Manish Kumar

1_MANISH KUMAR_2K24_PES_27 Plag Check

Publications

Document Details

Submission ID

trn:oid:::27535:141381805

Submission Date

Jun 2, 2026, 2:23 PM GMT+5:30

Download Date

Jun 2, 2026, 2:27 PM GMT+5:30

File Name

1_MANISH KUMAR_2K24_PES_27 Plag Check.pdf

File Size

3.1 MB

51 Pages

12,070 Words

66,707 Characters

10% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Small Matches (less than 9 words)

Match Groups

115 Not Cited or Quoted 10%
Matches with neither in-text citation nor quotation marks

0 Missing Quotations 0%
Matches that are still very similar to source material

4 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

6%	Internet sources
5%	Publications
8%	Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

115 Not Cited or Quoted 11%
Matches with neither in-text citation nor quotation marks

0 Missing Quotations 0%
Matches that are still very similar to source material

4 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

6%	Internet sources
5%	Publications
8%	Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet	**www.mdpi.com**	<1%
2	Internet	**next.gr**	<1%
3	Internet	**nextbms.eu**	<1%
4	Student papers	**University of Warwick on 2019-08-20**	<1%
5	Student papers	**University of Birmingham on 2024-02-05**	<1%
6	Student papers	**University of Birmingham on 2015-12-01**	<1%
7	Student papers	**Anna University on 2024-06-20**	<1%
8	Publication	**Priyanka D. Inamati, Kavya B. Meti, Ranjita D. Gaddanakeri, Hanumanthagouda R...**	<1%
9	Internet	**eprints.nottingham.ac.uk**	<1%
10	Internet	**ijireeice.com**	<1%

11	Internet	
	www.frontiersin.org	<1%
12	Student papers	
	National Institute Of Technology, Tiruchirappalli on 2025-12-30	<1%
13	Internet	
	studyres.com	<1%
14	Internet	
	theses.ncl.ac.uk	<1%
15	Internet	
	upcommons.upc.edu	<1%
16	Student papers	
	Coventry University on 2019-01-08	<1%
17	Student papers	
	International Islamic University Malaysia on 2018-08-14	<1%
18	Internet	
	www.nature.com	<1%
19	Internet	
	www.ufinebattery.com	<1%
20	Internet	
	liu.diva-portal.org	<1%
21	Publication	
	Amar Nath, Bhooshan Rajpathak. "Analysis Of Cell Balancing Techniques In BMS ...	<1%
22	Student papers	
	Birzeit University Main Library on 2018-06-09	<1%
23	Internet	
	www.classace.io	<1%
24	Student papers	
	Imperial College of Science, Technology and Medicine on 2010-03-08	<1%

25	**Student papers**	
	University of Nottingham on 2025-03-24	**<1%**
26	**Student papers**	
	College of Engineering, Pune on 2018-04-14	**<1%**
27	**Student papers**	
	Indian Institute of Technology-Bhubaneswar on 2020-12-20	**<1%**
28	**Publication**	
	M. Premkumar, Pasumarthi Usha, Sujit Kumar, Manikanta Gopisetti. "Intelligent ...	**<1%**
29	**Publication**	
	Shaowei Zhang, Yuli Hu, Silun Luo, Yuhan Li, Hairui Liang, Juchen Li, Liteng Zeng, ...	**<1%**
30	**Internet**	
	encyclopedia.pub	**<1%**
31	**Student papers**	
	Middle Technical University on 2023-10-08	**<1%**
32	**Student papers**	
	Monash University on 2025-10-25	**<1%**
33	**Internet**	
	aaltodoc.aalto.fi	**<1%**
34	**Internet**	
	dehesa.unex.es	**<1%**
35	**Publication**	
	Murat Mustafa Savrun, Tahsin Koroglu, Erdem Unal, Burak Onur, Mehmet Ugras ...	**<1%**
36	**Student papers**	
	Oxford Brookes University on 2024-06-04	**<1%**
37	**Publication**	
	Shang, Yunlong, Chenghui Zhang, Naxin Cui, and Josep M. Guerrero. "A Cell-to-Cel...	**<1%**
38	**Student papers**	
	Technical University of Cluj-Napoca on 2024-07-11	**<1%**

39	Student papers	
	University of East London on 2024-09-11	<1%
40	Student papers	
	University of Nottingham on 2023-04-17	<1%
41	Student papers	
	University of Stellenbosch, South Africa on 2022-10-31	<1%
42	Student papers	
	University of the West Indies on 2014-04-03	<1%
43	Internet	
	odr.chalmers.se	<1%
44	Student papers	
	Oxford Brookes University on 2026-04-28	<1%
45	Student papers	
	PSG Institutions on 2025-05-16	<1%
46	Student papers	
	RMIT University on 2017-10-16	<1%
47	Publication	
	Shiyun Liu, Kang Li, James Yu. "Battery pack condition monitoring and characteri...	<1%
48	Student papers	
	University of Leeds on 2020-08-20	<1%
49	Student papers	
	University of Nottingham on 2023-04-19	<1%
50	Publication	
	Yunlong Shang, Naxin Cui, Bin Duan, Chenghui Zhang. "Analysis and Optimizatio...	<1%
51	Internet	
	arxiv.org	<1%
52	Internet	
	eprints.utm.my	<1%

