M. Tech (Power Electronics and Systems) Manish Kumar 2026

DESIGN AND PERFORMANCE EVALUTION OF CAPACITOR-BASED, INDUCTOR-BASED, AND RESISTIVE CELL BALANCING METHODS IN BATTERY MANAGMENT SYSTEM USING MATLAB/SIMULINK

A DISSERTATION

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Submitted by:

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CANDIDATE'S DECLARATION

I, **MANISH KUMAR**, Roll No. 2K22/PES/27 student of M. Tech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"DESIGN AND PERFORMANCE EVALUTION OF CAPACITOR-BASED, INDUCTOR-BASED, AND RESISTIVE CELL BALANCING METHODS IN BATTERY MANAGMENT SYSTEM USING MATLAB/SIMULINK"** which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is originaland not copied from any source without proper citation. This work has not previously submitted for the award of any Degree, Diploma.

Place: Delhi
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CERTIFICATE

I hereby certify that the project Dissertation titled **"DESIGN AND PERFORMANCE EVALUTION OF CAPACITOR-BASED, INDUCTOR-BASED, AND RESISTIVE CELL BALANCING METHODS IN BATTERY MANAGMENT SYSTEM USING MATLAB/SIMULINK"** which is submitted by Manish Kumar, Roll No. 2K22/PES/27, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology,is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diplomato this University or elsewhere.

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ABSTRACT

This thesis presents a detailed study of different cell balancing methods used in Battery Management Systems (BMS) through MATLAB/Simulink simulations. In lithium-ion battery packs, cells often develop unequal voltages and states of charge due to manufacturing variations, temperature differences, and aging effects. If not properly balanced, these differences can reduce battery efficiency, shorten lifespan, and create safety risks. To address this issue, the project compares three major balancing techniques: resistive balancing, capacitor-based balancing, and inductor-based balancing.

Also the thesis studies the work compares capacitor-based, inductor-based, and resistive balancing techniques to understand their performance in maintaining equal battery cell voltage. The study focuses on factors such as balancing time, energy efficiency, and overall battery performance. Simulation results show that each method has its own advantages and limitations. The project helps in understanding how proper cell balancing can improve battery life, safety, and reliability in applications such as electric vehicles and energy storage systems.

The resistive method is simple and low-cost but causes energy loss in the form of heat. In contrast, capacitor-based and inductor-based methods are active balancing techniques that transfer energy between cells more efficiently, reducing power loss and improving battery utilization. The simulations evaluate each method based on balancing speed, energy efficiency, voltage equalization capability, and overall battery performance.

The simulation outcomes confirm that the proposed active balancing technique successfully minimizes cell-voltage differences, lowers stress on each cell, and enhances the overall performance and lifespan of the battery pack

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LIST OF ABBREVIATIONS

EV	Electric Vehicle
HEV.	Hybrid Electric Vehicle
BMS	Battery Management System
SMPC	Switch Mode Power Converters
SC	Switched Capacitor
ZCS	Zero Current Switching
SPDT	Single Pole Double Throw
SoC	State of Charge
C-Rate	Charging/ Discharging Rate
LC	Inductor-Capacitor
EMI	Electro Magnetic Interference
CC	Constant Current
CV	Constant Voltage
ZVG	Zero Voltage Gap
ESR	Equivalent Series Resistance

LIST OF SYMBOLS

B_n	nth cell in top group
$B_{n'}$	nth cell in bottom group
S_n	nth switch in top group
$S_{n'}$	nth switch in bottom group
V_{Bn}	Voltage of nth cell in top group
$V_{Bn'}$	Voltage of nth cell in bottom group
f_s	Switching frequency
f_r	Resonant frequency
L	Inductance in every RLC tank
C	Capacitance in every RLC tank
R	Parasitic resistance
R_{SC}	Equivalent resistance
i_{Cn}	Capacitor current of nth cell in top group
$i_{Cn'}$	Capacitor current of nth cell in bottom group
ωr	Resonant angular frequency
V_L	Inductor voltage
V_C	Capacitor voltage
V_R	Resistance voltage
V_{cn_min}	Minimum voltage of nth capacitor in top group
$V_{cn'\_min}$	Minimum voltage of nth capacitor in bottom group
V_{cn_max}	Maximum voltage of nth capacitor in top group
$V_{cn'\_max}$	Maximum voltage of nth capacitor in bottom group
ΔVcn	nth capacitor ripple voltage in top group
$\Delta Vcn'$	nth capacitor ripple voltage in bottom group
Q	Quality factor
I_{Bn}	Current from nth cell in top group
$I_{Bn'}{}^{*}$	Current from nth cell in bottom group

CHAPTER 1

INTRODUCTION

1.1 Background of Battery Management Systems

Batteries play an important role in modern electrical systems, especially in electric vehicles (EVs) and renewable energy applications. In electric vehicles, batteries provide the electrical energy required to run the motor and other vehicle components. The increasing use of EVs is mainly due to the growing need for clean and sustainable transportation. Similarly, in renewable energy systems such as solar and wind power plants, batteries are used to store excess energy and supply power when generation is low. Among different battery technologies, lithium-ion batteries are widely preferred because of their high energy density, long life cycle, lightweight nature, and better efficiency. Since these applications require reliable and safe battery operation, proper battery management becomes very important.

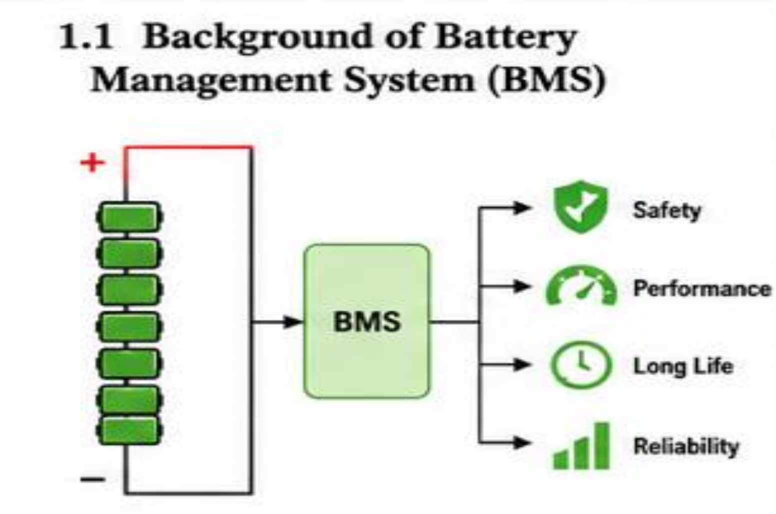


Figure 1.1 Background of BMS

1.1.1 Need for Battery Management Systems

A battery pack is usually made up of many cells connected together in series or parallel combinations. During operation, differences in temperature, aging, and manufacturing variations can cause unequal behavior among the cells. This may lead to problems such as overcharging, deep discharging, overheating, and reduced battery life. To avoid these issues, a Battery Management System (BMS) is used. A BMS is an electronic control system that monitors and controls the battery pack to ensure safe, reliable, and efficient operation. It helps improve battery performance, increases lifespan, and protects the system from damage.

Figure 1.1.1 Need for BMS

1.1.2 Monitoring Function of BMS

One of the main functions of the BMS is monitoring the battery parameters such as voltage, current, and temperature. The system continuously checks the condition of individual cells and the overall battery pack during charging and discharging. By monitoring these parameters in real time, the BMS can detect abnormal conditions early and maintain stable battery performance.

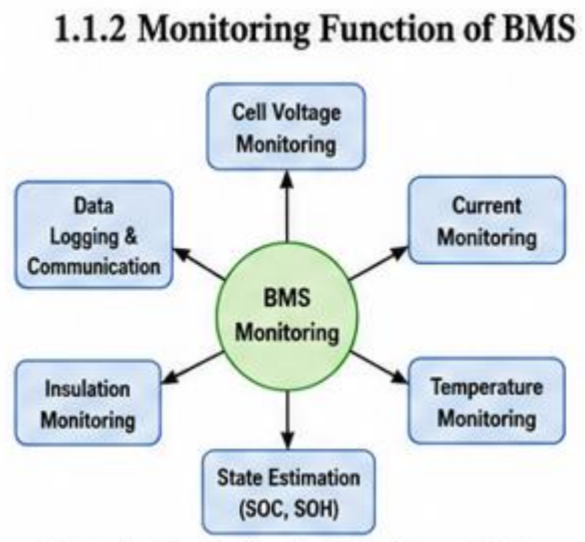


Figure 1.1.2 Monitoring Functions of BMS

1.1.3 Protection Function of BMS

The BMS also provides protection to the battery pack from unsafe operating conditions. Lithium-ion batteries are sensitive to overcharging, over-discharging, overheating, and short circuits. If these conditions are not controlled, they can damage the battery and create safety risks. The BMS protects the battery by disconnecting the circuit whenever abnormal conditions occur, thereby improving safety and reliability.

1.1.3 Protection System of BMS

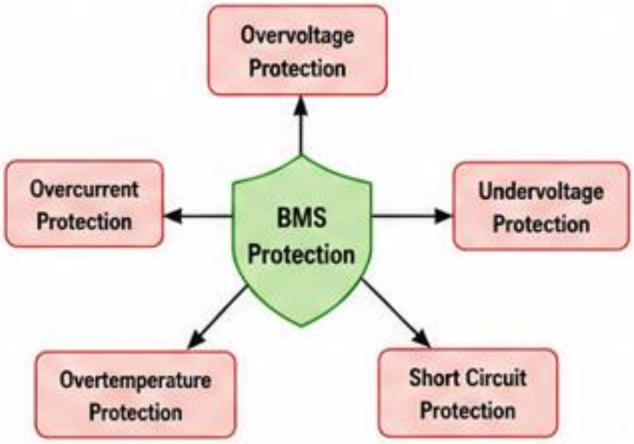


Figure 1.1.3 Protection System of BMS

1.1.4 State of Charge (SOC) Estimation

Another important function of the BMS is estimating the State of Charge (SOC) of the battery. SOC indicates the amount of charge remaining in the battery and is usually expressed as a percentage. Accurate SOC estimation helps determine the available battery capacity and improves energy management in electric vehicles and energy storage systems. Since SOC cannot be measured directly, the BMS calculates it using battery voltage, current, and mathematical methods.

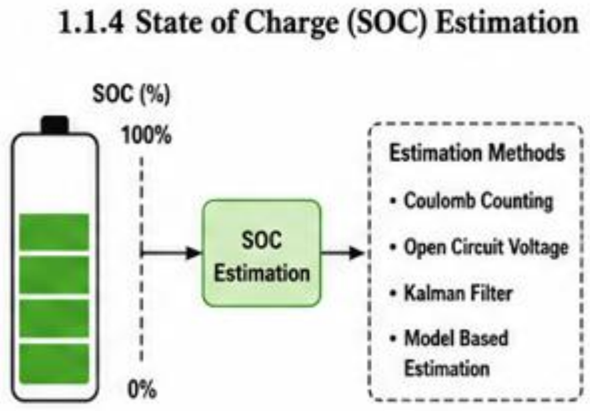


Figure 1.1.4 SOC Estimation

1.1.5 Cell Balancing Function of BMS

Cell balancing is one of the most important functions of the Battery Management System. In a battery pack, some cells may charge or discharge faster than others due to differences in capacity and internal resistance. This creates imbalance among the cells, which can reduce battery efficiency and lifespan. Cell balancing helps maintain equal voltage and charge levels among all cells. Balancing methods are mainly classified into passive and active techniques. Passive balancing removes excess energy as heat using resistors, while active balancing transfers energy between cells using components such as capacitors and inductors. Proper cell balancing improves battery performance, increases safety, and extends the overall life of the battery pack.

1.2 Need for Cell Balancing

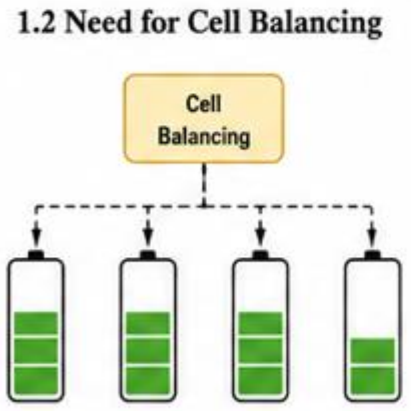


Figure 1.2 Need for Cell Balancing

1.2.1 Why Cells Become Unbalanced

In a battery pack, multiple cells are connected together to achieve the required voltage and capacity. During charging and discharging, these cells do not behave exactly the same because of differences in manufacturing, internal resistance, temperature, and aging. Some cells may charge faster while others discharge more quickly, leading to unequal voltage and State of Charge (SOC) levels among the cells. Over time, this difference increases and creates imbalance within the battery pack. Therefore, cell balancing is necessary to maintain uniform performance of all cells.

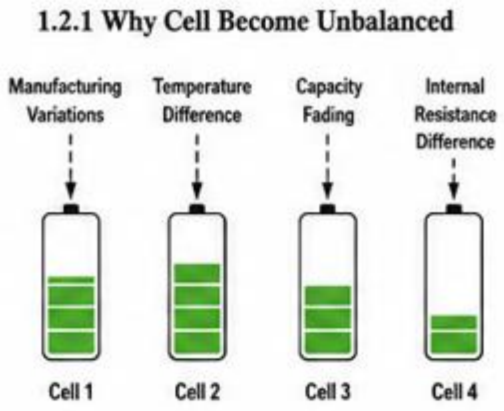


Figure 1.2.1 Why Cell Become Unbalanced

1.2.2 Reduced Battery Life

Cell imbalance can significantly reduce the lifespan of the battery pack. When certain cells are repeatedly overcharged or deeply discharged, they experience higher stress and degrade faster than other cells. As a result, the overall battery pack performance decreases even if some cells are still in good condition. Proper cell balancing helps distribute charge evenly among all cells and improves battery life.

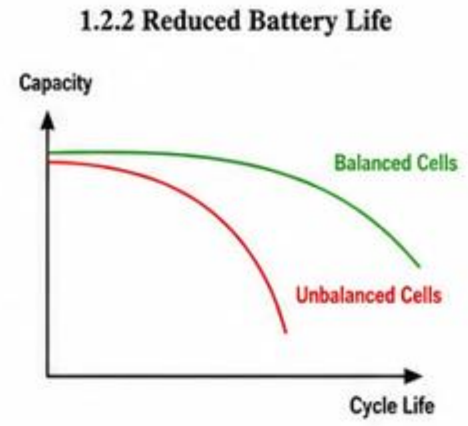


Figure 1.2.2 Reduced Battery Life

1.2.3 Reduced Capacity

An unbalanced battery pack cannot utilize its full capacity efficiently. During charging, the charging process may stop when the highest voltage cell reaches its limit, even if other cells are not fully charged. Similarly, during discharging, the process may stop when the weakest cell reaches the minimum voltage limit. This reduces the usable capacity and overall efficiency of the battery pack.

Figure 1.2.3 Reduced Capacity

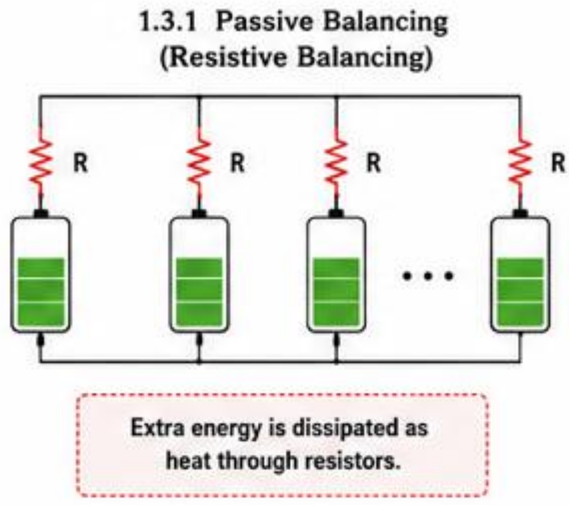
1.2.4 Safety Issues and Overcharging/Discharging

Cell imbalance can also create serious safety problems in lithium-ion batteries. Overcharging a cell may cause overheating, swelling, or thermal runaway, while deep discharging can permanently damage the cell. These conditions not only reduce battery performance but also increase the risk of fire and system failure. Cell balancing helps maintain safe voltage limits for all cells and ensures reliable and safe battery operation.

