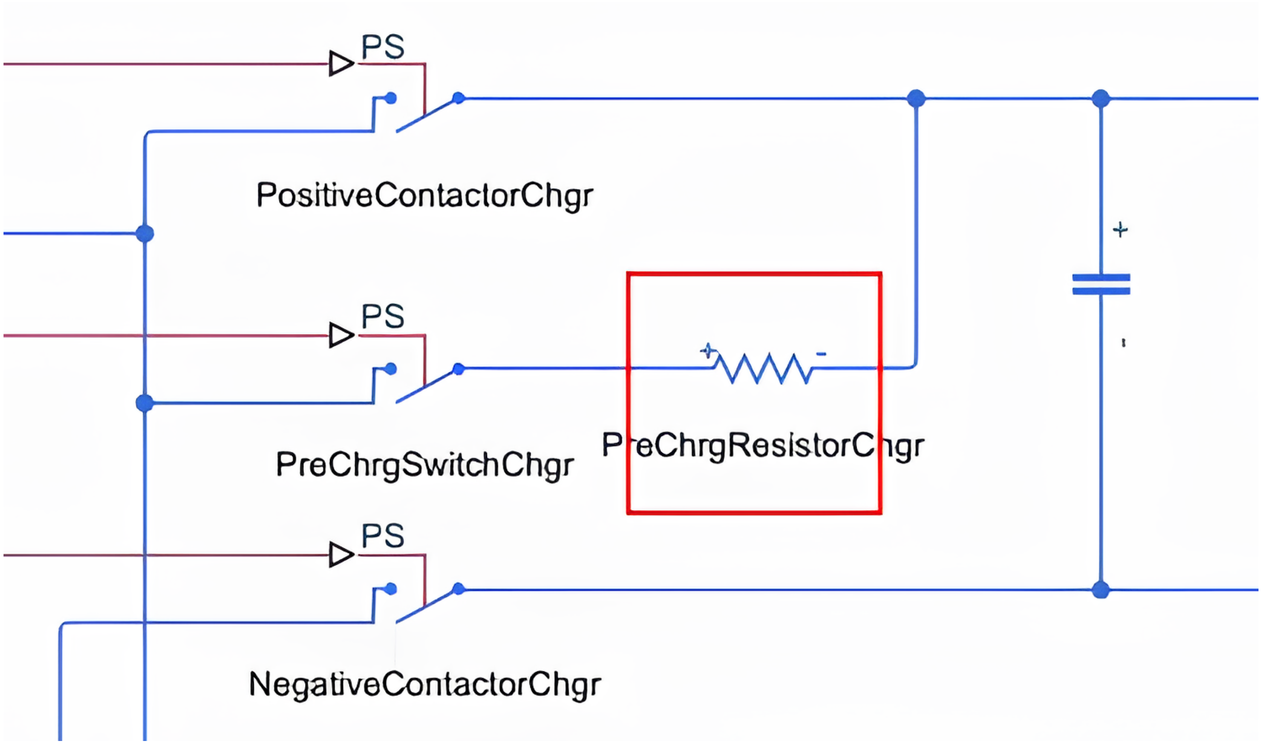


Figure 23: Precharge module circuit [10].

9.4 Charger Load

The final unit within the battery pack is designed to simulate the behavior of current sources. These current sources represent both the Charger and the DriveLoad, which are important components in the system that shown in the Figure 24. The Charger and DriveLoad are simplified as current sources, and their output is governed by the charging and driving profiles, respectively. These profiles are obtained from the source block, ensuring that the current sources accurately follow the real-time dynamics of the charging and discharging processes. This allows for precise modeling of the energy flow and performance within the battery system, facilitating better analysis and control [10].