53	Internet	
	studentsrepo.um.edu.my	<1%
54	Internet	
	www.tdx.cat	<1%
55	Student papers	
	Amrita Vishwa Vidyapeetham on 2020-05-15	<1%
56	Student papers	
	Anna University on 2026-02-16	<1%
57	Publication	
	Hongchun Shu, Botao Shi, Jiannan Li, Guangxue Wang, Shunguang Lei. "Fuzzy con...	<1%
58	Publication	
	Jinhao Meng, Mattia Ricco, Guangzhao Luo, Maciej Swierczynski, Daniel-Ioan Stro...	<1%
59	Student papers	
	National University of Singapore on 2015-05-13	<1%
60	Student papers	
	Oxford Brookes University on 2023-05-05	<1%
61	Student papers	
	RMIT University on 2015-10-13	<1%
62	Publication	
	Shweta Koraddi, K V Samprita, Keerti S Yadgir, Laxmi M Biradarpatil, Spandana V ...	<1%
63	Student papers	
	University of East London on 2025-04-29	<1%
64	Student papers	
	University of Houston System on 2009-10-27	<1%
65	Student papers	
	University of Nottingham on 2017-05-19	<1%
66	Publication	
	Y.-S. Lee, M.-W. Cheng. "Intelligent Control Battery Equalization for Series Connec...	<1%

67	**Publication**	
	Yasaman Tavakol-Moghaddam, Mehrdad Boroushaki. "A multi-agent reinforceme...	**<1%**
68	**Publication**	
	Youngbin Song, Minjun Park, Minhwan Seo, Sang Woo Kim. "Online State-of-Char...	**<1%**
69	**Internet**	
	api.intechopen.com	**<1%**
70	**Student papers**	
	Anna University on 2025-07-01	**<1%**
71	**Student papers**	
	Central Queensland University on 2012-10-04	**<1%**
72	**Student papers**	
	Coventry University on 2017-08-20	**<1%**
73	**Student papers**	
	JNEC on 2026-05-19	**<1%**
74	**Publication**	
	Jeon, Seonwoo, Jae-Jung Yun, and Sungwoo Bae. "Active cell balancing circuit for ...	**<1%**
75	**Publication**	
	Mitul M. Modi, Rakesh A. Patel. "Internet of Things Infused Vigilance of Li-Ion Bat...	**<1%**
76	**Student papers**	
	National Institute Of Technology, Tiruchirappalli on 2026-05-21	**<1%**
77	**Publication**	
	Neha Khan, Chia Ai Ooi, Abdulrahman Alturki, Mohammad Amir, Shreasth, Talal ...	**<1%**
78	**Publication**	
	S. Nejad, D. T. Gladwin, D. A. Stone. "On-chip implementation of Extended Kalman...	**<1%**
79	**Student papers**	
	Saint Louis University on 2025-07-19	**<1%**
80	**Publication**	
	Semnani, Ali Khosravani. "Economic, Technical and Environmental Analysis of Hy...	**<1%**

81	Student papers	
	University of Calabar on 2018-12-04	<1%
82	Student papers	
	University of Leicester LTI on 2026-04-27	<1%
83	Student papers	
	University of Michigan, Dearborn on 2010-12-04	<1%
84	Student papers	
	University of New South Wales on 2026-04-20	<1%
85	Student papers	
	University of Warwick on 2021-09-28	<1%
86	Student papers	
	University of Western Sydney on 2012-05-31	<1%
87	Student papers	
	University of Western Sydney on 2012-06-24	<1%
88	Publication	
	Ye, Yuanmao, and Ka Wai E. Cheng. "Modeling and Analysis of Series–Parallel Swit...	<1%
89	Internet	
	d.lib.msu.edu	<1%
90	Internet	
	eccl.ulsan.ac.kr	<1%
91	Internet	
	mdpi-res.com	<1%
92	Internet	
	opus.lib.uts.edu.au	<1%
93	Internet	
	vtechworks.lib.vt.edu	<1%

CHAPTER 1

INTRODUCTION

1.1 Background of Battery Management Systems

The batteries form an integral part in modern electrical systems, particularly in electric vehicles and renewable sources of energy systems. For instance, in electric vehicles, the batteries serve the function of supplying electricity that drives the motor and other parts of the car. The increase in the number of electric vehicles is attributed to the increasing demand for environmentally friendly vehicles. Also, for renewable energy sources, the batteries are used to store extra energy for future use, particularly when there is reduced power production from solar and wind sources. Out of several types of batteries, lithium-ion batteries are most common owing to their high energy density, longevity, and lightweight among others. Therefore, management of these batteries is very crucial.