1.3 Types of Cell Balancing Techniques

1.3.1 Passive Balancing (Resistive Balancing)

Passive balancing is the simplest and most commonly used cell balancing technique in Battery Management Systems. In this method, excess energy from higher charged cells is dissipated as heat through resistors until all cells reach a similar voltage level. The circuit design of passive balancing is simple, low in cost, and easy to implement. However, since the extra energy is wasted in the form of heat, the overall efficiency of the system is lower compared to active balancing methods.

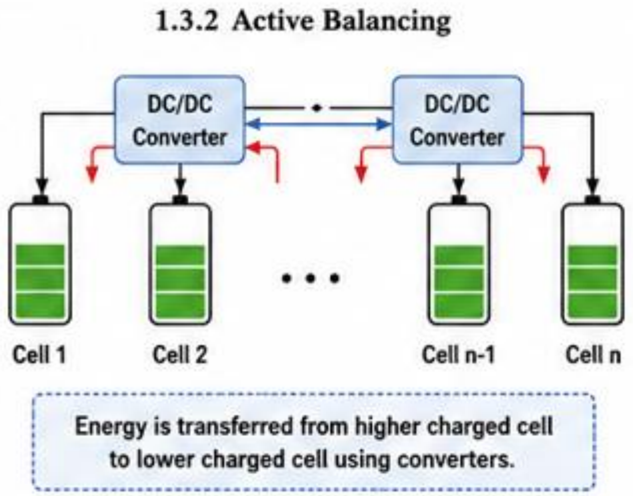


Extra energy is dissipated as heat through resistors.

Figure 1.3.1 Passive Balancing

1.3.2 Active Balancing

Active balancing methods improve battery efficiency by transferring energy from higher charged cells to lower charged cells instead of wasting it as heat. These methods are more efficient and suitable for applications such as electric vehicles and renewable energy storage systems where energy conservation is important. Although active balancing circuits are more complex and expensive, they provide better battery performance and longer lifespan.



1.3.2 Active Balancing

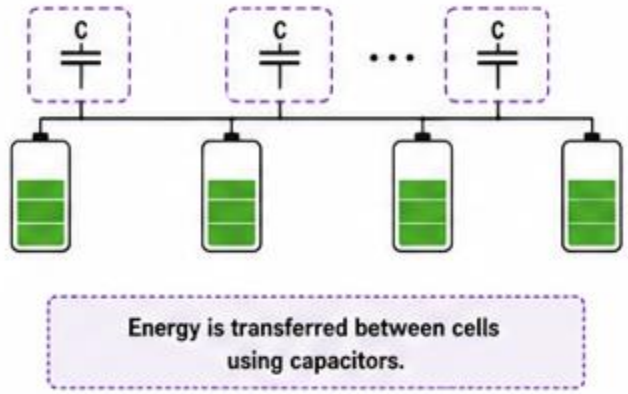
Energy is transferred from higher charged cell to lower charged cell using converters.

Figure 1.3.2 Active Balancing

1.3.3 Capacitor-Based Balancing

Capacitor-based balancing is an active balancing technique that uses capacitors to transfer energy between cells. In this method, the capacitor stores energy from a higher voltage cell and then transfers it to a lower voltage cell through controlled switching operations. This technique provides better efficiency than passive balancing and has a relatively simple structure among active balancing methods. However, the balancing speed is moderate and depends on the capacitor size and switching frequency.

1.3.3 Capacitive-based Balancing

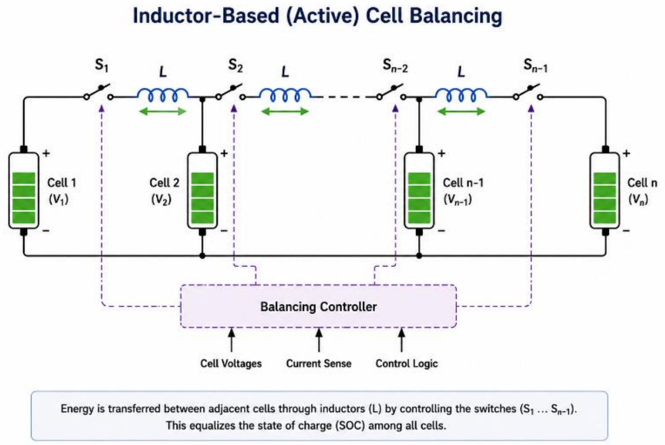


Energy is transferred between cells using capacitors.

Figure 1.3.3 Capacitive-based Balancing

1.3.4 Inductor-Based Balancing

Inductor-based balancing uses inductors or converter circuits to transfer energy between battery cells. This method is highly efficient and provides faster balancing compared to capacitor-based techniques. The inductor temporarily stores energy from higher charged cells and delivers it to lower charged cells with minimal energy loss. Due to its high efficiency and fast operation, inductor-based balancing is widely used in advanced battery systems. However, the circuit design and control strategy are more complex and costly.


Inductor-Based (Active) Cell Balancing

Energy is transferred between adjacent cells through inductors (L) by controlling the switches (S_1 … S_{n-1}).
This equalizes the state of charge (SOC) among all cells.

Figure 1.3.4 Inductor-based balancing

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This studies different cell balancing methods used in Battery Management Systems (BMS) with the help of MATLAB/Simulink. The work compares capacitor-based, inductor-based, and resistive balancing techniques to understand their performance in maintaining equal battery cell voltage. The study focuses on factors such as balancing time, energy efficiency, and overall battery performance. Simulation results show that each method has its own advantages and limitations. The project helps in understanding how proper cell balancing can improve battery life, safety, and reliability in applications such as electric vehicles and energy storage systems.

The simulation outcomes confirm that the proposed active balancing technique successfully minimizes cell-voltage differences, lowers stress on each cell, and enhances the overall performance and lifespan of the battery pack

2.2 Review of Battery Technologies

2.2.1 Lead-acid Battery

Lead-acid batteries are one of the oldest rechargeable batteries and are widely used in automobiles and backup power systems. They are low in cost, reliable, and capable of delivering high current. However, they are heavy, have low energy density, and require regular maintenance. Their environmental impact is also a concern because they contain lead and acid.

2.2.2 Nickel-Metal Hydride (NiMH) Battery

NiMH batteries provide higher energy density than lead-acid batteries and are more environmentally friendly because they do not contain toxic cadmium. They are commonly used in hybrid vehicles and portable electronic devices. These batteries have good performance and longer life, but they suffer from high self-discharge and are more expensive than lead-acid batteries.

2.2.3 Lithium-ion Battery

Lithium-ion batteries are the most advanced and widely used rechargeable batteries in modern devices and electric vehicles. They have high energy density, lightweight design, fast charging capability, and long lifespan. These batteries require low maintenance and provide high efficiency, making them ideal for modern applications. However, they are expensive and sensitive to overheating, so proper battery management systems are needed for safe operation.

2.3 Review Battery Parameters

2.3.1 State of Charge (SOC)

State of Charge, commonly known as SOC, represents the amount of energy remaining in a battery. It is usually expressed as a percentage, where 100% means the battery is fully charged and 0% means it is empty. SOC helps users understand how long a battery can continue to operate before recharging is needed.

2.3.2 State of Health (SOH)

State of Health refers to the overall condition and performance capability of a battery compared to a new battery. It indicates battery aging, capacity loss, and efficiency over time. A higher SOH means the battery is still in good condition, while a lower SOH shows that the battery performance has degraded.

2.3.3 Voltage

Voltage is one of the most important battery parameters because it indicates the electrical potential of the battery. The voltage level changes during charging and discharging processes and helps determine the operating condition of the battery. Stable voltage is necessary for proper and safe operation of electronic devices.

2.3.4 Temperature

Temperature greatly affects battery performance, safety, and lifespan. High temperatures can cause overheating and damage the battery, while very low temperatures can reduce battery efficiency and capacity. Therefore, maintaining an appropriate temperature is important for reliable battery operation.

2.3.5 Internal Resistance

Internal resistance is the opposition to the flow of current inside the battery. As a battery ages, its internal resistance increases, which reduces efficiency and causes heat generation. Lower internal resistance helps the battery deliver power more effectively and improves overall performance.

2.4 Review of Cell Balancing Methods

2.4.1 Passive Balancing

Passive balancing is one of the simplest and most commonly used battery balancing methods. In this method, extra energy from higher charged cells is removed as heat through resistors to make all cells reach the same voltage level. It is easy to design, low in cost, and reliable for small battery systems. However, passive balancing wastes energy in the form of heat and is less efficient for large battery packs.

2.4.2 Capacitor-Based Active Balancing

Capacitor-based active balancing transfers energy from one cell to another instead of wasting it. The switched capacitor method uses capacitors and switches to move charge between cells with different voltage levels. This method improves energy efficiency and reduces heat generation compared to passive balancing. Although it is more efficient, the balancing speed is usually slow and the control circuit becomes more complex for larger battery systems.

2.4.3 Inductor-Based Active Balancing

Inductor-based balancing uses inductors to transfer energy between cells more efficiently. In the single inductor method, one inductor is shared among multiple cells to move energy from high-voltage cells to low-voltage cells. This method provides better efficiency but requires complex switching control.

The multi-inductor method uses separate inductors for different cells, which increases balancing speed and improves performance. However, it also increases circuit size, cost, and design complexity.

Flyback converter-based balancing uses a transformer-based converter to transfer energy between cells or battery packs. It offers high efficiency and electrical isolation, making it suitable for large battery systems such as electric vehicles. However, the circuit design is more complicated and expensive compared to other balancing methods.

Previous Research Papers on Cell Balancing Methods

One important research paper is **"Performance Comparison of Active Balancing Techniques for Lithium-Ion Batteries"** published in the *Journal of Power Sources* in 2014. The paper compares different balancing methods such as passive balancing, capacitor-based balancing, and inductor-based balancing. The study concluded that active balancing methods are more efficient because they transfer energy between cells instead of wasting it as heat.

Another useful study is **"An Active Balancing Method Based on SOC and Capacitance for Lithium-Ion Batteries in Electric Vehicles"** published in *Frontiers in Energy Research* in 2021. In this research, the authors used a capacitor-based balancing method combined with SOC estimation to improve balancing performance in electric vehicle batteries. The results showed better balancing accuracy and improved battery life.

A research paper titled **“Battery Management System Implementation with the Passive Control Method Using MOSFET as a Load”** explains the use of passive balancing in lithium-ion battery packs. The study focused on reducing voltage imbalance between cells using simple resistor-based balancing circuits. The paper highlighted that passive balancing is low-cost and easy to implement but causes energy loss in the form of heat.

Another recent review paper is **“Review of Cell-Balancing Schemes for Electric Vehicle Battery Management Systems”** published in 2024. This paper discussed different balancing methods including switched capacitor, single inductor, multi-inductor, and flyback converter techniques. The authors concluded that active balancing methods provide higher efficiency and are more suitable for electric vehicle applications.

CHAPTER 3

BATTERY MODELING AND BMS ARCHITECTURE

3.1 INTRODUCTION

The accurate modeling of lithium-ion batteries and the design of a robust Battery Management System (BMS) are foundational to the safe, efficient, and reliable deployment of energy storage systems. As lithium-ion technology continues to dominate portable electronics, electric vehicles, and grid-scale storage, understanding the electrochemical and electrical behavior of these cells becomes increasingly critical. A well-designed BMS not only monitors and controls the battery pack but also relies on precise mathematical models to estimate internal states that cannot be measured directly, such as the State of Charge (SOC) and State of Health (SOH).

This chapter presents the theoretical framework underlying lithium-ion battery modeling, with particular emphasis on the Equivalent Circuit Model (ECM) and the governing equations that describe battery terminal behavior. The chapter then describes the architecture of a Battery Management System, detailing its core functional blocks and how they interact with the battery model to deliver real-time monitoring, protection, and state estimation. Together, these elements form the analytical backbone of the work presented in subsequent chapters.

3.2 Lithium-Ion Battery Modeling

Lithium-ion batteries are complex electrochemical systems whose behavior spans multiple physical domains — electrochemical reactions, ionic transport, thermal dynamics, and electrical circuit response. Accurately capturing this behavior in a form suitable for real-time computation requires a model that balances physical fidelity with computational tractability. Several modeling paradigms have been proposed in the literature, ranging from high-fidelity physics-based models such as the Doyle–Fuller–Newman (DFN) model to purely data-driven approaches. For the purposes of BMS implementation, however, the Equivalent Circuit Model offers the most practical trade-off between accuracy and computational cost, and is therefore the focus of this section.

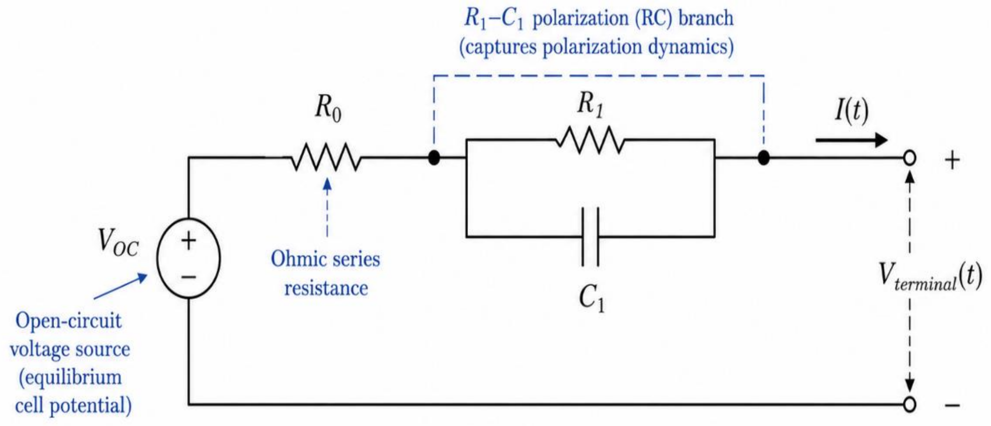
3.2.1 Equivalent Circuit Model

The Equivalent Circuit Model represents the battery as a network of idealized electrical components — resistors, capacitors, and a voltage source — whose parameters are derived from empirical measurements of the cell's electrical response. The fundamental idea is that the terminal voltage of a battery under load can be decomposed into three distinct contributions:

the open-circuit voltage that reflects the battery's thermodynamic equilibrium state, the instantaneous ohmic voltage drop due to the internal series resistance, and the time-varying voltage transients caused by charge diffusion and polarization processes within the cell.

The simplest form of the ECM is the first-order Randles circuit, also known as the single RC model, which captures these contributions using one series resistance and one parallel RC pair. The series resistance R_0 models the combined ohmic resistance of the electrolyte, electrode materials, and current collectors, and accounts for the instantaneous voltage step observed when a current is applied or removed. The parallel RC branch, consisting of polarization resistance R_1 and capacitance C_1, models the electrochemical double-layer effect and the slower diffusion-limited dynamics that produce the gradual voltage recovery seen after a load transient. The voltage source V_{OC}(SOC) represents the open-circuit voltage, which is a nonlinear, empirically determined function of the cell's State of Charge.

Figure 3.1: First-order Equivalent Circuit Model (Randles circuit) of a lithium-ion battery.



- V_{OC} represents the equilibrium cell potential (open-circuit voltage source).
- R_0 is the ohmic series resistance (captures instantaneous voltage drop due to internal resistance).
- R_1–C_1 is the RC branch capturing polarization dynamics (charge transfer and diffusion effects).
- $V_{terminal}$ is the measurable terminal voltage under load current $I(t)$.

Figure 3.1: First-order Equivalent Circuit Model (Randles circuit) of a lithium-ion battery. The open-circuit voltage source V_{OC} represents the equilibrium cell potential; R_0 is the ohmic series resistance; R_1–C_1 is the RC branch capturing polarization dynamics; and $V_{terminal}$ is the measurable terminal voltage under load current I(t).

For applications requiring greater accuracy over a wider range of operating conditions — particularly at high current rates or during fast transients — a second-order ECM can be employed, which adds an additional RC branch to capture the distinct time constants associated with surface film resistance and bulk diffusion. However, the first-order model is sufficient for most BMS applications and strikes a reasonable balance between parameter identifiability and model fidelity. In this work, the first-order ECM is adopted as the primary representation of cell dynamics.