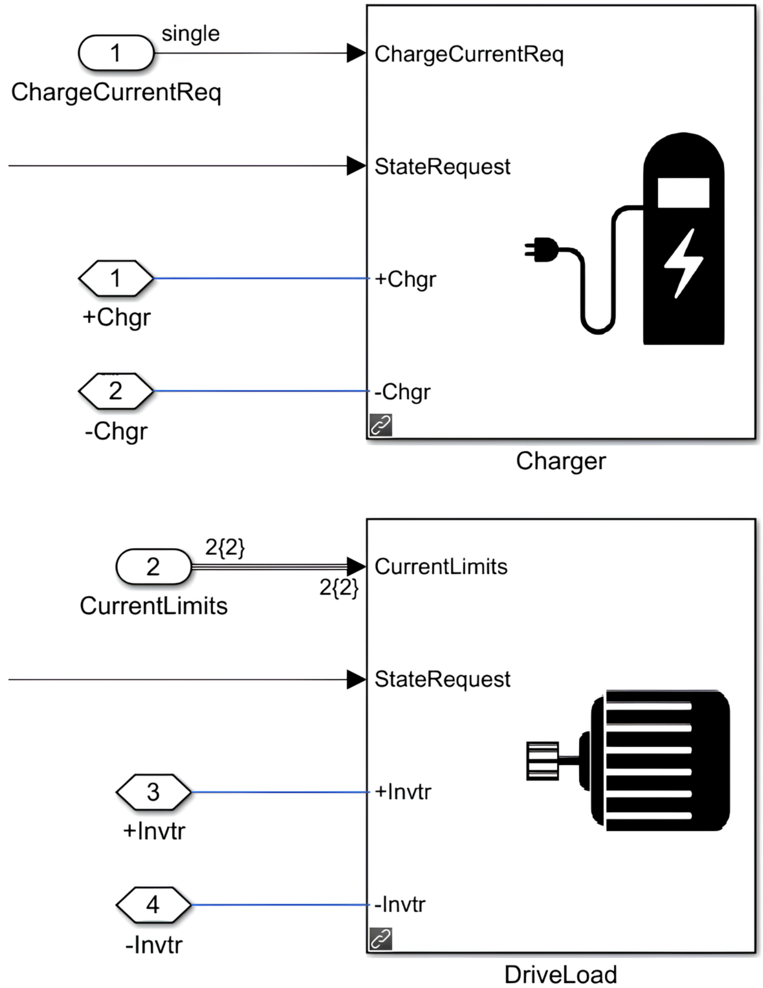


Figure 24: Charger and load [10].

9.5 BMS ECU and Current Power Limit

The BMS ECU performs important functions such as monitoring, protecting, limiting, and reporting measurements from the battery pack.

The BMS uses individual cell voltages and temperatures to determine the maximum allowable charge and discharge current levels. A low SOC corresponds to a low voltage, making it critical to prevent cells from delivering excessive current, as this could result in a significant voltage drop. To address this, the system at the Figure 25 compares the minimum cell voltage within the module to the "discharge current limit" threshold and calculates a voltage-based current threshold [11].

Temperature also plays a crucial role in limiting current delivery and intake. At excessively high or low temperatures, current thresholds are adjusted to protect the cell materials during charging and discharging processes. The BMS compares high and low temperature thresholds using the most restrictive value as the current limit to ensure safe operation [11].

- **State of Charge (SOC):** Low SOC correlates with low voltage, influencing current thresholds.
- **Cell Voltages:** Voltage thresholds are used to determine current limits.
- **Cell Temperatures:** The allowable current delivery is modulated on the basis of cell temperatures, ensuring safe operation.

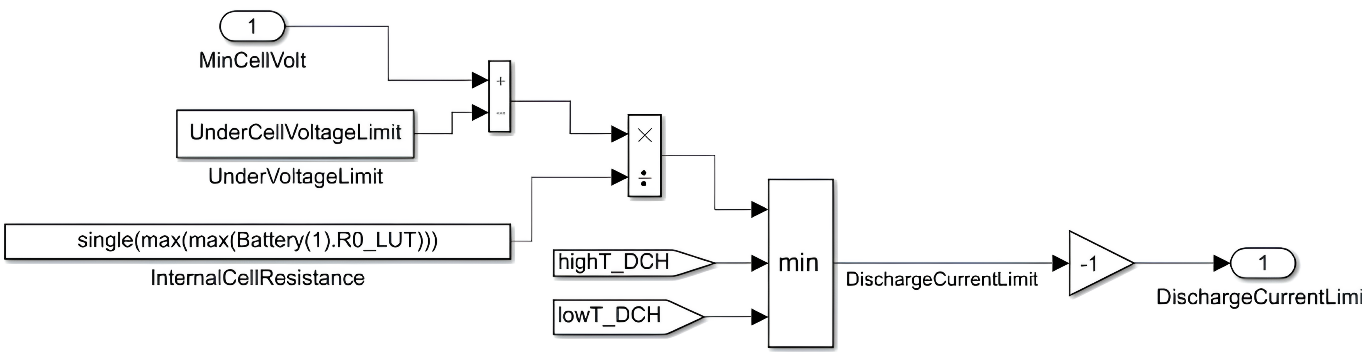


Figure 25: Discharge current limit [11].