1.1 Background of Battery Management System (BMS)

Figure 1.1 Background of BMS

1.1.1 Need for Battery Management Systems

Typically, battery packs consist of a large number of cells joined in series or parallel arrangements. As a result of temperature changes, aging, and other factors during use, there may be an imbalance in the functioning of the individual cells in the battery pack.

This can pose risks like overcharging, deep discharging, overheating, etc. In order to prevent these and other issues, the use of a Battery Management System (BMS) is needed. A BMS refers to an electronic control system for managing the battery pack.

Figure 1.1.1 Need for BMS

1.1.2 Monitoring Function of BMS

Some of the key roles of the BMS include the ability to monitor battery parameters like the battery voltage, current, and temperature. BMS monitors the health of individual batteries and entire battery packs while charging and discharging them. Monitoring the parameters helps BMS detect any anomalies early on and ensure optimum operation of the battery.

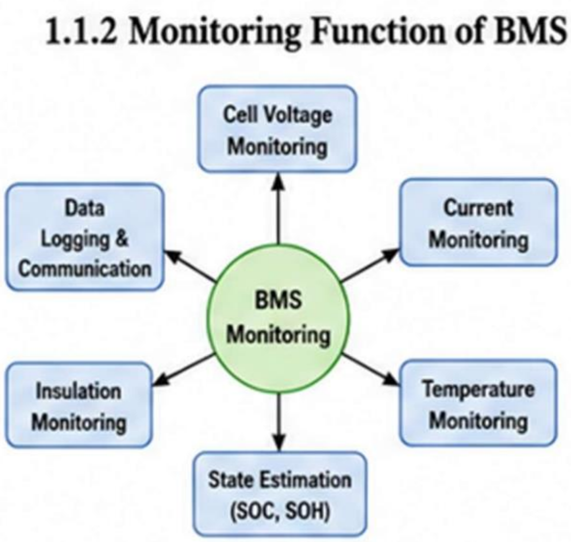


Figure 1.1.2 Monitoring Functions of BMS

1.1.3 Protection Function of BMS

Furthermore, the BMS ensures that the battery is safe from any unfavorable operating conditions. Lithium-ion cells are very susceptible to overcharging, over-discharging, overheating, and short circuits. In the case where such unfavorable conditions are encountered, the battery could be damaged, causing safety issues. The BMS keeps the battery safe through disconnection of the circuit when there are any abnormal operations.

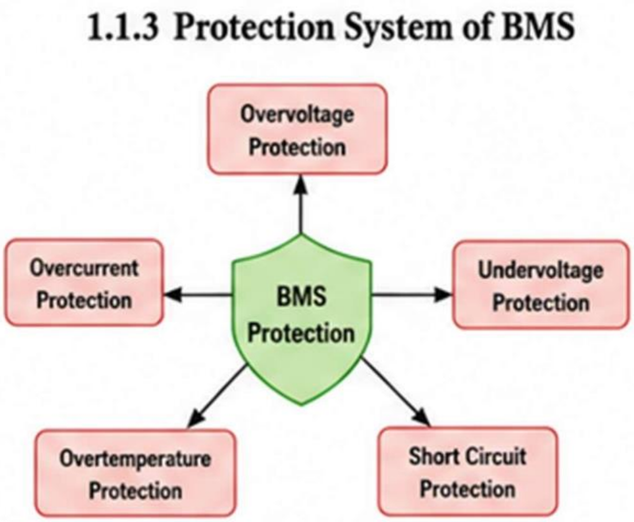


Figure 1.1.3 Protection System of BMS

1.1.4 State of Charge (SOC) Estimation

Yet another role of the BMS is to estimate the State of Charge (SOC) of the battery. The SOC refers to the amount of charge stored in the battery and is normally specified in terms of a percentage. SOC is not measurable and hence the BMS estimates it based on the battery voltage and current as well as some mathematical approaches.

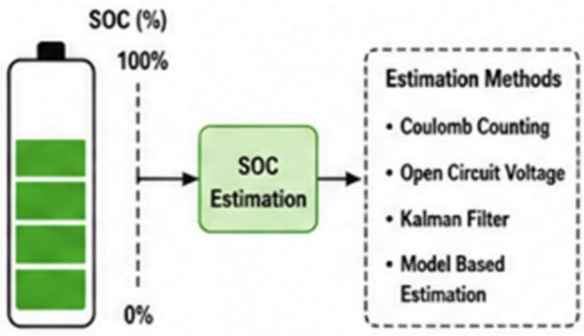

1.1.4 State of Charge (SOC) Estimation

Figure 1.1.4 SOC Estimation

1.1.5 Cell Balancing Function of BMS

Cell balancing is one of the key activities of Battery Management System. During charging and discharging of the battery cells, there may be discrepancies between the speeds at which individual cells discharge or charge owing to differences in capacity and internal resistance of each cell. Such differences in charge or discharge rates lead to imbalances, which affect battery efficiency and life. The activity of cell balancing ensures that voltages in the battery cells remain balanced during discharge and recharge cycles. The balancing methods are categorized into two types, passive and active. Passive balancing involves dissipation of the excess energy generated through resistive heaters. On the other hand, active balancing involves transfer of energy between cells through capacitors and inductors.