The mathematical representation of the first-order ECM is governed by a set of coupled differential equations. The state variable of the RC branch, denoted V_1, represents the voltage across the parallel RC element and evolves according to the following first-order linear ODE:

$$dV_1/dt = -V_1 / (R_1 C_1) + I(t) / C_1 \qquad (3.1)$$

The terminal voltage of the battery, which is the quantity measured directly by the BMS hardware, is then expressed as the algebraic combination of the open-circuit voltage, the ohmic drop across R_0, and the polarization voltage V_1:

$$V_t(t) = V_{OC}(SOC) - I(t) \cdot R_0 - V_1(t) \qquad (3.2)$$

Here, the sign convention follows the convention that discharge current $I(t)$ is positive. Under this convention, both the ohmic drop and the polarization voltage reduce the terminal voltage during discharge and increase it during charging. The parameters R_0, R_1, and C_1 are not fixed constants but are functions of both the State of Charge and temperature, and are typically identified through pulse discharge experiments combined with curve fitting or recursive least-squares methods.

3.2.2 State of Charge Estimation

The State of Charge is perhaps the most critical internal state variable in a battery management system, as it serves as a direct indicator of the remaining available energy. Despite its fundamental importance, SOC cannot be measured directly by any available sensor — it must be estimated through algorithms that integrate measured quantities such as current, voltage, and temperature. Two principal approaches are widely employed: the Coulomb counting method, which integrates the current over time, and the Extended Kalman Filter (EKF), which fuses Coulomb counting with voltage-based correction using the ECM as a process model.

The Coulomb counting equation, also known as the ampere-hour integration method, defines the SOC at time t as follows:

$$SOC(t) = SOC(t_0) - \int_{t_0}^{t} [\eta \cdot I(\tau) / Q_n] \, d\tau \qquad (3.3)$$

In this equation, SOC(t_0) is the initial SOC at the start of estimation, $I(\tau)$ is the instantaneous current at time τ (positive for discharge), η is the Coulombic efficiency (typically close to unity for lithium-ion cells), and Q_n is the nominal capacity of the battery in ampere-hours. In discrete-time implementation, which is the form used in embedded BMS controllers, this equation reduces to:

$$SOC[k+1] = SOC[k] - (\eta \cdot I[k] \cdot \Delta / Q_n \qquad (3.4)$$

where k denotes the discrete time index and Δt is the sampling interval. The simplicity of this formulation makes it computationally inexpensive and suitable for low-power microcontroller implementations. However, Coulomb counting accumulates errors over time due to sensor noise, current measurement offset, and uncertainty in the initial SOC value. These limitations motivate the use of observer-based methods such as the Extended Kalman Filter, which continuously corrects the SOC estimate by exploiting the relationship between SOC and terminal voltage captured by the ECM.

The following table summarizes the key variables and parameters used in the ECM and SOC equations presented in this section.

Symbol	**Description**	**Unit**
$V_t(t)$	Battery terminal voltage at time t	V
$V_{OC}(SOC)$	Open-circuit voltage as a function of SOC	V
$V_1(t)$	Voltage across polarization RC branch	V
$I(t)$	Applied current (positive = discharge)	A
R_0	Internal ohmic resistance	Ω
R_1	Polarization resistance	Ω
C_1	Double-layer	F

Symbol	Description	Unit
	capacitance	
Q_n	Nominal battery capacity	Ah
H	Coulombic (charge) efficiency	—
Δt	Sampling time interval	s
SOC[k]	State of Charge at discrete time step k	0–1

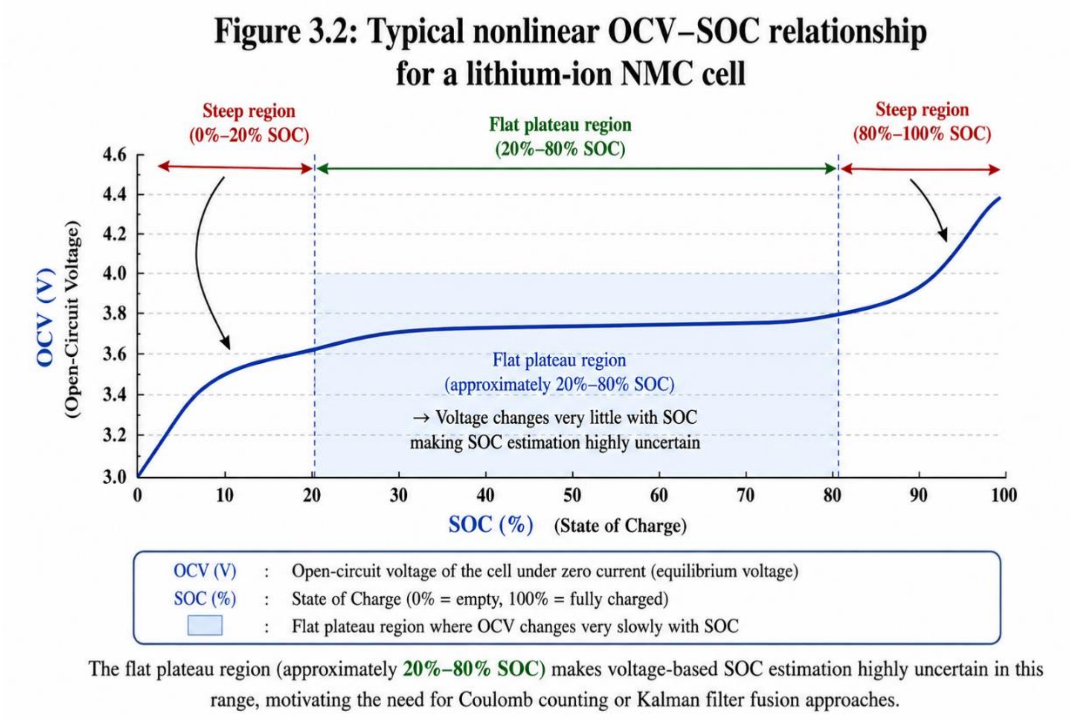


Figure 3.2: Typical nonlinear OCV–SOC relationship for a lithium-ion NMC cell. The flat plateau region (approximately 20%–80% SOC) makes voltage-based SOC estimation highly uncertain in this range, motivating the need for Coulomb counting or Kalman filter fusion approaches.

A critical characteristic of lithium-ion cells that complicates SOC estimation is the nonlinear shape of the OCV–SOC curve. As illustrated in Figure 3.2, the open-circuit voltage exhibits a relatively flat plateau over a wide range of SOC — typically between 20% and 80% for NMC chemistry — where a large change in SOC produces only a small change in open-circuit voltage. In this plateau region, voltage measurements alone are nearly uninformative for estimating SOC, and even small measurement errors translate to large SOC uncertainties. At the extremes of the SOC range, the curve becomes steep, providing stronger observability but also indicating regions of potential lithium plating and accelerated aging. This nonlinear characteristic underscore the importance of combining current integration with voltage-based correction in any practical SOC estimation scheme.

The ECM-based model and the SOC estimation equations presented in this section form the computational core of the BMS state estimation algorithm implemented in this work. In subsequent sections, the architecture of the full BMS is described, including the hardware sensing front-end, the embedded estimation algorithms, and the protection and balancing functions that together constitute a complete battery management solution.

3.3 Battery Pack Configuration

In practical applications, a single lithium-ion cell rarely delivers the voltage or energy capacity required by the load. Electric vehicles, energy storage systems, and industrial equipment demand pack-level voltages and capacities that are orders of magnitude beyond what a single cell — typically rated between 3.0 V and 4.2 V with a capacity of a few ampere-hours — can provide. To meet these demands, individual cells are interconnected in specific topologies, of which series connection and parallel connection are the two fundamental configurations. A real battery pack generally employs a combination of both, and the resulting arrangement introduces challenges related to cell mismatch that the BMS must actively manage.

3.3.1 Series Connection

When cells are connected in series, the positive terminal of each cell is linked to the negative terminal of the next, forming a single current path through all cells in the string. This arrangement multiplies the terminal voltage of the pack by the number of series-connected cells while keeping the total current capacity equal to that of a single cell. For a string of n_s cells connected in series, the pack voltage is given by:

$$V_{pack} = \sum_{i=1}^{n_s} V_i \approx n_s \cdot V_{nom} \qquad (3.5)$$

where V_i is the terminal voltage of the i-th cell and V_{nom} is the nominal voltage of a single cell. Since the same current flows through every cell in the string, the capacity of the series pack is identical to that of one cell — the series configuration offers voltage scaling without energy capacity gain. A critical implication of the series topology is that the weakest cell in the string governs the discharge and charge limits of the entire pack: if any single cell reaches its minimum or maximum voltage threshold before the others, the BMS must terminate the operating cycle for the whole string to prevent damage. This asymmetry between cell states becomes the primary source of energy loss in a series pack and motivates the need for cell balancing.

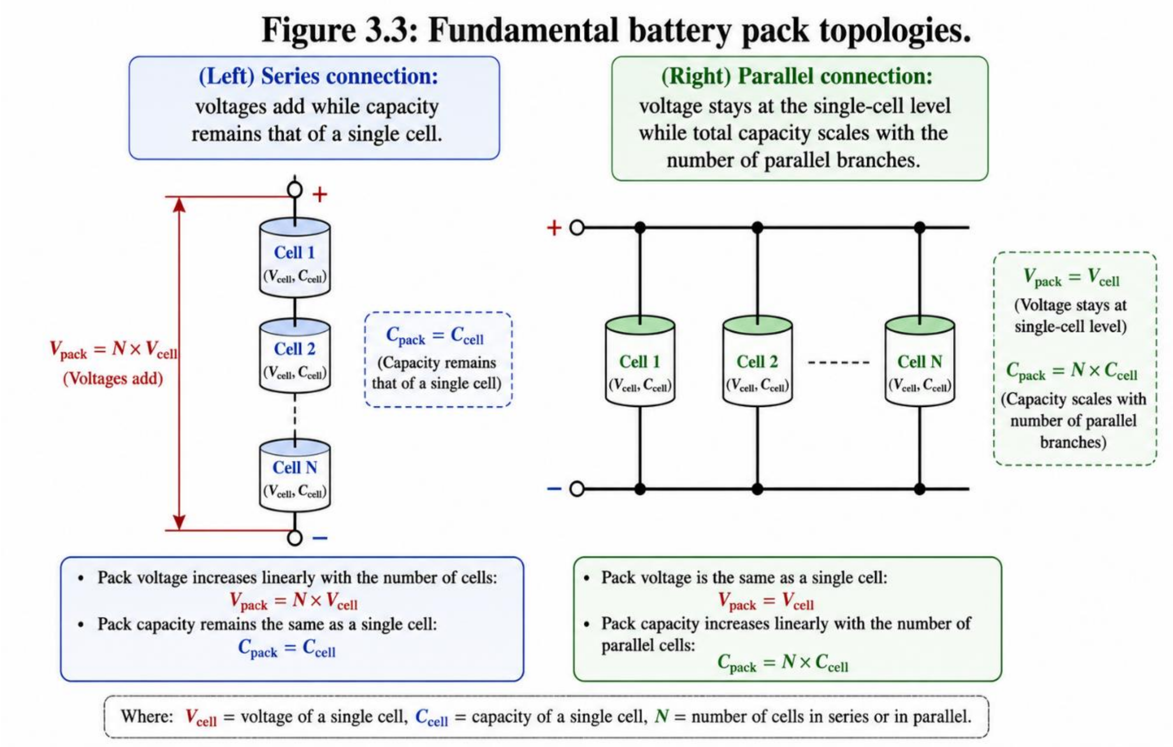


Figure 3.3: Fundamental battery pack topologies. (Left) Series connection: voltages add while capacity remains that of a single cell. (Right) Parallel connection: voltage stays at the single-cell level while total capacity scales with the number of parallel branches.

3.3.2 Parallel Connection

In the parallel configuration, all positive terminals are connected together and all negative terminals are connected together, forming a single large equivalent cell. Because every parallel-connected cell is exposed to the same terminal voltage, the pack voltage equals the voltage of any single cell, while the total deliverable capacity is the sum of the capacities of all parallel branches. For a group of n_p cells in parallel, the aggregate capacity is:

$$Q_{total} = n_p \cdot Q_{cell} \quad \text{and} \quad I_{total} = \sum_{j=1}^{n_p} I_j \qquad (3.6)$$

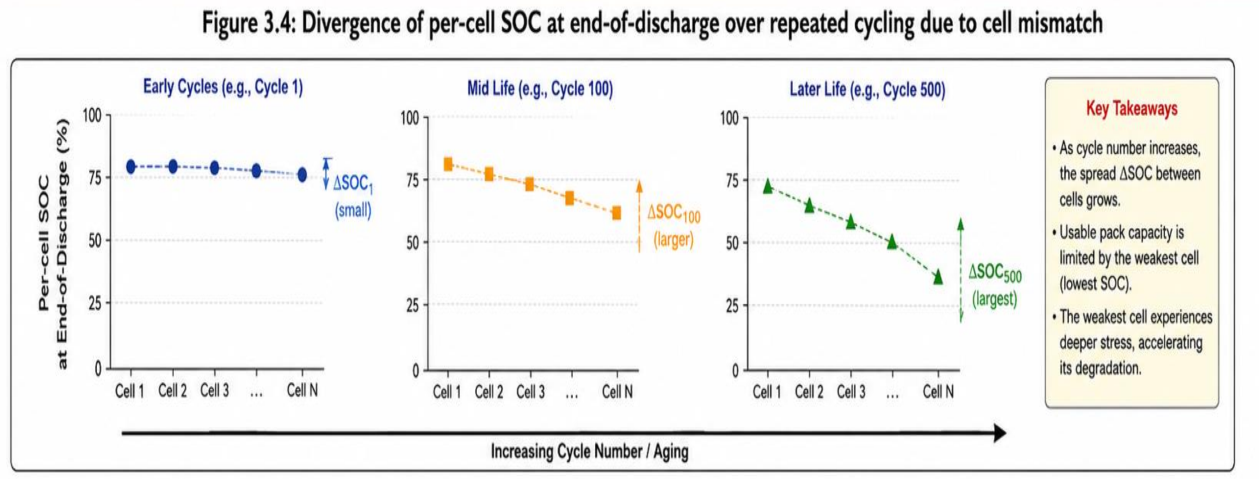
Since the voltage across each parallel branch is constrained to be equal, the current distributes among cells in proportion to their individual internal conductances. In an ideal case where all cells are perfectly matched, the current is shared equally. In practice, differences in internal resistance cause unequal current sharing, which can lead to thermal gradients and differential aging within the parallel group. Unlike the series case — where voltage monitoring of individual cells is straightforward — monitoring individual cell currents within a parallel group requires additional current sensors, making state estimation more complex and expensive.

In real battery packs, a combination of both configurations is employed, typically described as an n_sP×n_pS arrangement. For example, a 4P×10S pack consists of groups of four parallel cells, with ten such groups connected in series. This hybrid arrangement achieves the desired pack voltage through series connectivity while using parallel grouping to obtain the required capacity and to reduce the effective internal resistance of each series element.

3.3.3 Cell Mismatch and Its Consequences

Even when cells are manufactured to the same nominal specification, no two lithium-ion cells are perfectly identical. Variations arising during manufacturing — differences in electrode coating thickness, separator porosity, electrolyte fill volume, and tab welding quality — result in cells with slightly different initial capacities, internal resistances, and self-discharge rates. These initial manufacturing tolerances are compounded over time by differential aging: cells at different positions in the pack experience different thermal environments, different depth-of-discharge profiles, and different mechanical stresses, all of which cause their states to diverge progressively.

In a series string, this state divergence manifests as a spread in the cell SOC values at any given point in time. Consider a series string of cells that begins with small initial SOC differences. During discharge, all cells carry the same current and therefore undergo the same incremental capacity removal. However, because cells differ in their usable capacity and self-discharge behavior, their SOC trajectories evolve at slightly different rates. Over repeated cycles, the spread in cell SOC values grows, a phenomenon known as SOC imbalance. The operational consequence is that the most discharged cell in the string will reach the lower voltage cutoff while other cells still have residual charge, reducing the effective pack capacity below the sum of individual cell capacities. Similarly, during charging, the cell with the highest SOC will reach the upper voltage limit first, halting the charge cycle prematurely. If the BMS fails to detect and respond to this imbalance, the most stressed cells will be repeatedly pushed to their limits, accelerating their degradation and ultimately leading to pack-level capacity fade and potential safety hazards.