9.6 State Machine

The BMS state machine defines its main operational states using components that are either active or inactive depending on specific conditions. Three parallel states are defined, which can operate simultaneously [11]:

- Charging: Includes constant current and constant voltage phases.
- Fault Monitoring: Activates fault states if current, voltage, or temperature values reach unsafe levels.
- Contactor Control: Controls the on and off switching sequences for the charger and inverter to avoid large current surges when charging begins.

9.7 SOC Estimation

In this simulation, the SOC is not measured directly. Instead, the model compares different estimation methods, including Coulomb counting, Unscented Kalman Filter (UKF), and Extended Kalman Filter (EKF) which are shown at the Figure 26 [12].

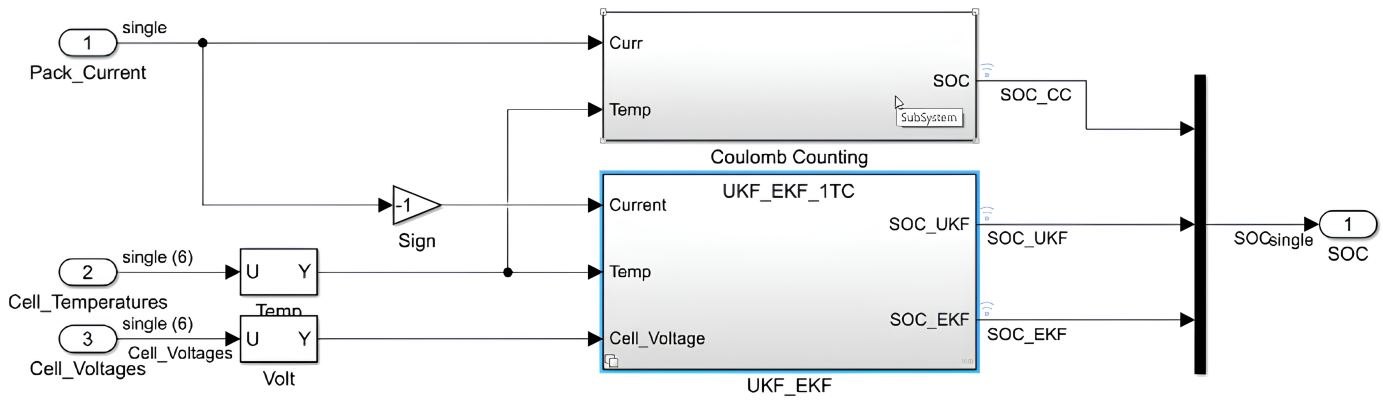


Figure 26: SOC estimation [12].

9.8 Cell Balancing Logic

Maintaining consistent SOC levels across individual battery cells is important for overall pack performance. Cells with the highest SOC limit the total amount of charge that can be added to the pack. The balancing logic calculates the peak-to-peak voltage across cells to activate passive balancing circuits [12].

9.9 Simulation Results

The graphs illustrate the behavior of various components of the battery under different conditions such as driving, charging, and idle states. The analyzed components include cell voltages, pack current, cell temperatures, and SOC estimation. These factors play a crucial role in determining the performance and reliability of battery systems, directly affecting their lifespan and efficiency. The simulation results emphasize the importance of thermal management and balancing operations in maintaining the battery's health and performance.The different stages of the simulation are shown in the Figure 27.