Need for Cell Balancing

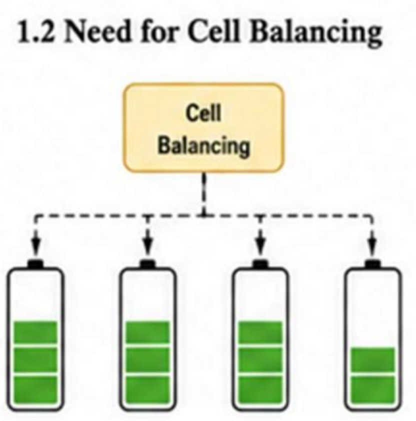


Figure 1.2 Need for Cell Balancing

1.2.1 Why Cells Become Unbalanced

Cell balancing is required because in a battery pack, several cells are combined together to obtain the needed voltage level and capacity. While charging or discharging, there is some variance between these cells as a result of variations in manufacturing process, resistance levels, temperature, and age. The faster charging cells will differ from those with a fast discharge rate in terms of the voltage level and State of Charge (SOC) . This difference will gradually widen until imbalance is created in the battery pack.

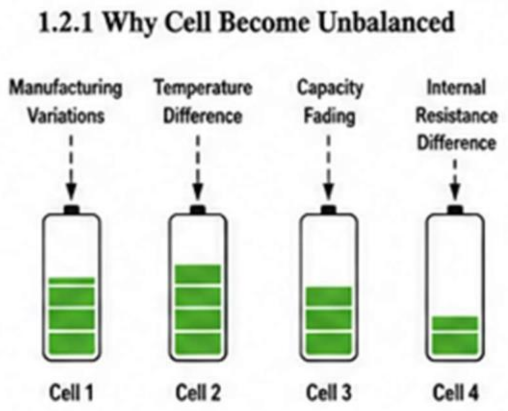


Figure 1.2.1 Why Cell Become Unbalanced

1.2.2 Reduced Battery Life

Any imbalance in the cells can greatly diminish the lifetime of the battery pack. Since some cells are often charged or discharged more than others, they tend to wear out faster than the rest. In spite of the fact that some cells function effectively, the whole battery pack's operation is compromised. The importance of balancing the cells lies in their equal distribution of charge.

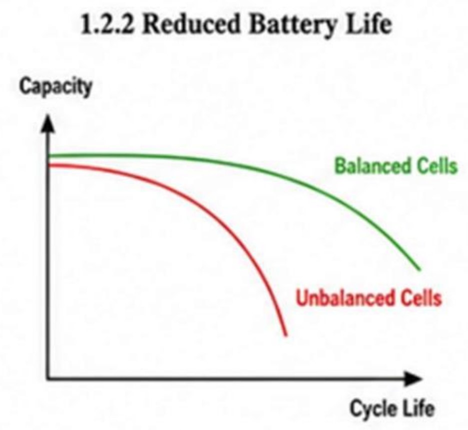


Figure 1.2.2 Reduced Battery Life

1.2.3 Reduced Capacity

Unbalanced cells will be unable to achieve maximum usage of their capacity. For example, during the charging process, the charging operation may cease due to one cell being fully charged, while the other cells are still being charged. The same applies during the discharge operation whereby the discharge process ceases because of the low voltage attained by the weaker cell.

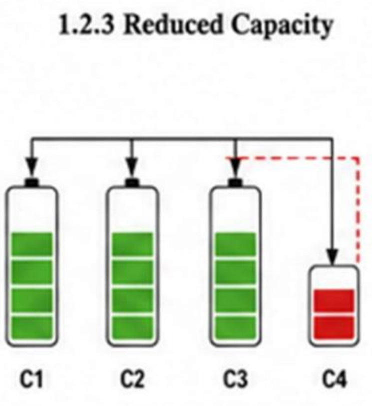


Figure 1.2.3 Reduced Capacity

1.2.4 Safety Issues and Overcharging/Discharging

Unbalance of the cells can lead to major safety issues in the batteries. Charging beyond the recommended limit may lead to overheating, bulging, or even thermal runaways. Discharging the cell beyond the limit will cause permanent damage to the cell. Apart from degrading the battery performance, this increases the likelihood of fires and failures of the system.

1.3 Types of Cell Balancing Techniques

65

1.3.1 Passive Balancing (Resistive Balancing)

Passive Balancing is the easiest and most frequently used type of cell balancing technology in BMS. With this system, any surplus energy from cells having higher charge is discharged into heat via resistors until all cells have nearly similar voltages. Passive Balancing has a fairly uncomplicated circuit structure and is both cheap and easy to use. But due to its inefficiency because of wastage of energy as heat, it is not preferred as much as Active Balancing techniques..