- As cycle number increases, the spread ΔSOC between cells grows.
- Usable pack capacity is limited by the weakest cell (lowest SOC).
- The weakest cell experiences deeper stress, accelerating its degradation.

Figure 3.4: Divergence of per-cell SOC at end-of-discharge over repeated cycling due to cell mismatch. As cycle number increases, the spread ΔSOC between cells grows, reducing usable pack capacity and accelerating degradation of the weakest cell.

Addressing cell mismatch is one of the central functions of the BMS. Cell balancing algorithms — either passive (dissipating excess charge from higher-SOC cells as heat) or active (redistributing charge between cells) — are designed to minimize the SOC spread and allow the pack to operate at maximum utilization. The mismatch problem also has direct implications for pack sizing: engineers must either over-provision capacity to tolerate the expected spread or invest in tighter manufacturing tolerances and active balancing hardware.

3.4 BMS Architecture

A Battery Management System is the intelligent electronic subsystem responsible for monitoring, protecting, and optimizing the operation of a battery pack throughout its service life. It acts as the interface between the battery and the rest of the system, providing real-time state information to the host controller while enforcing safe operating boundaries at all times. The architecture of a modern BMS can be conceptually organized into four functional layers: the sensing front-end, the central controller and estimation engine, the cell balancing circuit, and the protection system. These layers do not operate in isolation but interact continuously, with measurement data flowing from the sensing layer upward to the controller, and control commands flowing downward from the controller to the balancing and protection circuits.

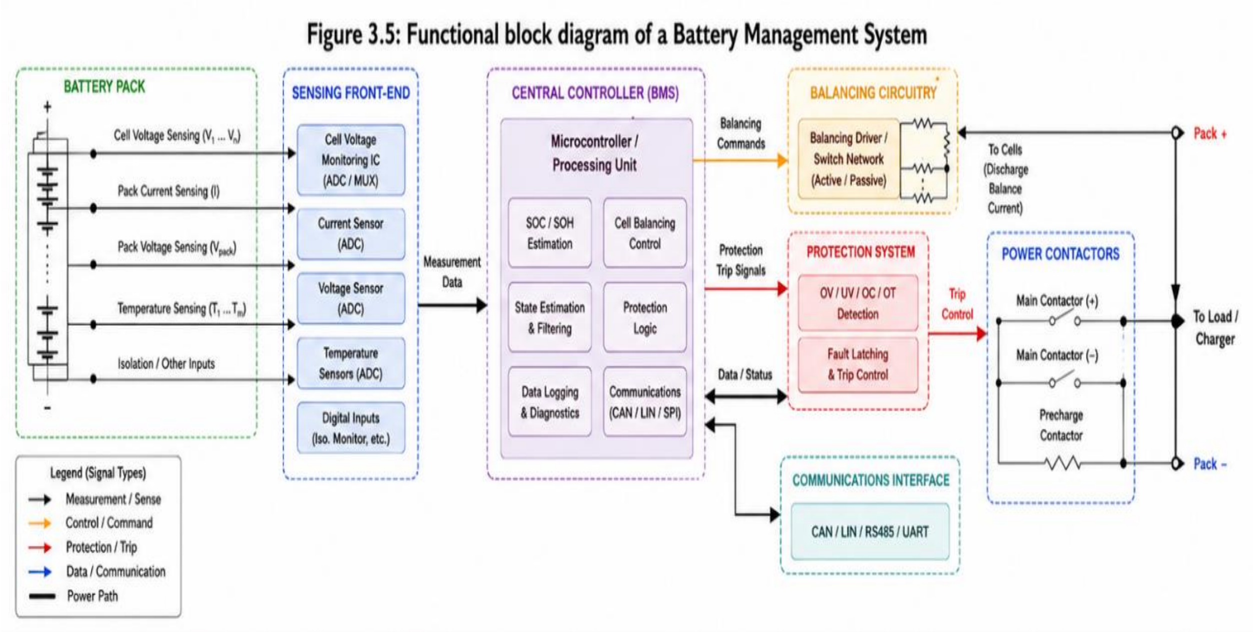


Figure 3.5: Functional block diagram of a Battery Management System. Measurement data flows from the sensing front-end to the central controller, which issues balancing commands and protection trip signals. The protection system controls the main contactors that isolate the pack from the load or charger.

3.4.1 Sensing Front-End

The sensing front-end is the data acquisition layer of the BMS, responsible for converting physical quantities — cell voltages, pack current, and temperature — into digital signals that can be processed by the controller. Cell voltage measurement is the most granular sensing requirement: each cell in the series string must be individually monitored to detect overvoltage, undervoltage, and SOC imbalance. High-precision analog-to-digital converters, often integrated into dedicated battery monitoring ICs, sample cell voltages with resolutions typically in the range of 0.5 mV to 2 mV and at rates of several samples per second. Pack current is measured using either a Hall-effect transducer or a precision shunt resistor, the latter offering higher accuracy at the cost of a small power dissipation. Temperature is sensed using negative temperature coefficient (NTC) thermistors placed at representative locations within the pack, including near cells, bus bars, and the power electronics. Because lithium-ion cells exhibit strong temperature-dependent behavior in their electrochemical kinetics and their degradation mechanisms, accurate temperature measurement is critical for both state estimation and thermal management.

3.4.2 Central Controller

The central controller is the computational core of the BMS. It receives digitized measurements from the sensing front-end and executes the state estimation algorithms — primarily Coulomb counting, the Extended Kalman Filter, or model-based observers — to produce real-time estimates of SOC, SOH, and remaining useful life. Beyond state estimation, the controller implements the cell balancing algorithm, deciding at each sampling interval which cells to balance and by how much. It also enforces the operating window by comparing measured quantities against pre-defined protection thresholds and issuing gate signals to the protection circuit when a limit is exceeded. In multi-module or multi-pack systems, the controller communicates pack status to the host system through a serial communication bus, most commonly the Controller Area Network (CAN) protocol, which provides robust error-checking and real-time data exchange suitable for automotive and industrial environments.

3.4.3 Cell Balancing Circuit

The balancing circuit acts on the controller's commands to redistribute or dissipate charge among cells in the series string, progressively reducing the SOC spread that arises from cell mismatch. Passive balancing, the simpler and more economical approach, connects a bypass resistor across cells that are identified as overcharged relative to the rest of the string, dissipating the excess charge as heat until all cells reach a uniform SOC. While passive balancing is straightforward to implement, its energy efficiency is poor for large SOC imbalances, since all the redistributed energy is wasted as heat. Active balancing, by contrast, transfers charge from high-SOC cells to low-SOC cells using inductive or capacitive converters — such as inductors, flying capacitors, or small DC-DC converters — achieving efficiencies of 80–95%. The choice between passive and active balancing involves trade-offs among cost, complexity, heat management, and the severity of the expected cell mismatch in the target application.

3.4.4 Protection System

The protection system is the last line of defense against conditions that could cause irreversible damage to the cells or create a safety hazard. It monitors six principal fault conditions: overvoltage (OVP), undervoltage (UVP), overcurrent (OCP), short-circuit detection (SCD), overtemperature (OTP), and under-temperature charging (which can induce lithium plating). Upon detection of any of these conditions, the protection circuit opens the main contactors — high-current switching elements placed in series with the battery pack — to immediately disconnect the pack from the load or charger. Modern BMS designs distinguish between hardware protection, which responds within microseconds using analog comparators and requires no firmware involvement, and software protection, which implements more nuanced algorithms that tolerate brief excursions above thresholds before tripping. The coexistence of both layers ensures that a firmware failure or software fault does not leave the pack unprotected.

CHAPTER 4

DESIGN OF CELL BALANCING METHODS

4.1 Resistive Cell Balancing Method

The resistive cell balancing method, also known as passive balancing, is one of the simplest and most widely used techniques in Battery Management Systems (BMS). In this method, excess energy from cells with higher voltage or higher state of charge (SOC) is dissipated in the form of heat through resistors. The main objective of resistive balancing is to ensure that all cells in the battery pack maintain nearly equal voltage and charge levels during charging and discharging operations.

In a lithium-ion battery pack, individual cells do not behave exactly the same because of manufacturing tolerances, temperature variations, and aging effects. Over time, some cells become overcharged while others remain undercharged. If this imbalance is not corrected, it can reduce battery capacity, decrease battery life, and create safety issues. The resistive balancing method solves this problem by discharging the cells that have higher voltage until all cell voltages become equal.

4.1.1 Working Principle

In the resistive balancing method, a resistor is connected across each battery cell through a controlled switch such as a MOSFET. When the BMS detects that a particular cell voltage exceeds a predefined threshold, the corresponding switch is turned ON. As a result, current flows through the resistor, and the extra energy stored in that cell is dissipated as heat. The balancing process continues until the voltage difference among the cells is minimized.

The balancing current flowing through the resistor can be calculated using Ohm’s law:

where $\boldsymbol{I_b}$is the balancing current, $\boldsymbol{V_{cell}}$is the cell voltage, and $\boldsymbol{R_b}$is the balancing resistor.

This equation shows that the balancing current depends on the value of the resistor. A smaller resistance produces a larger balancing current, resulting in faster balancing, but it also increases heat generation and power loss.

The power dissipated in the balancing resistor is given by:

$$\boldsymbol{P = I_b^2 R_b \ldots\ldots (4.1)}$$

The same power equation can also be expressed as:

$$P = \frac{V_{cell}^2}{R_b} \ldots\ldots\ldots(4.2)$$

where Prepresents the heat power dissipated through the resistor. This energy is lost as heat, which is the main disadvantage of passive balancing.

4.1.2 Balancing Operation

During charging, the BMS continuously monitors the voltage of each cell. If one cell reaches the maximum voltage limit earlier than others, the balancing resistor connected to that cell is activated. The resistor removes excess charge from the cell while the remaining cells continue charging. This allows all cells to reach a balanced state simultaneously.

The amount of charge removed from the cell during balancing is calculated as:

$$Q = I_b t \ldots\ldots\ldots(4.3)$$

where $Q$is the discharged charge, $I_b$is the balancing current, and $t$is the balancing time.

The reduction in State of Charge (SOC) during balancing can be represented by:

$$SOC = SOC_0 - \frac{1}{C_n} \int i(t)\, dt \ldots\ldots\ldots(4.4)$$

where $SOC_0$is the initial state of charge, $C_n$is the nominal battery capacity, and $i(t)$is the balancing current over time.

Terminal Voltage Equation

The battery terminal voltage is:

$$V_{terminal} = V_{OC} - IR_{int} \ldots\ldots\ldots(4.5)$$

Where:

- V_{OC}= Open circuit voltage
- I= Cell current
- R_{int}= Internal resistance

Power Dissipation in Resistor

- Energy is dissipated as heat:
- $P_b = I_b^2 R_b$
- Alternative form:
- $P_b = \frac{V_{cell}^2}{R_b}$

Energy Loss During Balancing

Energy dissipated over balancing time:

$$\boldsymbol{E_{loss} = P_b t}\ \ldots\ldots\ldots(\mathbf{4.6})$$

Where:

- $\boldsymbol{t}$= Balancing duration

Voltage Difference Between Cells

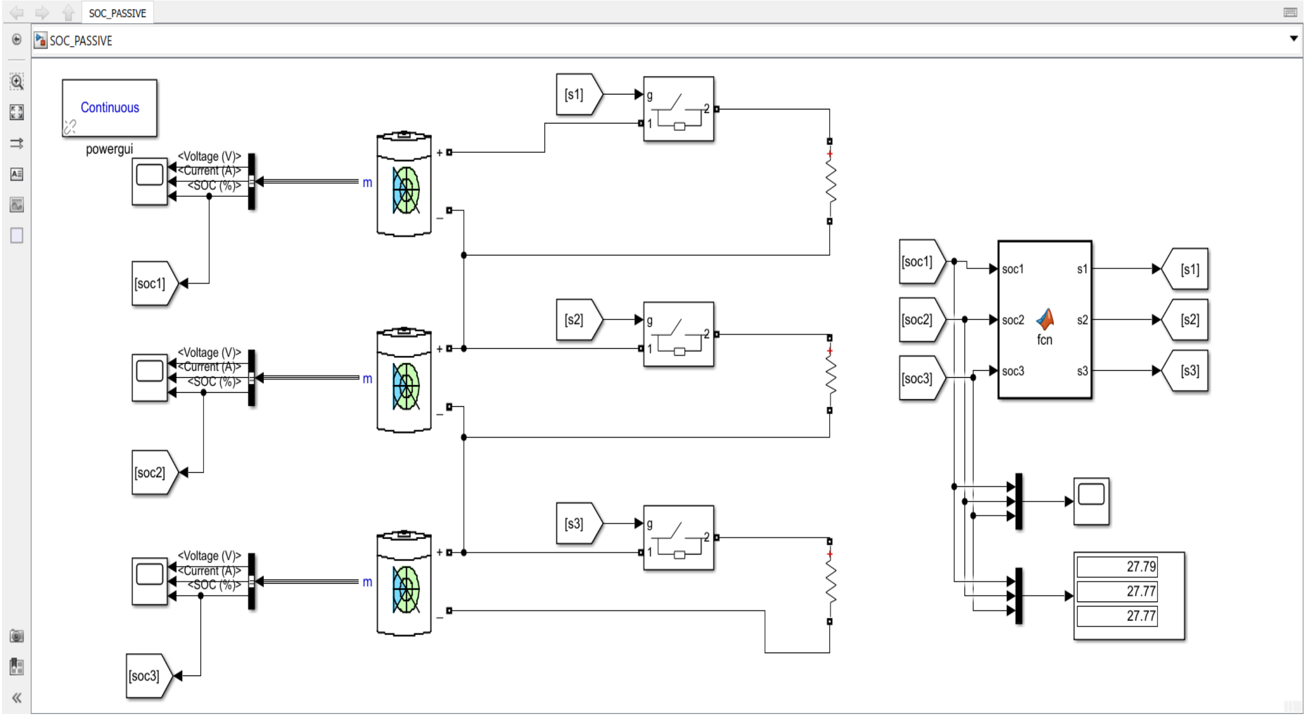
Voltage imbalance:

$$\Delta V = V_{max} - V_{min}\ \ldots\ldots\ldots(4.7)$$

Balancing starts when:

$$\boldsymbol{\Delta V > \Delta V_{threshold}}$$

4.1.3 MATLAB simulation



4.1.4 Advantages of Resistive Balancing

The resistive balancing method is simple, low-cost, and easy to implement in practical battery systems. It requires fewer components and simple control circuitry compared to active balancing techniques. Because of its simplicity and reliability, passive balancing is widely used in portable electronics, electric scooters, and low-cost electric vehicle battery packs.

4.1.5 Limitations of Resistive Balancing

Although resistive balancing is simple, it has some disadvantages. The major limitation is energy loss because the excess energy is converted into heat instead of being transferred to weaker cells.

This reduces overall system efficiency, especially in large battery packs. Additional cooling arrangements may also be required to manage the generated heat. Furthermore, passive balancing is slower compared to active balancing methods and is less suitable for high-capacity electric vehicle battery systems where energy efficiency is critical.

4.2 Switched Capacitor Balancing

The switched capacitor balancing method is one of the most commonly used capacitor-based balancing techniques because of its simple structure and low component count. In this method, a capacitor and electronic switches such as MOSFETs are used to transfer energy between neighboring cells. The switches are controlled by the BMS to connect the capacitor sequentially across different cells.

When the capacitor is connected to a cell with higher voltage, it stores electrical energy by charging to that cell voltage. After charging, the switch configuration changes, and the capacitor is connected to a neighboring lower-voltage cell. The stored energy is then released into the lower-voltage cell. This process repeats continuously until the voltage difference among the cells becomes very small.