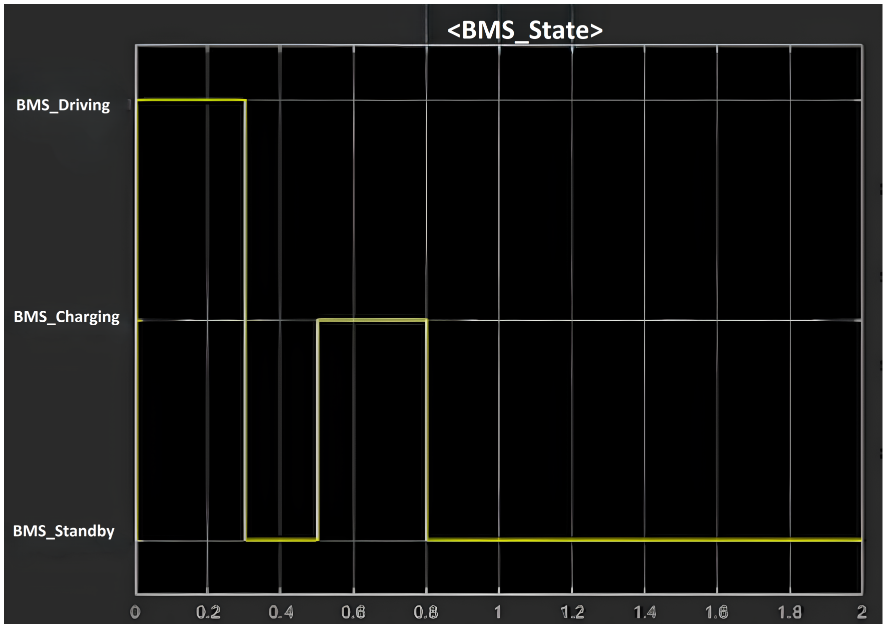


Figure 27: Different stages of simulation [13].

At the beginning of the simulation, slight variations were observed in the individual cell voltages that shown at the Figure 28, reflecting the differences in the initial SOC of each cell. As current flows through the cells, these differences diminish, and by the end of the simulation, cell voltages converge. This process is a result of the balancing procedure, which ensures the battery functions more efficiently and has a longer lifespan [13].

Initially, variations in cell voltages were observed due to the current flow, but by the end of the balancing process, the voltages of all cells closely matched. The balancing operation ensures a homogeneous charge distribution among the battery cells, thus improving the overall performance of the battery [13].

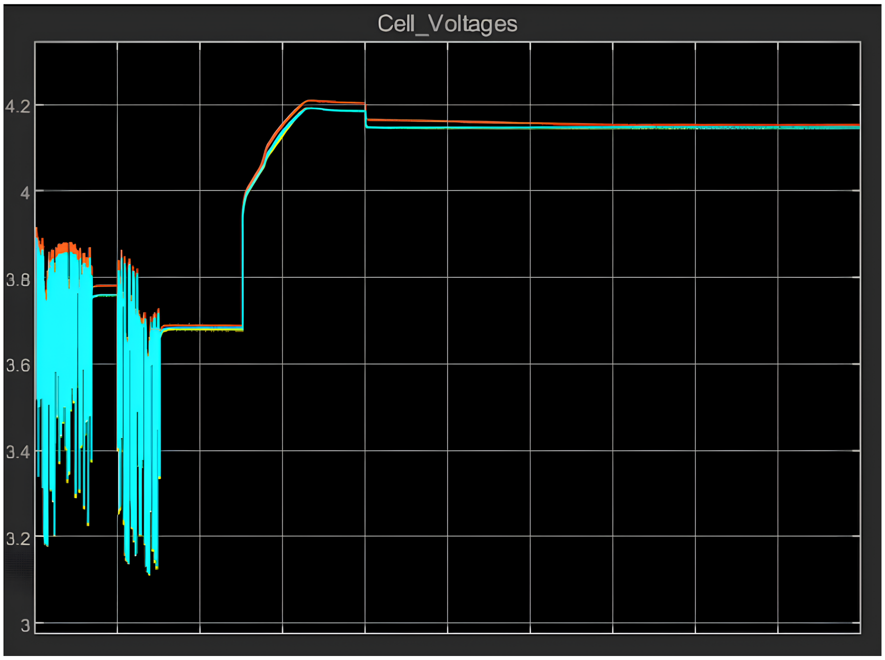


Figure 28: Cell Voltages [13].

The pack current that shown at the Figure 29 is a critical parameter that shows how different current values impact the battery during the simulation. During the charging phase, when cell voltages approached their maximum values, the pack current was observed to remain stable. This indicates that the current was limited to prevent overcharging, as maximum cell voltages approached the 4.2V threshold. This current limitation is a strategy used to extend battery life by preventing damage caused by excessive current [13].

During the charging process, the limitation of current once the voltage threshold is reached is a key strategy to protect the battery's longevity. Without this limitation, excessive current flow could cause dangerous levels in cell voltages, shortening the battery's lifespan significantly [13].