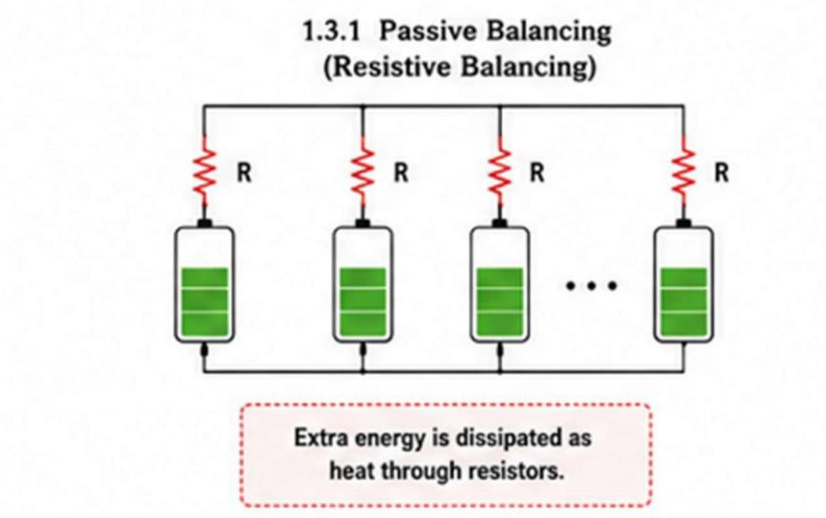


Figure 1.3.1 Passive Balancing

1.3.2 Active Balancing

86

The balancing techniques can increase efficiency because, rather than being wasted, the energy is shifted from the fully charged cells to partially charged cells. Active balancing is more efficient and appropriate in uses such as automobiles and solar cells where energy loss is critical. Despite the fact that the active balance circuits are complicated and expensive, they increase battery efficiency.

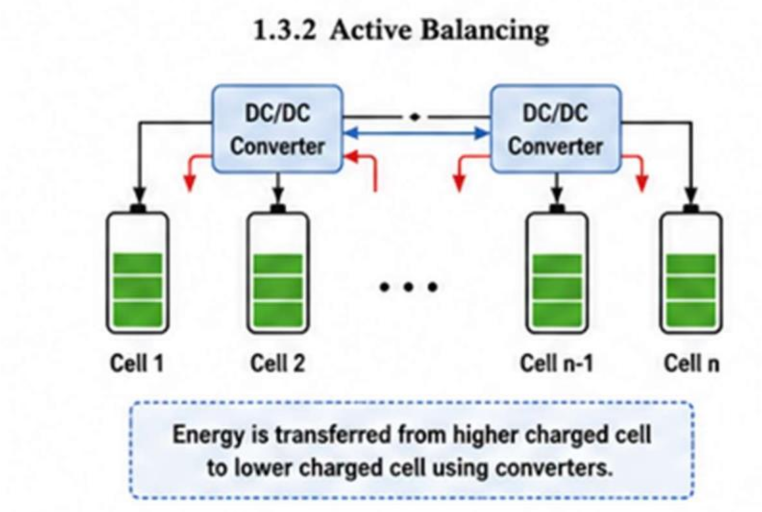


Figure 1.3.2 Active Balancing

1.3.3 Capacitor-Based Balancing

The balancing of capacitors is an example of an active balancing approach where capacitors are used to move energy from one cell to another. The principle behind this balancing approach involves the use of capacitors whereby energy is first collected from cells having high voltage and then moved to cells having low voltage using switching. The advantage of this balancing technique is that it has high efficiency and a simple design compared to other balancing approaches.