The voltage across a charging capacitor is expressed as:

$$\boldsymbol{V_c(t) = V_s\left(1 - e^{-\frac{t}{RC}}\right)} \ldots\ldots\ldots (\mathbf{4.8})$$

where $\boldsymbol{V_c(t)}$is the capacitor voltage at time $\boldsymbol{t}$, $\boldsymbol{V_s}$is the source voltage, $\boldsymbol{R}$is the equivalent resistance, and $\boldsymbol{C}$is the capacitance.

During discharging, the capacitor voltage decreases according to:

$$\boldsymbol{V_c(t) = V_0 e^{-\frac{t}{RC}}} \ldots\ldots\ldots (\mathbf{4.9})$$

where $\boldsymbol{V_0}$is the initial capacitor voltage before discharge.

These equations show the charging and discharging behavior of the capacitor during energy transfer between cells.

4.2.1 Charge Transfer Mechanism

The charge transfer mechanism in switched capacitor balancing is based on the movement of electric charge between adjacent battery cells through the capacitor. If two neighboring cells have different voltages, the capacitor naturally transfers charge from the higher-voltage cell to the lower-voltage cell. The balancing speed depends on the capacitance value, switching frequency, and voltage difference between cells.

Initially, the capacitor is connected to the higher-voltage cell. The capacitor charges and stores energy according to:

$$\boldsymbol{Q = CV \ldots\ldots\ldots(4.10)}$$

where $\boldsymbol{Q}$is the stored charge, $\boldsymbol{C}$is the capacitance, and $\boldsymbol{V}$is the capacitor voltage.

The energy stored in the capacitor is given by:

$$\boldsymbol{E = \frac{1}{2}CV^2 \ldots\ldots(4.11)}$$

After charging, the capacitor is switched to the adjacent lower-voltage cell. Because the capacitor voltage is higher than the receiving cell voltage, current flows into the lower-voltage cell, transferring stored energy. The balancing current during charge transfer can be approximated by:

$$\boldsymbol{I(t) = \frac{\Delta V}{R}e^{-\frac{t}{RC}} \ldots\ldots(4.12)}$$

where $\boldsymbol{\Delta V}$is the voltage difference between cells and $\boldsymbol{R}$is the equivalent resistance in the transfer path.

The amount of charge transferred during one switching cycle is proportional to the voltage difference between adjacent cells. As balancing continues, the voltage difference gradually decreases, reducing the transfer current until equilibrium is reached.

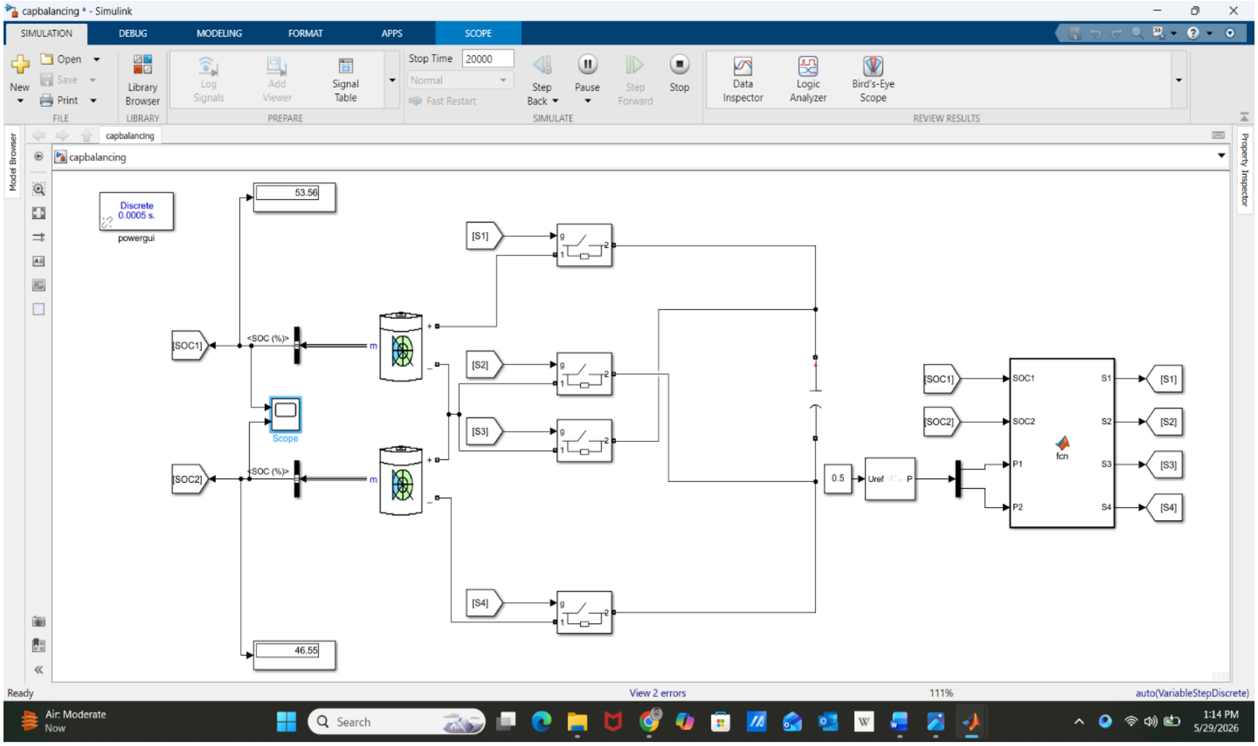
The average balancing current in switched capacitor balancing can be represented as:

$$\boldsymbol{I_{avg} = fC\Delta V \ldots\ldots(4.13)}$$

where $\boldsymbol{f}$is the switching frequency, $\boldsymbol{C}$is the capacitance, and $\boldsymbol{\Delta V}$is the voltage difference between cells.

This equation indicates that increasing the switching frequency or capacitance improves balancing speed. However, larger capacitors increase system size and cost, while very high switching frequencies may increase switching losses.

4.2.2 MATLAB Simulation



4.2.3 Performance of Capacitor-Based Balancing

Capacitor-based balancing offers better efficiency than resistive balancing because energy is redistributed among cells rather than dissipated as heat. The circuit structure is simpler than inductor-based balancing methods and does not require magnetic components. It also provides moderate balancing speed with relatively low cost.

However, switched capacitor balancing mainly transfers energy between adjacent cells, making the balancing process slower in large battery packs. The balancing current is also limited by the capacitor value and switching frequency. Despite these limitations, capacitor-based balancing remains a popular active balancing technique in medium-power battery applications because of its simplicity, compact design, and improved energy efficiency compared to passive balancing methods

4.2.4 Advantages of Capacitor-Based Balancing Method

The capacitor-based balancing method offers several important advantages compared to passive balancing techniques. One of the major advantages is higher energy efficiency. In this method, excess energy from higher-voltage cells is transferred to lower-voltage cells through capacitors instead of being dissipated as heat. As a result, energy loss is significantly reduced, which improves the overall efficiency of the battery pack. This characteristic makes capacitor-based balancing more suitable for electric vehicles and renewable energy storage systems where energy conservation is important.

Another important advantage is the simple circuit structure. Switched capacitor balancing circuits mainly consist of capacitors and semiconductor switches such as MOSFETs. Unlike inductor-based balancing methods, no magnetic components or transformers are required. This reduces circuit complexity, simplifies control implementation, and lowers the overall system size and weight. Because of the simple hardware configuration, the balancing circuit can also be integrated easily into compact battery management systems.

Capacitor-based balancing provides better thermal performance than resistive balancing. Since the transferred energy is reused rather than converted into heat, less heat is generated inside the balancing circuit. Reduced heat generation improves battery safety and minimizes the need for additional cooling systems. Lower thermal stress also helps improve the lifespan and reliability of both the battery cells and the electronic components.

The balancing speed of capacitor-based methods is generally faster than passive balancing methods. Continuous charge transfer between cells helps reduce voltage imbalance more efficiently during charging and discharging operations. The balancing current can be increased by selecting higher capacitance values or higher switching frequencies, allowing quicker equalization of cell voltages.

The method also provides automatic energy transfer between adjacent cells without requiring highly complex control algorithms. The natural voltage difference between cells drives the energy transfer process, making the system relatively easy to control and implement. This improves system reliability and reduces computational requirements for the battery management controller.

Capacitor-based balancing circuits are highly scalable and can be used in battery packs containing multiple lithium-ion cells. Because of their compact structure and moderate cost, they are widely used in medium-power applications such as electric scooters, portable energy systems, and hybrid electric vehicles.

4.2.5 Limitations of Capacitor-Based Balancing Method

Although capacitor-based balancing offers improved efficiency over passive balancing methods, it also has several limitations. One of the major limitations is the relatively slow balancing speed in large battery packs. In switched capacitor balancing, energy transfer mainly occurs between adjacent cells. Therefore, if the voltage imbalance exists between cells located far apart in the battery string, energy must pass through multiple intermediate cells before reaching the target cell. This indirect energy transfer process increases balancing time, especially in high-cell-count battery systems.

Another limitation is the restricted balancing current capability. The amount of charge transferred depends on the capacitance value and switching frequency. Practical limitations on capacitor size and switching speed restrict the maximum balancing current that can be achieved. As a result, capacitor-based balancing may not be suitable for applications requiring very fast balancing or high-power energy transfer.

The balancing performance is strongly affected by equivalent series resistance (ESR) of the capacitor and switching losses in semiconductor devices. During repeated charging and discharging cycles, energy losses occur because of internal resistance and switching operations. Although these losses are smaller than in passive balancing, they still reduce the overall efficiency of the system.

The switching control circuit becomes more complicated as the number of battery cells increases. Each capacitor requires multiple switches and proper timing control to ensure correct charge transfer between cells. In large battery packs, the number of switches and control signals increases significantly, making the circuit more difficult to design and manage.

Capacitor-based balancing also suffers from limited long-distance energy transfer capability. Unlike transformer-based or inductor-based balancing methods, switched capacitors cannot directly transfer energy from the highest-energy cell to the lowest-energy cell if they are far apart in the battery pack. This limitation reduces balancing efficiency in systems with severe cell imbalance.

Another disadvantage is capacitor voltage stress. Capacitors experience repeated charging and discharging cycles during balancing operation, which can reduce capacitor lifetime over long-term use. High-frequency switching may also introduce electromagnetic interference (EMI) and additional switching noise into the battery management system.

The balancing process becomes slower as the voltage difference between cells decreases. Since the balancing current depends on the voltage difference between adjacent cells, the transfer current naturally reduces near the final balancing stage. This increases the time required to achieve complete voltage equalization.

Despite these limitations, capacitor-based balancing remains an effective and widely used active balancing method because it provides a good compromise between circuit complexity, cost, balancing speed, and energy efficiency.

4.3 Single Inductor Balancing

The single inductor balancing topology uses one inductor and multiple switches to transfer energy among battery cells. The balancing controller connects the inductor sequentially to different cells using semiconductor switches such as MOSFETs. The inductor first absorbs energy from a higher-voltage cell and later releases that energy into a lower-voltage cell.

When the switch connected to the high-voltage cell is turned ON, current flows through the inductor, and energy is stored in the magnetic field. After a controlled switching interval, the first switch is turned OFF and another switch connected to the low-voltage cell is turned ON. The magnetic field then collapses, transferring stored energy into the lower-voltage cell.

The voltage-current relationship of the inductor is given by:

$$\boldsymbol{V_L = L\frac{di}{dt}} \;\dots\dots\dots\dots(\mathbf{4.14})$$

where $\boldsymbol{V_L}$is the voltage across the inductor, $\boldsymbol{L}$is the inductance, and $\boldsymbol{\frac{di}{dt}}$represents the rate of change of current.

This equation shows that the inductor opposes sudden changes in current and stores energy in the form of a magnetic field.

The energy stored in the inductor is expressed as:

$$\boldsymbol{E = \frac{1}{2}LI^2} \quad \dots\dots..(4.15)$$

where $\boldsymbol{E}$is the stored magnetic energy, $\boldsymbol{L}$is the inductance, and $\boldsymbol{I}$is the inductor current.

This stored energy is later transferred to the weaker cell during the balancing process.

4.3.1 Energy Transfer Principle

The energy transfer principle of inductor-based balancing is based on electromagnetic energy storage and controlled switching operations. When a cell with higher voltage is selected, the balancing circuit connects the inductor across that cell. Current gradually increases through the inductor, and magnetic energy accumulates inside it.

The current growth in the inductor during charging can be represented as:

$$\boldsymbol{i(t) = \frac{V}{L}t} \dots\dots\dots(\mathbf{4.16})$$

where $\boldsymbol{V}$is the source voltage and $\boldsymbol{L}$is the inductance.

After sufficient energy is stored, the switch connected to the source cell is turned OFF, and another switch connects the inductor to the lower-voltage cell. The magnetic field collapses and transfers the stored energy into the target cell.

The current decay during energy release is expressed as:

where I_0 is the initial inductor current and R is the equivalent resistance in the discharge path.

The transferred charge during balancing is given by:

$$Q = \int i(t)dt \ldots\ldots (4.17)$$

The balancing current depends on switching frequency, inductance value, and voltage difference between cells. Higher switching frequency allows faster energy transfer and quicker balancing operation.

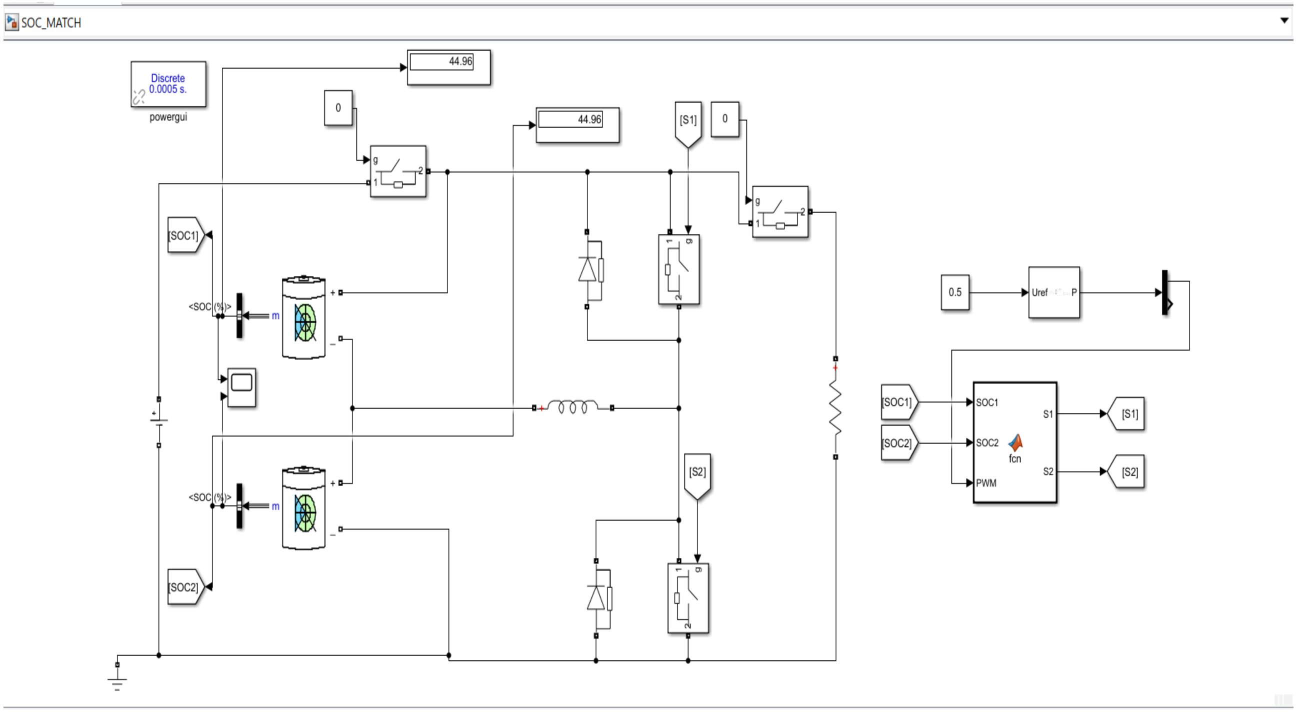
The average balancing current can be approximated by:

$$I_{avg} = \frac{\Delta VDT}{L} \ldots\ldots\ldots (4.18)$$

where ΔV is the voltage difference between cells, D is the duty cycle, T is the switching period, and L is the inductance.