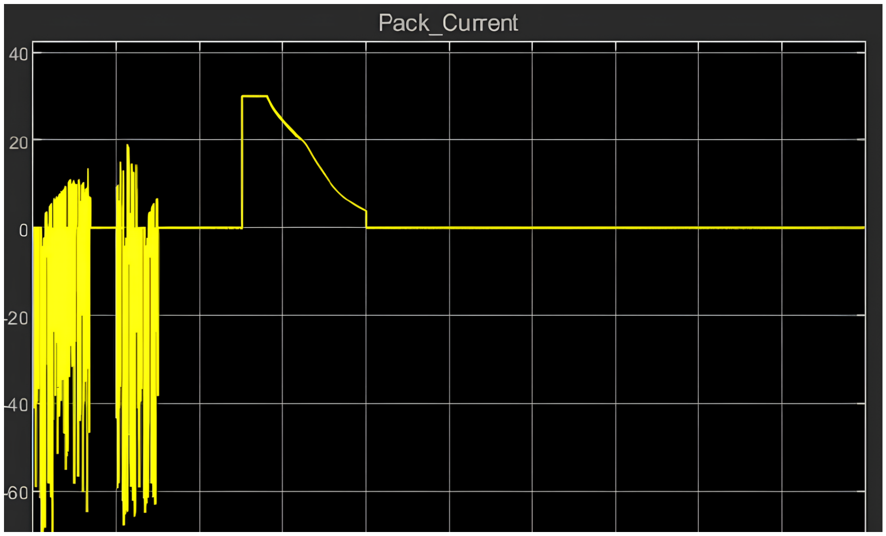


Figure 29: Pack current [13].

Throughout the simulation, cell temperatures showed variability across different cells that shown at the Figure 30. Notably, Cell 6 reached significantly higher temperatures compared to Cell 1. This difference is attributed to Cell 6 being thermally insulated on one side. The temperature difference between cells is critical, as uneven thermal distribution can lead to accelerated degradation, particularly in Cell 6 [13].

Although the maximum temperatures observed during the simulation were not alarming from a safety perspective, the activation of thermal management systems becomes important. Reducing temperature variations among cells is important for extending the overall life of the battery. Thus, efficient thermal management is crucial for the balanced and effective operation of batteries [13].

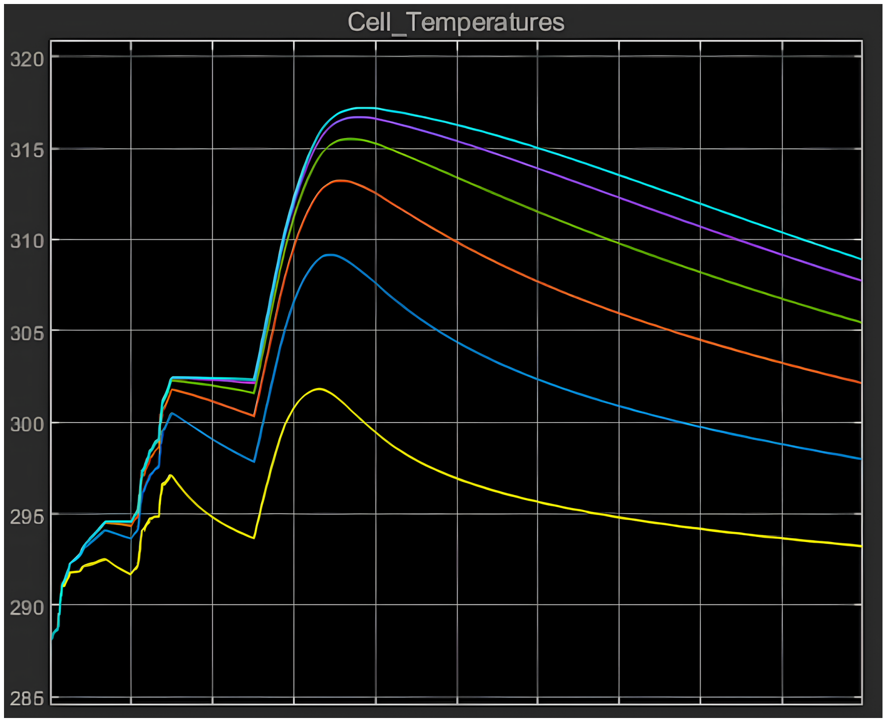


Figure 30: Cell temperatures [13].

SOC estimation which is shown at the Figure 31 is an important parameter for determining the battery's charge level and was examined in the simulation using three different methods: Coulomb counting, UKF, and EKF. The yellow curve represents Coulomb counting, the blue curve represents UKF, and the orange curve represents EKF. Accurate SOC estimation is critical for optimizing battery life and ensuring safe operation [13].