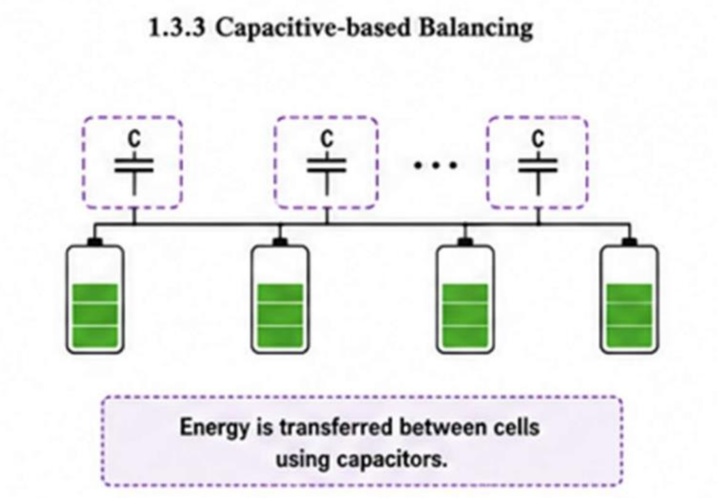
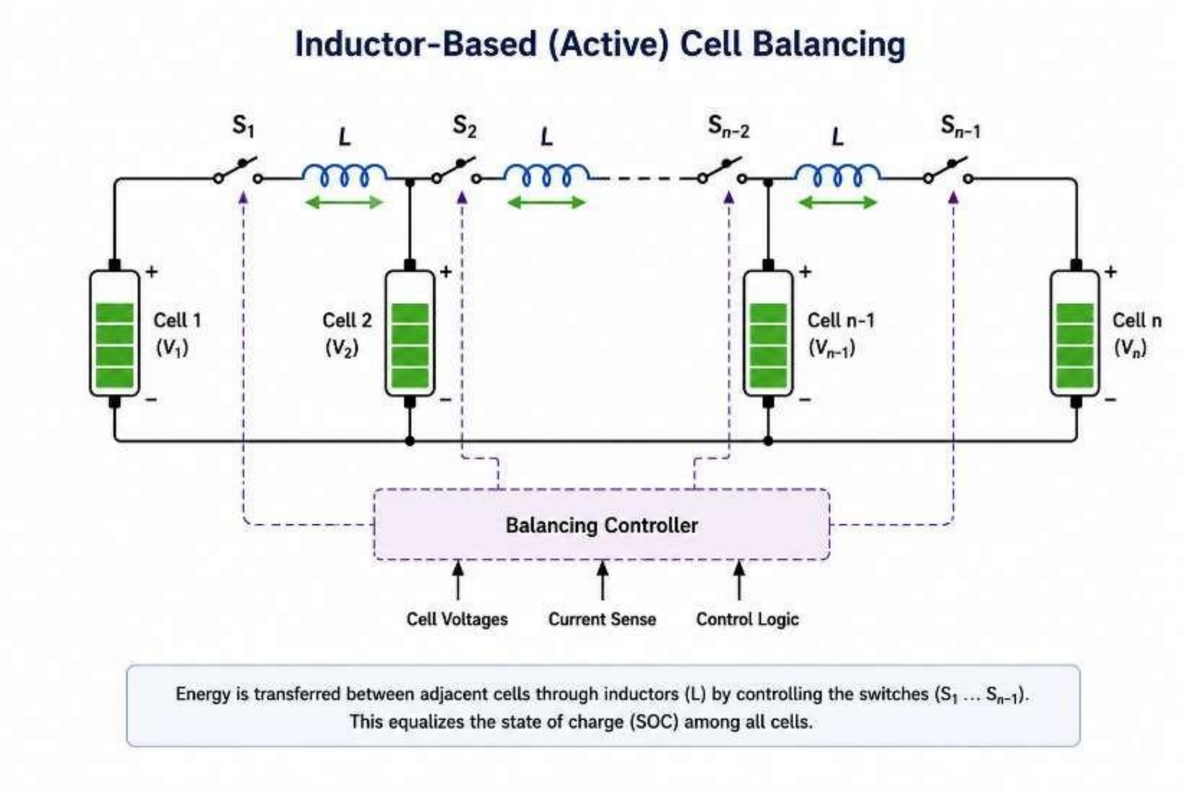


Figure 1.3.3 Capacitive-based Balancing

1.3.4 Inductor-Based Balancing

The inductive approach makes use of inductors or converters for transferring energy between the battery cells. This is a very efficient technique that balances the battery cells quickly than any other technique such as the capacitor technique. In this approach, the inductor stores the energy from the highly charged cells temporarily before discharging it to the less charged cells without losing much of the energy. However, this technique is very expensive due to the sophisticated design involved.



Inductor-Based (Active) Cell Balancing

Energy is transferred between adjacent cells through inductors (L) by controlling the switches ($S_1 \ldots S_{n-1}$). 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 study examines various cell balancing strategies employed by Battery Management Systems (BMS) with the aid of MATLAB/Simulink software. In this research, we compare the balancing methods using capacitors, inductors, and resistors to evaluate their effectiveness in ensuring uniformity of voltages in battery cells. The study evaluates aspects including balance time, energy efficiency, and performance of the battery as a whole. The simulation demonstrates the pros and cons of each strategy. This research highlights the importance of cell balancing for optimal operation of batteries in practical application areas.

The results obtained through simulation indicate that the proposed method for balancing the active cells effectively reduces the voltage differential among cells and increases the longevity of the battery pack.

2.2 Review of Battery Technologies

2.2.1 Lead-acid Battery

The lead acid battery is one of the most ancient forms of rechargeable batteries that are used extensively in cars and backup systems. It is cheap and dependable while having the ability to deliver a high current; however, it is bulky and has poor energy density while being difficult to maintain.

2.2.2 Nickel-Metal Hydride (NiMH) Battery

Compared to lead acid batteries, NiMH batteries have better energy densities and are environment-friendly since they lack toxic cadmium compounds. NiMH batteries are used in hybrid cars and other electronic gadgets. These batteries exhibit improved characteristics; however, they face problems of high self-discharge rates and higher costs compared to lead acid batteries.