This equation shows that balancing speed increases with larger voltage difference and higher duty cycle.

4.3.2 MATLAB Simulation



4.3.3 Converter Operation

The inductor balancing circuit operates similarly to a DC-DC converter. The balancing controller continuously monitors cell voltages and determines which cells require energy transfer. The converter operation consists mainly of two stages: energy storage mode and energy transfer mode.

During the energy storage stage, the switch connected to the higher-voltage cell turns ON, allowing current to build in the inductor. During the energy transfer stage, the source switch turns OFF and the target switch turns ON, transferring stored energy into the lower-voltage cell.

The duty cycle of the converter is defined as:

$$D = \frac{T_{ON}}{T} \dots\dots\dots (4.19)$$

where $T_{ON}$is the ON time of the switch and $T$is the total switching period.

The converter output voltage relationship for a buck-boost type balancing converter is approximately:

$$V_o = \frac{D}{1 - D} V_{in} \quad \dots\dots\dots (4.20)$$

where $V_o$is the output voltage and $V_{in}$is the input voltage.

These converter principles allow efficient and controlled energy transfer between cells.

4.3.4 High Efficiency

One of the most important advantages of inductor-based balancing is its high efficiency. Since energy is transferred magnetically rather than dissipated as heat, efficiency can reach very high values compared to passive balancing methods. Most of the excess energy from higher-voltage cells is recovered and delivered to weaker cells, minimizing energy loss.

The balancing efficiency can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \dots\dots\dots (4.21)$$

where $\eta$is efficiency, $P_{out}$is useful transferred power, and $P_{in}$is input power.

Because of low power dissipation, thermal stress is reduced, improving battery safety and lifetime.

4.3.5 Fast Balancing

Inductor-based balancing provides faster balancing speed than both resistive and capacitor-based methods. Large balancing currents can be achieved because inductors can handle higher power transfer. Direct energy transfer between distant cells is also possible, reducing balancing time in large battery packs.

Fast balancing is especially important in electric vehicles where large battery packs contain hundreds of cells. Quick balancing improves charging efficiency and ensures uniform battery operation during high-power conditions.

4.3.6 Complex Control

Although inductor-based balancing offers high efficiency and fast operation, its control system is more complex than other balancing methods. The balancing controller must carefully manage switch timing, current flow, duty cycle, and protection mechanisms to ensure safe energy transfer.

The system requires multiple sensors, gate driver circuits, and advanced switching algorithms. Improper switching may produce current spikes, voltage overshoot, or electromagnetic interference (EMI). The controller must also prevent simultaneous switching errors that could create short circuits.

In high-frequency operation, switching losses and magnetic core losses must also be considered. Therefore, the design and implementation of inductor-based balancing circuits require advanced control techniques and more sophisticated hardware.

4.3.7 Advantages of Inductor-Based Balancing Over Resistive and Capacitor-Based Balancing

Compared to resistive balancing, inductor-based balancing provides significantly higher energy efficiency because energy is redistributed instead of dissipated as heat. This reduces power loss and improves overall battery utilization. Thermal generation is much lower, which minimizes cooling requirements and improves battery lifespan.

Compared to capacitor-based balancing, the inductor method supports faster energy transfer and higher balancing current capability. Capacitor balancing mainly transfers energy between adjacent cells, whereas inductor balancing can directly transfer energy between non-adjacent cells. This makes balancing more effective in large battery packs with severe imbalance conditions.

Inductor-based balancing also achieves better scalability for high-power applications. It is widely used in electric vehicles, aerospace systems, and renewable energy storage because of its superior balancing performance.

4.3.8 Limitations of Inductor-Based Balancing

Despite its advantages, inductor-based balancing has several limitations. The major disadvantage is increased circuit complexity. The balancing system requires inductors, multiple power switches, current sensors, and sophisticated control circuits, making the hardware design more complicated than capacitor-based and resistive balancing methods.

The cost of the balancing system is also higher because magnetic components and advanced switching devices are required. Inductors occupy more physical space and increase the overall size and weight of the battery management system.

Another limitation is electromagnetic interference caused by high-frequency switching operations. Rapid switching produces electrical noise that may affect nearby electronic circuits. Additional filtering and shielding techniques are often required to reduce EMI.

Switching losses, core losses, and conduction losses also reduce practical efficiency. Although efficiency remains higher than other methods, these losses become significant at very high switching frequencies.

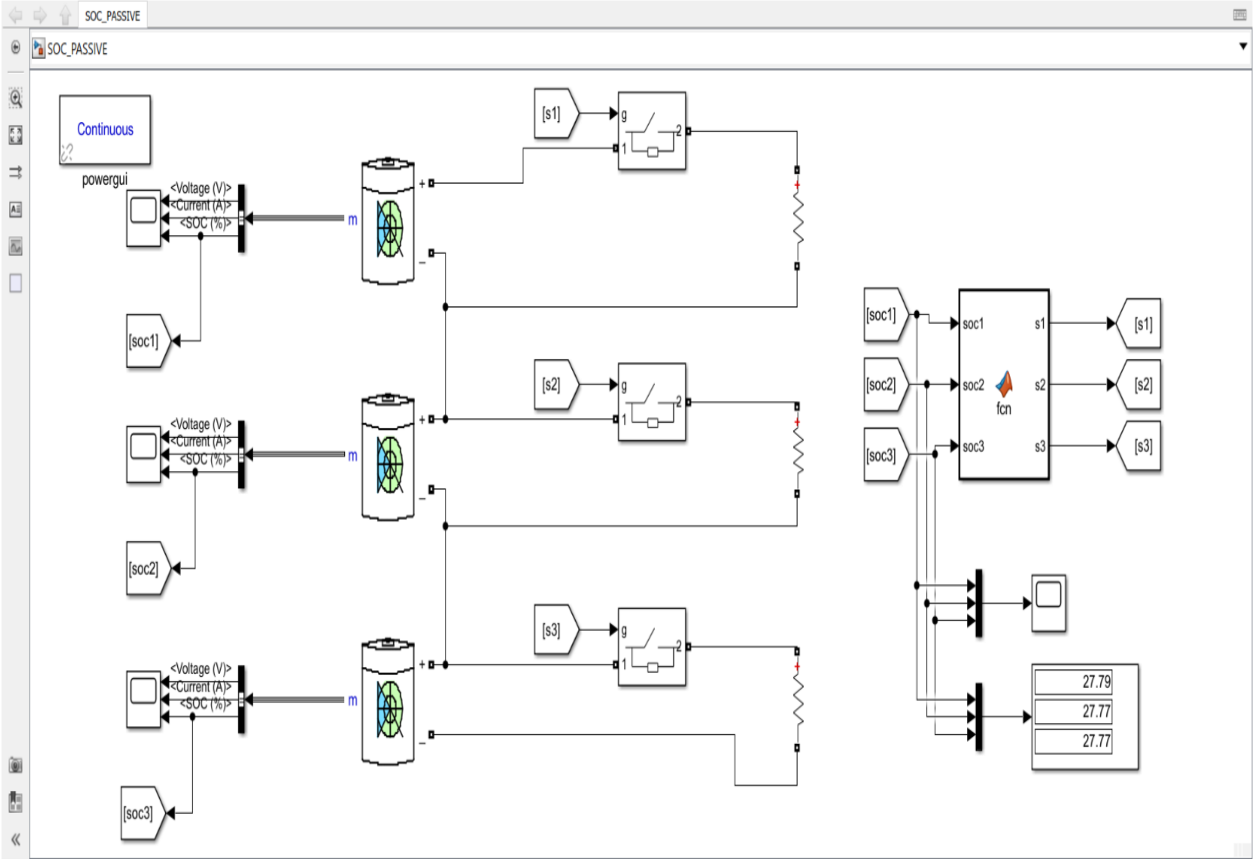
Furthermore, control algorithms for inductor-based balancing are more difficult to implement and require precise synchronization of switching signals. This increases computational requirements and system complexity in real-time battery management applications.

CHAPTER 5

RESULTS AND PERFORMANCE EVALUATION

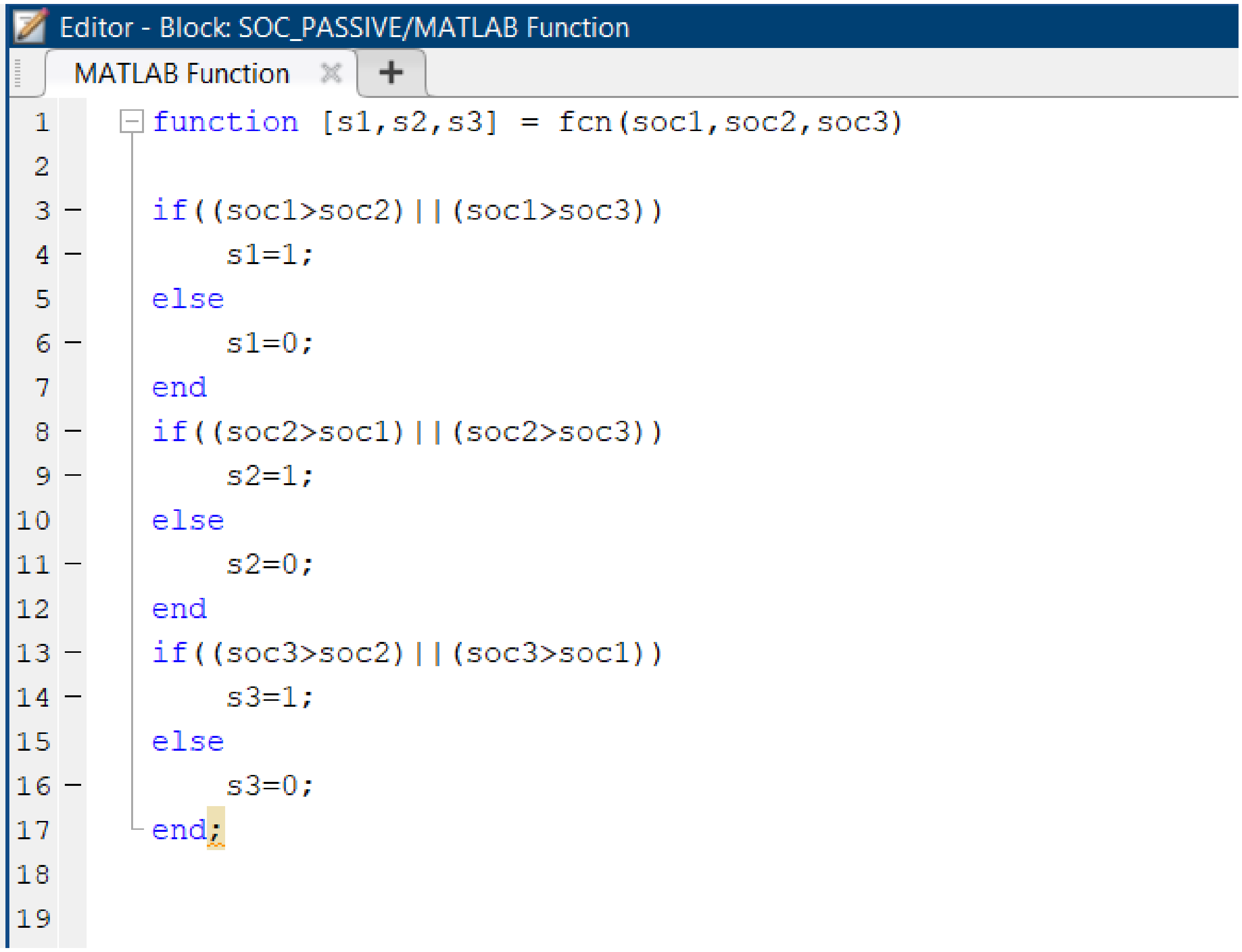
5.1 Resistive (Passive) cell balancing MATLAB/Simulation Setup

Resistive active cell balancing in MATLAB/Simulink provides a simple and effective method for studying battery equalization in lithium-ion battery packs. The simulation helps analyze voltage balancing behavior, SOC equalization, balancing current, and energy loss. Although the method is easy to implement, its major drawback is power dissipation in balancing resistors, which reduces overall system efficiency.



5.1.1 Switching sequence

The MATLAB function shown in the SOC_PASSIVE block is used to generate switching signals for passive cell balancing based on the comparison of the State of Charge (SOC) values of three battery cells. The logic continuously compares the SOC of each cell with the remaining cells in the battery pack. If the SOC of a particular cell is greater than the SOC of any other cell, the corresponding switching signal becomes HIGH (s1 = 1, s2 = 1, or s3 = 1). This HIGH signal activates the balancing switch connected to that cell, allowing excess energy to dissipate through the balancing resistor. For example, if soc1 is greater than either soc2 or soc3, switch s1 turns ON to discharge Cell 1. Similarly, the same logic is applied for Cells 2 and 3. When a cell does not have the highest SOC, its switching signal remains LOW (0), keeping the balancing circuit OFF. This switching sequence ensures that cells with higher charge levels are gradually discharged until all cell SOC values become nearly equal, thereby reducing imbalance within the battery pack.



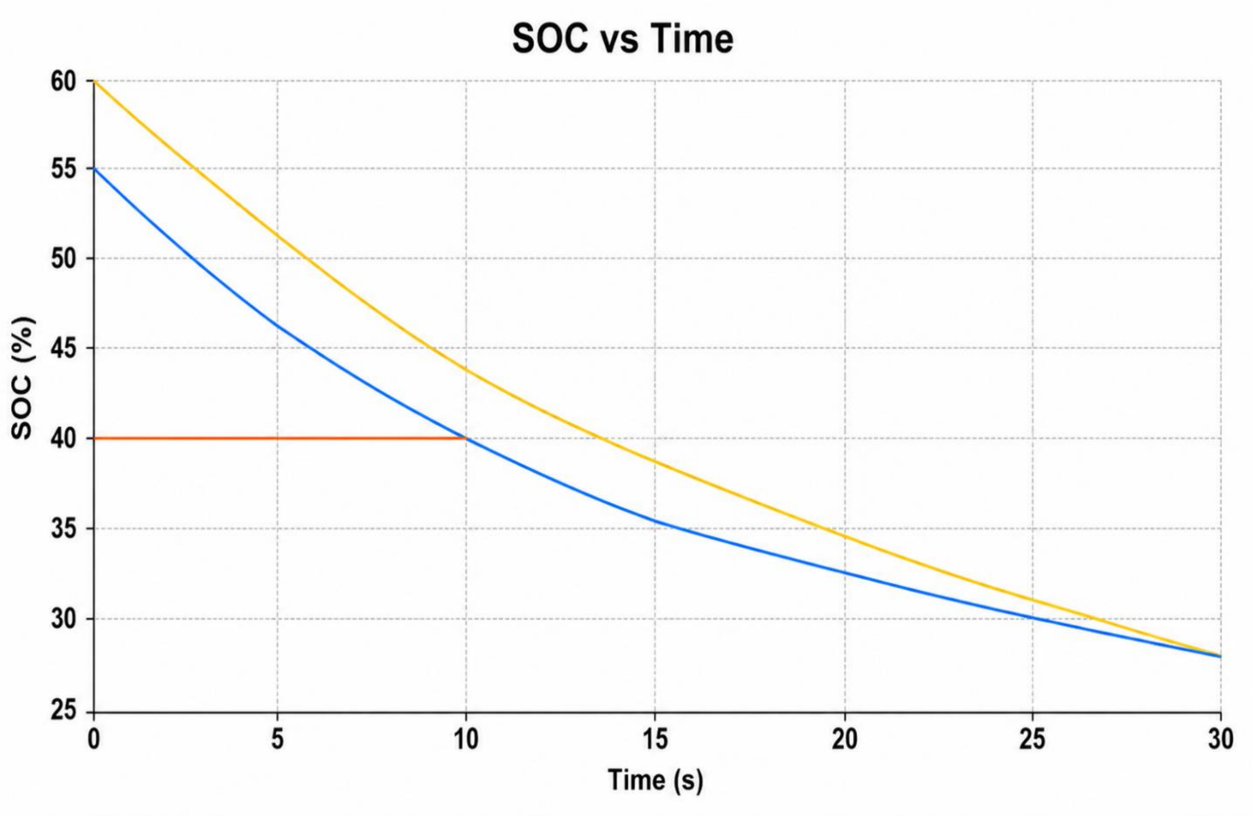
```
function [s1,s2,s3] = fcn(soc1,soc2,soc3)

if((soc1>soc2)||(soc1>soc3))
    s1=1;
else
    s1=0;
end
if((soc2>soc1)||(soc2>soc3))
    s2=1;
else
    s2=0;
end
if((soc3>soc2)||(soc3>soc1))
    s3=1;
else
    s3=0;
end;
```