While Coulomb counting is a simple and commonly used method, it is prone to cumulative errors. More advanced techniques, such as UKF and EKF, capture the dynamic variability of the system more effectively, offering more accurate results [13].

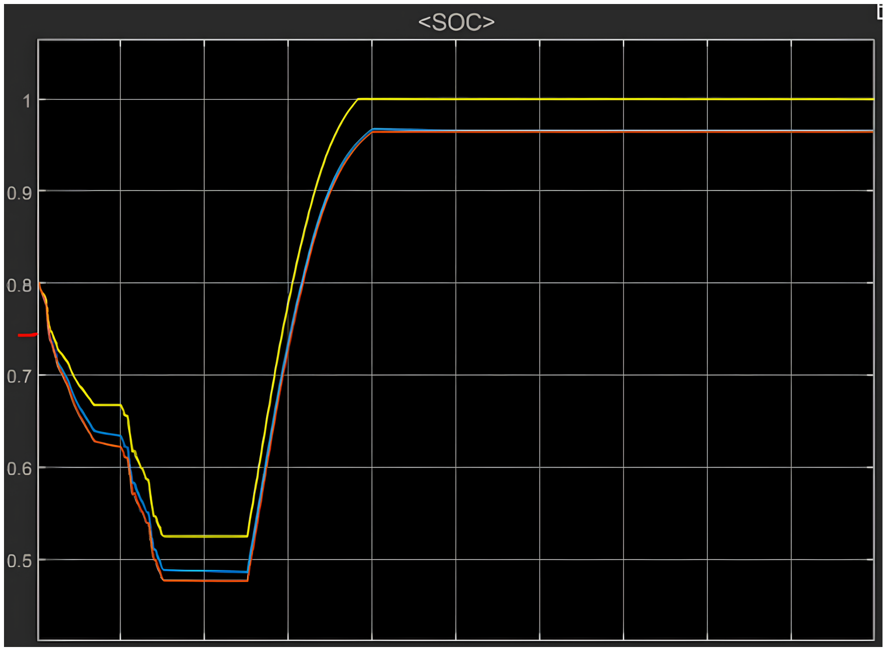


Figure 31: SOC estimation results [13].

10 RESULTS AND DISCUSSIONS

Results

The research and analysis in this report created a basic design for a BMS that meets the main needs of Li-ion battery packs. The proposed system combines monitoring, balancing, and estimation features, focusing on simplicity and cost-effectiveness.

The active balancing method is going to use capacitors to move energy between cells, helping to keep the charge balanced and extend the battery's life. This method is easier to implement compared to more complex approaches like inductor-based or converter-based balancing. While it may not be as efficient for large systems.

The voltage monitoring system will handle individual cell voltages directly through the STM32F409 ADC, as each Li-ion cell operates below 4.2V. To monitor the total pack voltage of 67.2V, the battery is divided into four sections, with each section's voltage reduced by a buck converter to a range of 0–5V, which the ADC can read. This approach avoids physically splitting the battery pack, making the system design simpler.

For current measurement, the design is going to use a shunt resistor along with the Analog Devices AD8418A current amplifier. This setup is going to provide accurate current readings while keeping costs low. The temperature monitoring system will use TMP36 sensors, which are reliable, affordable, and can operate in a wide temperature range of -40°C to +125°C, making them a good choice for Li-ion battery packs.

Because the STM32F409 Discovery Board has a limited number of input pins, a multiplexer is going to be used to manage more than 19 data points from cell voltages, temperature sensors, and buck converter outputs. This is going to introduce a small delay in data collection but that will allows the system to be expanded and scaled easily.

The proposed BMS design shows potential for effectively managing key battery parameters and provides a base for further development. However, the design is still in its really early stages, and its performance has not yet been tested in simulations or in real-world conditions.

Discussion

The proposed BMS design balances simplicity and functionality. Active balancing was selected instead of passive balancing because it is more efficient and better at maintaining battery health. Within active balancing methods, capacitor-based balancing is chosen because it is the easiest to implement and does not require complex circuits. While this method has some limits, such as slower energy transfer, it fits well with the goals of our project.

The STM32F409 Discovery Board was chosen for prototyping because it is easy to work with and provides enough functionality for initial testing. However, its limited input and output pins required the use of a multiplexer to handle all the data points. This adds some delays in reading data, but it was the most practical solution given our resources. If the implementation on the Discovery Board is successful, and time remains, the system could later be moved to a standalone STM32 or any microcontroller, which would make it more compact and scalable.