2.2.3 Lithium-ion Battery

The lithium-ion battery is the most efficient rechargeable battery, commonly used in current electronic gadgets and electric vehicles. The lithium-ion battery is characterized by high energy density, weight reduction, quick charge, and longevity. It needs minimum maintenance and is highly efficient; hence it serves current purposes effectively. It is however expensive and prone to overheating.

2.3 Review Battery Parameters

2.3.1 State of Charge (SOC)

The state of charge, which is abbreviated as SOC, denotes the total energy that remains in the battery. It is normally given in percentages, with 100% indicating a completely charged battery and 0% representing an empty battery. This measure enables individuals to determine how long the battery will run before charging is necessary.

2.3.2 State of Health (SOH)

State of Health (SOH) describes the general state of the condition as well as the performance ability of the battery relative to the performance ability of a brand-new battery. The SOH gives an indication of the level of degradation that is going on in the battery over time.

2.3.3 Voltage

The voltage value is an important parameter of the battery since it determines the electrical potential of the battery. Voltage levels change depending on the state of charging or discharging and help to evaluate the operational state of the battery. Voltage stability is important for normal functioning of electronic devices.

2.3.4 Temperature

The effects of temperature on batteries are significant in relation to the performance, safety, and longevity of the batteries. In cases of high temperatures, the batteries could easily overheat while in extremely low temperatures the efficiency of the batteries may be hindered.

2.3.5 Internal Resistance

Resistance within the battery refers to opposition in the flow of current through the battery. The older a battery becomes, the higher its internal resistance, which decreases efficiency and results in the production of heat. Resistance should be low for the battery to work efficiently.

2.4 Review of Cell Balancing Methods

2.4.1 Passive Balancing

One of the easiest and most widely employed techniques in battery balancing is that of passive balancing. This technique uses resistors to dissipate the excess energy in those cell that have a higher state of charge as heat. This makes sure that all cells have the same voltage level. The technique is easy to implement, inexpensive, and reliable in small battery systems. Nevertheless, this is an inefficient technique for large batteries as it generates heat.

2.4.2 Capacitor-Based Active Balancing

The active balancing using capacitor technology moves the energy from one cell to the other without waste. The technique utilizes switches and capacitors to transfer charges among cells operating at different voltages. Unlike passive balancing, which results to inefficient energy utilization and increased heating, active balancing offers improved efficiency and minimizes heat production. However, it tends to be slower and more complicated in its control process.

2.4.3 Inductor-Based Active Balancing

Balancing using inductors works by using inductors to transfer energy between the cells effectively. The single inductor balance uses an inductor for multiple cells where the energy is moved from the higher voltage cells to the lower voltage cells. This balancing method is highly efficient, but its control is complex.

Multi-inductors balancing, on the other hand, uses different inductors for different cells; it helps improve balancing speed and increase performance. This balancing method increases the cost of manufacturing and makes the circuit more complicated.

Balancing using a flyback converter is carried out using a transformer-based converter that is used for transferring energy between cells or packs. The advantages of the flyback converter method are high efficiency and electrical isolation; this balancing technique is effective for larger packs, especially those used for vehicles.

Previous Research Papers on Cell Balancing Methods

The first useful article is "Performance Comparison of Active Balancing Techniques for Lithium-Ion Batteries" published in the Journal of Power Sources in 2014. In this research, different kinds of balancing techniques were studied, including passive balancing, capacitor balancing, and inductor balancing. It was found that active balancing was more effective since energy was exchanged between batteries.

The second useful paper 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 paper, researchers proposed to use a capacitor balancing method together with SOC calculations to improve the accuracy of balancing in lithium-ion batteries used in electric vehicles.

In addition, a research paper titled **“Implementation of Battery Management System with Passive Control Method Using MOSFET as a Load”** explains how passive balancing can be applied to lithium-ion batteries. In this research, efforts were made to minimize the difference between voltages by adopting balancing resistors. In particular, it should be pointed out that although passive balancing is inexpensive and easy to implement, it results in losses of energy in the form of heat.

As another paper, one can note a recently published review article titled **“ Review of Cell-Balancing Schemes for Electric Vehicle Battery Management Systems. ”** Various cell-balancing schemes have been considered here, including the switched capacitor method, single inductor, multi-inductor, and flyback converter approach. It was emphasized that active balancing is more efficient compared to passive one.

CHAPTER 3

BATTERY MODELING AND BMS ARCHITECTURE

3.1 INTRODUCTION

An accurate modeling of lithium-ion batteries and design of reliable Battery Management System (BMS) are key requirements for their safe, efficient, and robust deployment in energy storage systems. As lithium-ion technology is ubiquitous in portable electronics, electric vehicles and grid scale storage, understanding its electrochemical and electrical behavior is becoming an increasingly critical issue. A well-designed BMS not only monitors but also controls the battery pack and relies on accurate mathematical models to estimate directly unobservable states such as the State of Charge (SOC) and the State of Health (SOH).