5.1.2 MATLAB Simulation result/Resistive cell balancing SOC Match

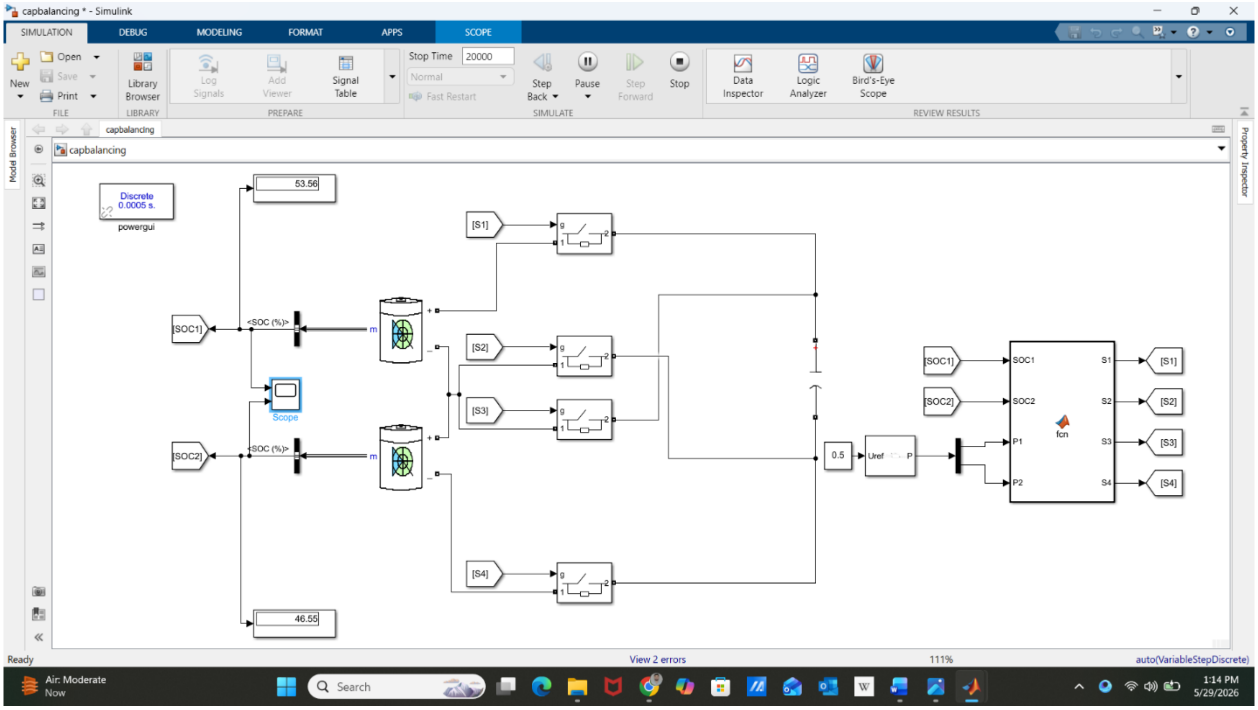
The first SOC matching simulation result illustrates the balancing behavior of three battery cells with initially different SOC values. At the beginning of the simulation, the cells start with approximately 60%, 55%, and 40% SOC, indicating a significant imbalance within the battery pack. As the simulation progresses, the balancing controller continuously monitors the SOC difference and activates the switching sequence for the higher SOC cells. The cells with higher charge gradually discharge while the lower SOC cell maintains or slowly changes its charge level. This causes all SOC curves to move closer together over time. Around the end of the simulation, the SOC values converge near 28%, showing that the balancing strategy successfully reduced the

SOC mismatch between cells. The result demonstrates the effectiveness of the balancing algorithm in achieving uniform charge distribution and improving battery pack consistency during discharge operation.



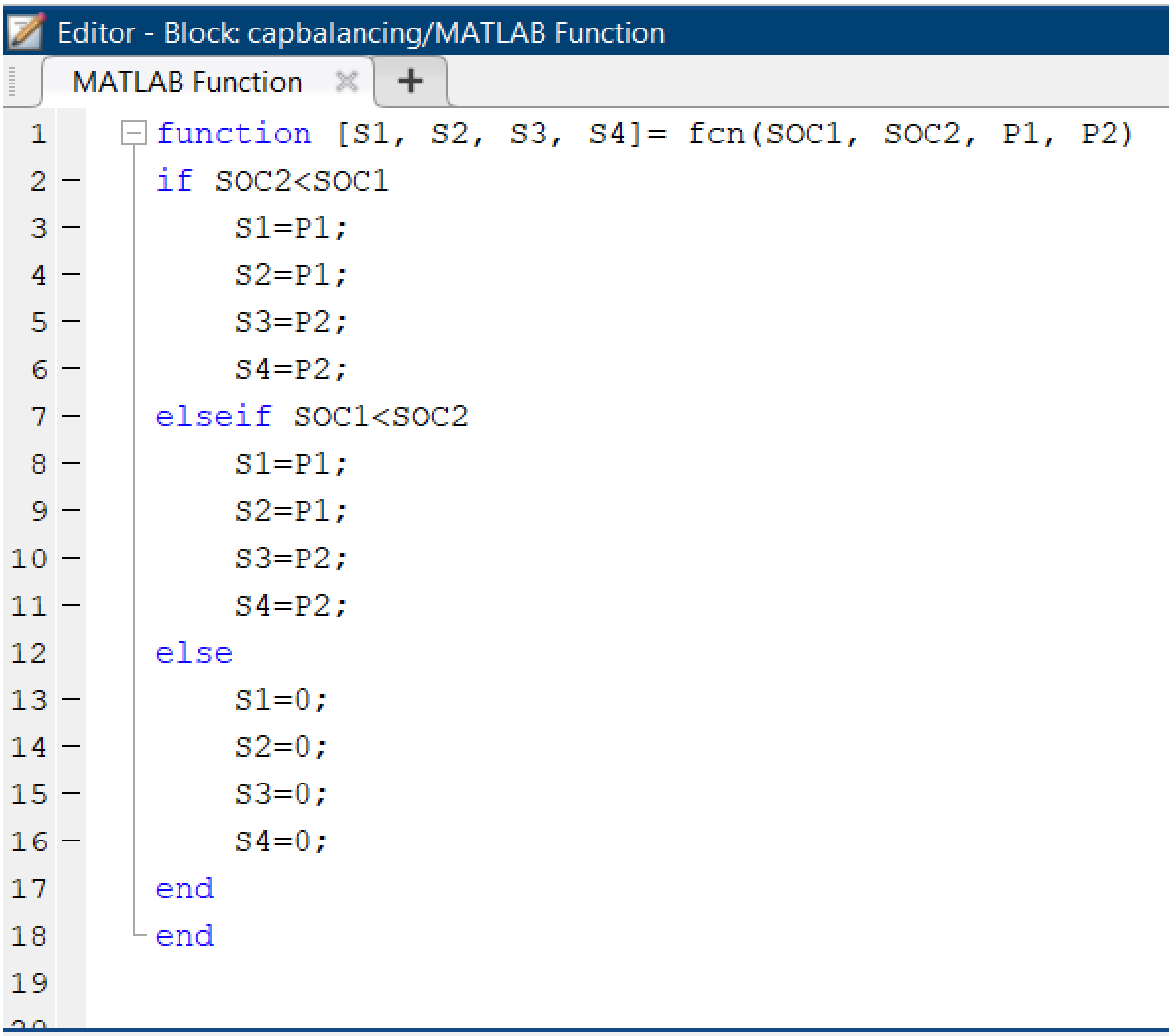
5.2 Capacitor (Active) cell balancing MATLAB/Simulation Setup

The capacitor-based active cell balancing system was developed in MATLAB/Simulink to study the transfer of energy between lithium-ion battery cells with different states of charge (SOC). In this setup, multiple battery cells were connected through switched capacitors controlled by MOSFET switching circuits. The balancing controller continuously monitored the voltage difference between adjacent cells and activated the switches to transfer charge from higher-voltage cells to lower-voltage cells through the capacitor. The simulation included battery models, capacitor elements, switching logic, voltage sensors, and SOC estimation blocks to evaluate balancing performance. This method provides improved energy efficiency compared to passive balancing because excess energy is redistributed between cells instead of being dissipated as heat.



5.2.1 Switching sequence

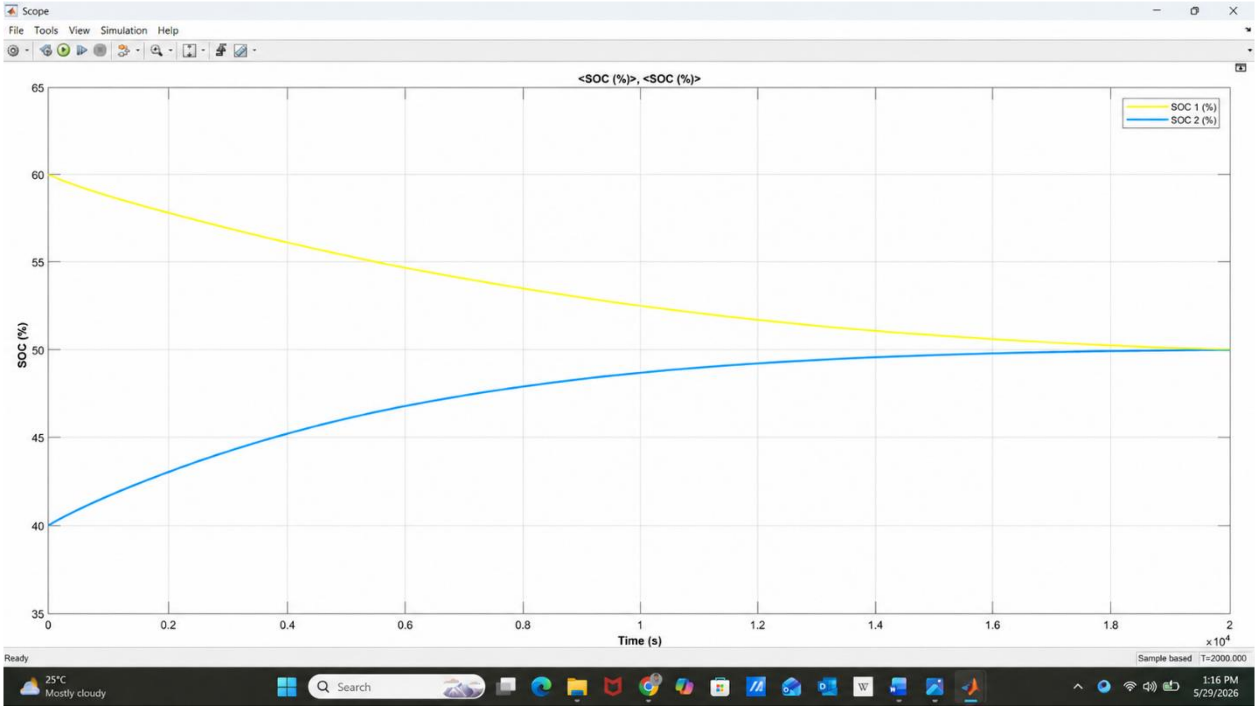
The MATLAB function controls the switching sequence for capacitor-based active cell balancing by comparing the State of Charge (SOC) of two battery cells. When SOC2 < SOC1, switches S1 and S2 are activated with signal P1, while S3 and S4 are controlled by P2, allowing energy transfer from the higher SOC cell to the lower SOC cell. Similarly, when SOC1 < SOC2, the same switching pattern operates to balance the cells in the opposite direction. Once both SOC values become equal, all switches are turned OFF (S1=S2=S3=S4=0), stopping the balancing process. This switching logic ensures gradual energy redistribution and helps achieve uniform SOC between the battery cells.



```
function [S1, S2, S3, S4]= fcn(SOC1, SOC2, P1, P2)
if SOC2<SOC1
    S1=P1;
    S2=P1;
    S3=P2;
    S4=P2;
elseif SOC1<SOC2
    S1=P1;
    S2=P1;
    S3=P2;
    S4=P2;
else
    S1=0;
    S2=0;
    S3=0;
    S4=0;
end
end
```

5.2.2 MATLAB Simulation result/Resistive cell balancing SOC Match

The graph shows the performance of capacitive cell balancing, where the State of Charge (SOC) of two battery cells gradually converges over time. Initially, Cell 1 has a higher SOC of about 60%, while Cell 2 starts at around 40%. Through the switched-capacitor balancing process, energy is transferred from the higher charged cell to the lower charged cell, causing the yellow curve to decrease and the blue curve to increase smoothly. Eventually, both SOC curves meet at nearly 50%, indicating successful balancing of the cells. This method provides efficient energy redistribution with lower power loss and improved battery pack uniformity.

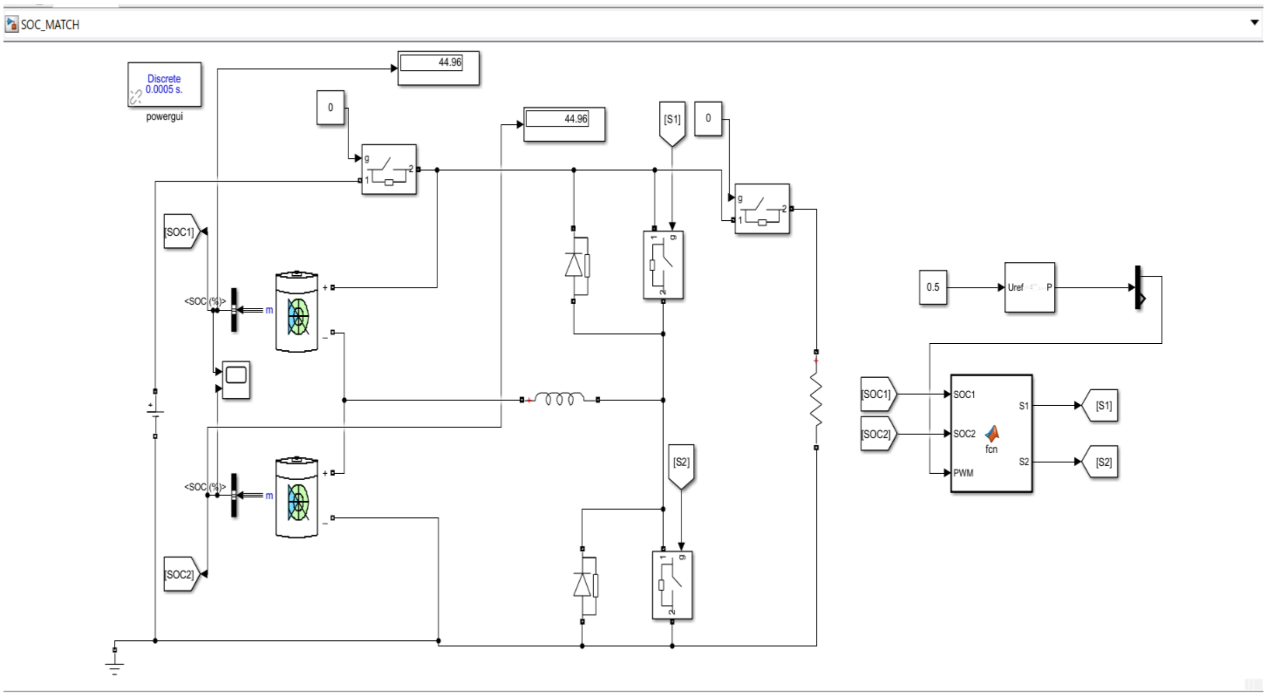


5.3 Inductor (Active) cell balancing MATLAB/Simulation Setup

The MATLAB/Simulink model for inductor-based active cell balancing is developed to study the transfer of energy from higher charged cells to lower charged cells using an inductor and controlled switching circuit. In this simulation, a battery pack consisting of multiple lithium-ion cells is connected with a balancing controller, MOSFET switches, and a single inductor. The controller continuously monitors the State of Charge (SOC) and cell voltage of each battery cell. Whenever a voltage difference is detected, the switching circuit transfers energy from the cell with higher energy to the weaker cell through the inductor.