This design focuses on simple and affordable components, such as the TMP36 temperature sensors and AD8418A current amplifier, to make the system cost-effective and easy. While the design is not perfect, it provides a base for understanding how a BMS works and can be improved in future stages.

11 CONCLUSIONS AND FUTURE WORKS

Conclusion

This report presents a detailed study of Battery Management Systems for lithium-ion batteries. It reviews important methods for monitoring and managing battery parameters and proposes a system that balances cost, simplicity, and functionality. The proposed BMS is going to use active balancing, reliable sensors, and simple monitoring techniques to ensure the safety and efficiency of the battery pack. The STM32F409 Discovery Board is going to be used for prototyping, with plans to move to a standalone microcontroller in the future if time is available. While the design has some limitations, it serves as a starting point for learning about BMS design and preparing for further development.

Future Works

The next steps for this project will focus on implementing and improving the proposed design. The key areas for future work include:

- **Expanded Testing and Simulations:** Additional tests and simulations will be performed to evaluate the system under different conditions, such as varying loads and temperatures before the prototyping stage. This will help improve the system's reliability and performance.
- **Prototyping:** The proposed design will be implemented on the STM32F409 Discovery Board to test its functionality. This will help identify any issues in the design and evaluate its performance under real-world conditions.
- **Standalone Microcontroller Integration:** If the Discovery Board implementation is successful and if we have time left, the system can be migrated to a standalone STM32 or any microcontroller. This will make the design more compact and reduce the overall cost.
- **Improving Balancing Methods:** Capacitor-based balancing is used in the current design for simplicity, but in the future, we might explore inductor-based or converter-based balancing to improve efficiency and energy transfer capabilities.

- **Circuit Design and Hardware Development:** Detailed circuit diagrams will be created, and the hardware will be prepared for fabrication. This will include designing PCBs and ensuring all components are correctly integrated.

By focusing on these areas, the project will move closer to a fully functional BMS that can be used in real applications.

REFERENCES

[1] X. Tan, A. Vezzini, Y. Fan, N. Khare, Y. Xu, and L. Wei, *Battery Management System and its Applications*. China: China Machine Press, 2022, first published: 12 November 2022.

[2] Battery University. (2021) Charging lithium-ion. Accessed: 2024-12-07. [Online]. Available: https://batteryuniversity.com/article/bu-409-charging-lithium-ion

[3] ——. (2023) Discharge characteristics of li-ion. Accessed: 2024-12-07. [Online]. Available: https://batteryuniversity.com/article/bu-501a-discharge-characteristics-of-li-ion

[4] ——. (2021) How to verify sufficient battery capacity. Accessed: 2024-12-07. [Online]. Available: https://batteryuniversity.com/article/bu-504-how-to-verify-sufficient-battery-capacity

[5] G. Z. Analog Devices, Mike Kultgen. (2024) Maximizing cell monitoring accuracy and data integrity in battery management systems. Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/resources/technical-articles/maximizing-cell-monitoring-accuracy-data-integrity-bms.html

[6] Analog Devices, *Battery Pack Monitor Data Sheet ADBMS2950B*, 2024, datasheet, Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/products/adbms2950.html

[7] P. Weicker, *A Systems Approach to Lithium-Ion Battery Management.*, ser. Power Engineering. Artech House, 2014. [Online]. Available: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=nlebk&AN=1155207&site=eds-live&scope=site&custid=ns108491

[8] S. N. Analog Devices, Kevin Scott. (2016) Passive battery cell balancing. Accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/resources/technical-articles/passive-battery-cell-balancing.html

[9] B. Paudyal, A. Timilsina, A. Khanal, and S. Ghimire, “Comparative analysis of cell balancing topologies in battery management system,” 05 2019.

[10] MathWorks. (2019) How to develop battery management systems in simulink. Accessed: 2025-01-05. [Online]. Available: https://www.mathworks.com/videos/how-to-develop-battery-management-systems-in-simulink-part-1-bms-overview-1574416523692.html

[11] MathWorks1. (2019) How to develop battery management systems in simulink. Accessed: 2025-01-05. [Online]. Available: https://www.mathworks.com/videos/how-to-develop-battery-management-systems-in-simulink-part-2-the-bms-algorithm-1574416562459.html

[12] MathWorks. (2019) How to develop battery management systems in simulink. Accessed: 2025-01-05. [Online]. Available: https://www.mathworks.com/videos/how-to-develop-battery-management-systems-in-simulink-part-3-state-of-charge-estimation-1574416618095.html

[13] ——. (2019) How to develop battery management systems in simulink. Accessed: 2025-01-05. [Online]. Available: https://www.mathworks.com/videos/how-to-develop-battery-management-systems-in-simulink-part-4-cell-balancing-1574416645415.html

[14] Analog Devices. Battery management systems (bms). Accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/solutions/automotive/electrification-and-powertrain/battery-management-systems-bms.html

[15] Battery University. (2022) Safety concerns with li-ion. Accessed: 2024-12-07. [Online]. Available: https://batteryuniversity.com/article/bu-304a-safety-concerns-with-li-ion

[16] S. N. Analog Devices, Kevin Scott. (2016) Active battery cell balancing. Accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/resources/technical-articles/active-battery-cell-balancing.html

[17] Z. Gao, C. S. Chin, J. H. K. Chiew, J. Jia, and C. Zhang, "Design and implementation of a smart lithium-ion battery system with real-time fault diagnosis capability for electric vehicles," *Energies*, vol. 10, no. 10, 2017. [Online]. Available: https://www.mdpi.com/1996-1073/10/10/1503

[18] M. Lelie, T. Braun, M. Knips, H. Nordmann, F. Ringbeck, H. Zappen, and D. U. Sauer, "Battery management system hardware concepts: An overview," *Applied Sciences*, vol. 8, no. 4, 2018. [Online]. Available: https://www.mdpi.com/2076-3417/8/4/534

[19] H. Wang, C. Xue, Y. Liu, and G. Li, "Design and application of monitoring system of li-ion battery pack," *International Journal of Hybrid Information Technology*, vol. 7, pp. 393–400, 2014.

[20] MokoEnergy. (2024) Types of bms topologies: Centralized, distributed, and modular. Accessed: 29-Dec-2024. [Online]. Available: https://www.mokoenergy.com/types-of-bms-topologies/

[21] Linear Technology, *LTC6804-1/LTC6804-2 Multicell Battery Monitors*, 2024, datasheet, Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/products/ltc6804-1.html

[22] Analog Devices. (2001) Using thermistors in temperature-tracking power supplies. Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/resources/technical-articles/using-thermistors-in-temperature-tracking-power-supplies.html

[23] B. C. Analog Devices. (2023) Redesigning the rtd-based temperature sensor for the smart factory age. Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/resources/technical-articles/redesigning-the-rtd-based-temperature-sensor-for-the-smart-factory-age.html

[24] Maxim Integrated. (2005) Irlink temperature sensor allows isolation of the temperature sensor. Accessed: 29-Dec-2024. [Online]. Available: https://www.analog.com/en/resources/design-notes/irlink-temperature-sensor-allows-isolation-of-the-temp-sensor.html

[25] R. M. Analog Devices. (2024) Unlocking efficiency: How adi battery management solutions empower safer, smarter mobile robots. Accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/resources/analog-dialogue/articles/adi-battery-mgmt-sols-empower-safer-smarter-mobile-robot.html

[26] A. G. Analog Devices, Martin Murnane. (2023) A closer look at state of charge (soc) and state of health (soh) estimation techniques for batteries. Accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/resources/technical-articles/a-closer-look-at-state-of-charge-and-state-health-estimation-tech.html

[27] I. Baccouche, S. Jemmali, A. Mlayah, B. Manai, and N. E. B. Amara, "Implementation of an improved coulomb-counting algorithm based on a piecewise soc-ocv relationship for

soc estimation of li-ionbattery," *ArXiv*, vol. abs/1803.10654, 2018. [Online]. Available: https://api.semanticscholar.org/CorpusID:4400854

[28] Z. Wang, X. Zhao, L. Fu, D. Zhen, F. Gu, and A. D. Ball, "A review on rapid state of health estimation of lithium-ion batteries in electric vehicles," *Sustainable Energy Technologies and Assessments*, vol. 60, p. 103457, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138823004502

[29] Analog Devices, *Bidirectional, Zero Drift, Current Sense Amplifier Data Sheet*, 2024, accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/products/ad8418a.html

[30] ——, *Low Voltage Temperature Sensors Data Sheet TMP35/TMP36/TMP37*, 2024, accessed: 2024-12-07. [Online]. Available: https://www.analog.com/en/products/tmp36.html

APPENDICES