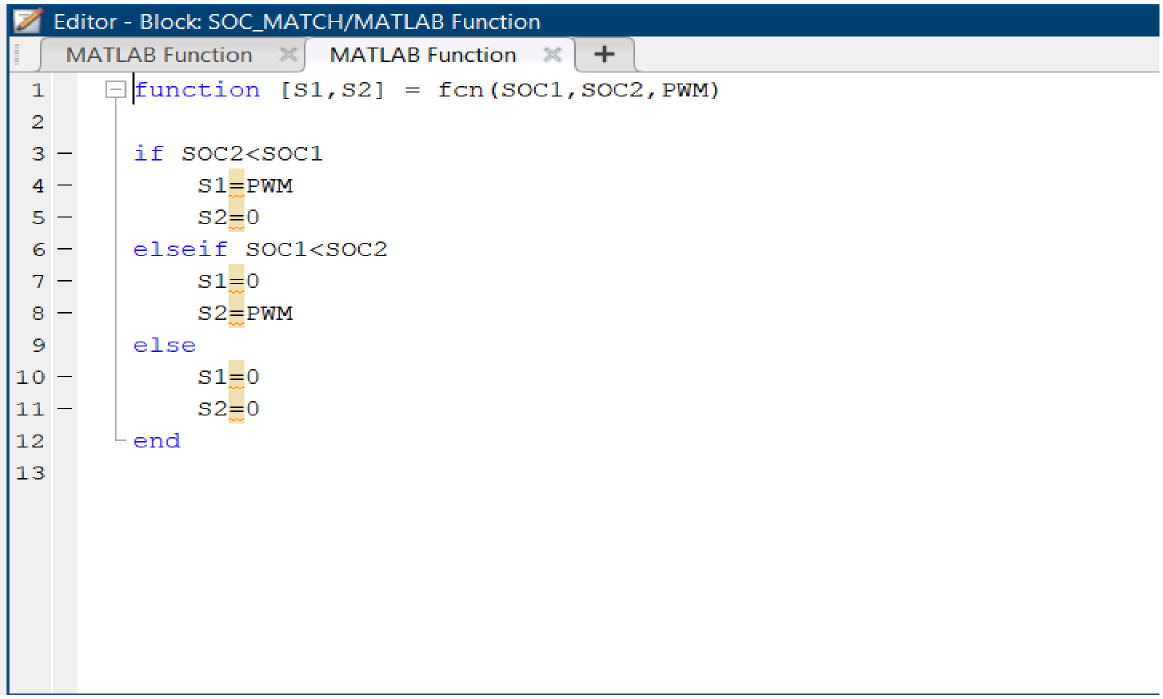
The simulation is designed using Simulink blocks such as battery models, inductors, PWM pulse generators, MOSFET switches, voltage sensors, and SOC estimation blocks. The balancing algorithm controls the charging and discharging interval of the inductor to achieve uniform energy distribution among cells. During operation, the inductor temporarily stores magnetic energy from the high-voltage cell and releases it to the low-voltage cell, resulting in efficient balancing with lower power loss compared to passive methods.

The performance of the balancing system is analyzed using parameters such as balancing current, SOC equalization time, cell voltage variation, and energy efficiency. The simulation results show that inductor-based balancing provides faster balancing speed and higher efficiency, making it suitable for electric vehicle and energy storage applications.



5.3.1 Switching Sequence

The MATLAB switching sequence compares the SOC of two battery cells and controls switches S1 and S2 accordingly. When SOC1 is higher than SOC2, switch S1 turns ON to transfer energy from Cell 1 to Cell 2. Similarly, when SOC2 is higher, switch S2 turns ON for reverse energy transfer. If both SOC values are equal, both switches remain OFF, indicating balanced cells. The PWM signal controls the switching operation and balancing current.



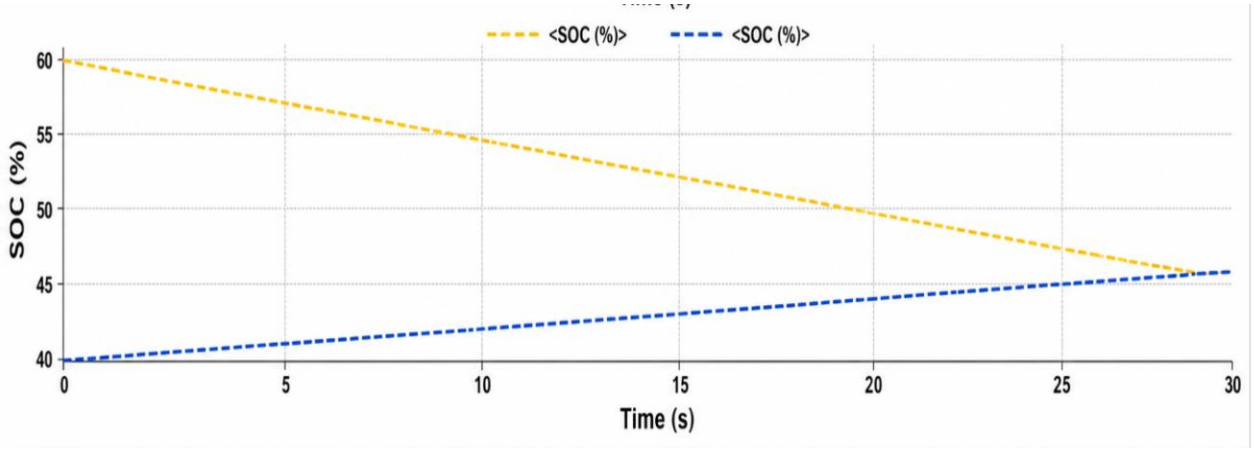
```
function [S1,S2] = fcn(SOC1,SOC2,PWM)

if SOC2<SOC1
    S1=PWM
    S2=0
elseif SOC1<SOC2
    S1=0
    S2=PWM
else
    S1=0
    S2=0
end
```

5.3.2 MATLAB Simulation result/Inductor (Active) cell balancing SOC Match

The graph shows the SOC balancing performance of two battery cells in an inductor-based active balancing system. Initially, one cell has a higher SOC of about 60%, while the other cell starts at around 40%. During the balancing process, energy is transferred from the higher SOC cell to the lower SOC cell through the inductor circuit. As a result, the SOC of the higher charged cell gradually decreases, while the SOC of the lower charged cell increases.

At the end of the simulation, both SOC curves meet at approximately 45%, indicating that the cells have reached a balanced condition. This result confirms that the active balancing system successfully equalizes the charge distribution between the cells with improved energy efficiency and reduced energy loss.



CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Cell balancing is an essential function of a Battery Management System (BMS) because it maintains uniform State of Charge (SOC) among lithium-ion battery cells connected in series. During charging and discharging, differences in internal resistance, temperature, aging, and manufacturing variations cause cell voltage and SOC imbalance. If balancing is not performed, weaker cells may experience overcharging or deep discharging, which reduces battery capacity, decreases cycle life, and increases safety risks. In this work, three balancing techniques — resistive balancing, capacitor-based active balancing, and inductor-based active balancing — were studied and compared using MATLAB/Simulink simulations.

6.1.1 Resistive Cell Balancing

Resistive balancing, also known as passive balancing, is the simplest balancing method. In this technique, excess energy from higher-voltage cells is dissipated through shunt resistors in the form of heat until all cell voltages become equal. The balancing current is controlled by the resistor value according to:

The power dissipated during balancing is:

$$\boldsymbol{P = I_{bal}^{2} R \ldots\ldots\ldots (6.1)}$$

The main advantage of resistive balancing is its simple circuit structure, low implementation cost, and easy control strategy. It requires fewer components and minimal computational complexity, making it suitable for low-cost and small battery systems. However, the method is highly inefficient because a significant amount of energy is lost as heat. This leads to higher temperature rise and reduced overall battery efficiency. In large battery packs, balancing speed becomes slow and thermal management becomes important due to continuous power dissipation.

Therefore, resistive balancing is best suited for applications where simplicity and low cost are more important than efficiency.

6.1.2 Capacitor-Based Active Cell Balancing

Capacitor-based active balancing improves system efficiency by transferring energy between cells instead of dissipating it as heat. In the switched-capacitor method, capacitors alternately connect adjacent cells through controlled switches, allowing charge redistribution from higher SOC cells to lower SOC cells.

The energy stored in the balancing capacitor is expressed as:

$$\boldsymbol{E = \frac{1}{2} C V^2} \ldots\ldots (\mathbf{6.2})$$

The capacitor charging current is approximately:

$$\boldsymbol{I_C = C \frac{dV}{dt}} \ldots\ldots (\mathbf{6.3})$$

Compared to resistive balancing, capacitor balancing significantly reduces energy loss and temperature rise because energy is reused within the battery pack. The balancing efficiency is moderate to high, and the balancing speed is faster than passive balancing. The method also offers relatively compact hardware implementation without requiring magnetic components such as inductors or transformers.

However, the balancing current depends on voltage difference and capacitor size, which limits balancing speed in large battery packs. The circuit complexity is greater than passive balancing because multiple switches and timing control circuits are required. Additionally, energy transfer usually occurs between adjacent cells, which can increase balancing time for long battery strings.

Overall, capacitor-based balancing provides a good compromise between efficiency, cost, and circuit complexity.

6.1.3 Inductor-Based Active Cell Balancing

Inductor-based balancing is the most efficient active balancing method among the three techniques studied. In this method, energy is transferred magnetically through inductors or DC-DC converter circuits from higher-energy cells to lower-energy cells with minimal loss.

The energy stored in the inductor is:

$$\boldsymbol{E = \frac{1}{2} L I^2} \ldots\ldots (\mathbf{6.4})$$

The voltage-current relationship of the inductor is:

$$\boldsymbol{V = L \frac{dI}{dt}} \ldots\ldots (\mathbf{6.5})$$

Inductor balancing achieves the fastest balancing speed and highest efficiency because energy transfer can occur directly between distant cells with very low power dissipation. Temperature rise is minimal, and the method is highly suitable for electric vehicles, renewable energy storage systems, and high-capacity lithium-ion battery packs.

Despite these advantages, the technique has several challenges. The control algorithm is complex and requires accurate switching synchronization. The hardware cost is also high because inductors, converters, sensors, and high-frequency switching devices are needed. In addition, switching stress and electromagnetic interference (EMI) are higher due to rapid switching operations.

Thus, inductor-based balancing is preferred in high-performance applications where efficiency, fast balancing, and energy conservation are critical.

6.1.4 Overall Comparison and Key Observations

From the comparative analysis, it can be concluded that each balancing technique has its own advantages and limitations depending on the application requirements.

- Resistive balancing provides the simplest and cheapest implementation but suffers from poor efficiency and high thermal losses.
- Capacitor-based balancing offers better efficiency and moderate balancing speed with acceptable circuit complexity.
- Inductor-based balancing delivers the highest efficiency, lowest energy loss, and fastest balancing performance, although its hardware and control complexity are significantly higher.

The MATLAB/Simulink results showed that active balancing methods outperform passive balancing in terms of energy utilization and thermal performance. Among the active methods, inductor-based balancing demonstrated the best overall performance for large-scale battery systems, while capacitor-based balancing provided a balanced tradeoff between cost and efficiency.

Therefore, the selection of a balancing method depends on system requirements such as battery size, efficiency target, cost limitations, balancing speed, and thermal constraints. For low-cost systems, resistive balancing remains practical, whereas modern electric vehicle and energy storage applications benefit more from active balancing techniques, particularly inductor-based balancing systems.

6.2 Future Scope

The development of advanced Battery Management Systems (BMS) and cell balancing techniques continues to be an important research area due to the rapid growth of electric vehicles (EVs), renewable energy storage systems, and portable electronic devices. Although resistive, capacitor-based, and inductor-based balancing methods have shown effective performance, several improvements and emerging technologies can further enhance balancing efficiency, safety, and battery lifespan in future applications.

6.2.1 Hardware Implementation of Balancing Systems

Future work can focus on the practical hardware implementation of the proposed balancing techniques using real lithium-ion battery packs. While MATLAB/Simulink simulations provide theoretical validation, hardware testing helps evaluate real-world performance under varying load and temperature conditions. Microcontrollers such as Arduino, DSP, STM32, or FPGA-based controllers can be used to implement balancing algorithms and switching control.

In hardware systems, additional factors such as switching losses, sensor accuracy, electromagnetic interference (EMI), thermal effects, and converter efficiency become significant. Future research can also investigate compact PCB design, thermal management systems, and high-efficiency power electronic components to improve balancing performance and reliability in practical applications.

6.2.2 AI-Based Intelligent Cell Balancing

Artificial Intelligence (AI) and Machine Learning (ML) techniques have the potential to significantly improve battery balancing systems. Conventional balancing methods operate using fixed threshold values, whereas AI-based systems can predict battery behavior and optimize balancing decisions dynamically.

Future BMS designs may use neural networks, fuzzy logic, or reinforcement learning algorithms to estimate State of Charge (SOC), State of Health (SOH), temperature variations, and aging characteristics more accurately. Intelligent balancing algorithms can reduce balancing time, improve energy efficiency, and extend battery life by selecting optimal balancing paths and switching sequences in real time.

AI-based systems can also predict cell degradation and identify faulty cells before failure occurs, thereby improving overall battery safety and reliability.

6.2.3 Wireless Battery Management Systems (WBMS)

Traditional BMS architectures use wired communication between battery cells and the controller, which increases system weight, wiring complexity, and maintenance difficulty. In future battery systems, Wireless Battery Management Systems (WBMS) can replace wired communication using wireless protocols such as Bluetooth, Zigbee, Wi-Fi, or CAN-based wireless networks.

Wireless BMS technology can reduce wiring harness complexity, improve system flexibility, and simplify battery pack assembly in electric vehicles. It also enables easier scalability for large battery packs used in EVs and renewable energy systems.

Future research may focus on secure wireless communication, low-power sensor networks, real-time data transmission, and protection against signal interference to improve the reliability and safety of WBMS architectures.

6.2.4 Real-Time Electric Vehicle Applications

As electric vehicle technology advances, future balancing systems must operate efficiently under real-time driving conditions involving rapid charging, regenerative braking, and varying load demands. Advanced active balancing techniques can be integrated with fast-charging infrastructure and smart energy management systems to improve EV performance.

Real-time balancing systems can continuously monitor battery parameters such as voltage, current, SOC, SOH, and temperature during vehicle operation. Future research may focus on ultra-fast balancing methods, adaptive converter control, and integration with vehicle energy optimization systems.

In addition, next-generation EV batteries with high energy density will require more accurate and faster balancing methods to ensure safe operation and maximize driving range.

6.2.5 Hybrid Cell Balancing Methods

Hybrid balancing methods combine the advantages of passive and active balancing techniques to achieve better overall system performance. For example, a hybrid system may use active balancing during normal operation for efficient energy transfer and passive balancing during final equalization stages for simplicity and cost reduction.

Future hybrid balancing architectures can combine capacitor-based and inductor-based methods to improve balancing speed, efficiency, and scalability while reducing circuit complexity and cost. Intelligent hybrid controllers can automatically select the most suitable balancing mode depending on battery condition, SOC difference, and operating environment.

Such hybrid systems are expected to provide improved thermal performance, reduced balancing time, and enhanced battery lifespan for large-scale energy storage and electric vehicle applications.

6.2.6 Overall Future Perspective

Future battery balancing systems will move toward intelligent, high-efficiency, compact, and fully automated designs. The integration of AI, wireless communication, advanced power electronics, and real-time monitoring technologies will greatly improve battery safety, efficiency, and operational reliability. Among all future directions, intelligent active balancing combined with real-time monitoring and hybrid energy transfer techniques is expected to play a major role in next-generation electric vehicles and renewable energy storage systems

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