In this chapter, the theoretical background of the underlying lithium ion battery modeling is presented, with a focus on the Equivalent Circuit Model (ECM) and governing equations describing the battery terminal characteristics. The chapter also introduces the architecture of a Battery Management System and explains the function of its core blocks and how it interacts with the battery model for real-time monitoring, protection and state estimation. Taken together, these form the analytical foundation for the work described in the following chapters.

3.2 Lithium-ion Battery Modeling

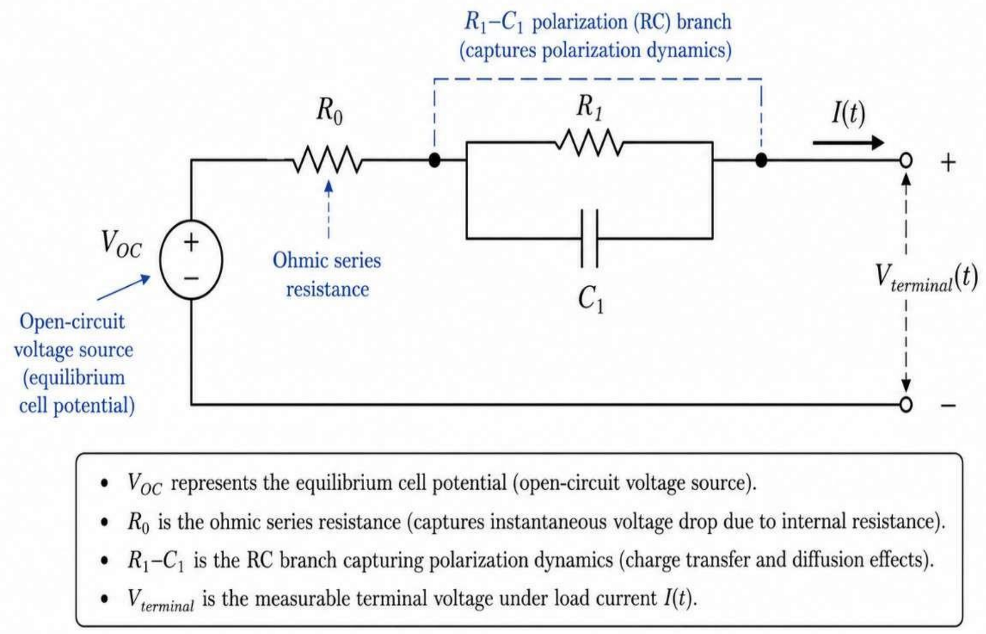
Lithium-ion batteries are increasingly complex electrochemical systems, whose behavior spans multiple physical domains: electrochemical reactions, ionic transport, thermal dynamics, and electrical circuit response. Accurately capturing this behavior in real-time computable models require models that balance physical fidelity with computational tractability. Several modeling paradigms have been proposed in literature, ranging from high-fidelity physics-based models, such as the Doyle-Fuller-Newman (DFN) model, to purely data-driven approaches. For BMS implementation, the Equivalent Circuit Model offers the most practical trade-off between accuracy and computational cost and thus will be the subject of this section.

3.2.1 Equivalent Circuit Model

The Equivalent Circuit Model represents the battery cell by a network of ideal electrical components (resistors, capacitors, and voltage source) whose parameters are identified from experimental measurements of the cell electrical response. The fundamental concept is that the cell terminal voltage under a load consists of three components: an open-circuit voltage (OCV) representing the thermodynamic equilibrium of the battery, the instant ohmic voltage drop caused by internal resistance, and the transient voltages that arise due to mass transfer and polarization within the cell and are dependent on time.

The simplest implementation of ECM, the single RC circuit, known as first-order Randles circuit. Captures these components by combining a resistance with a parallel RC branch, both in series with the battery OCV, VOC (SOC) represented by a voltage source (Figure 3.1). R0, the resistance term in series, captures the combined resistance of the cell electrolyte, electrodes, current collectors and interconnects. It causes an instantaneous voltage step upon application or removal of current. The polarization resistance R1 and capacitance C1 represent phenomena associated with double-layer formation at the electrode surfaces and diffusion limited phenomena within the electrodes respectively; they cause voltage dynamics that recover slowly upon the cessation of current. The cell terminal voltage is then given by the algebraic equation Vt = VOC -I R0 -V1, where V1 is the polarization voltage across the RC branch.

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 where a more accurate response is needed over a wider range of operation, especially for high current applications and transients, a higher order ECM may be used. A second-order ECM introduces another RC branch, allowing for additional time constants related to surface film and bulk diffusion to be included. In general, the order of the ECM chosen is influenced by application requirements, and a trade-off is often required between model fidelity and computational complexity; however, the first-order model is adequate for the purpose of this work.

Mathematical description of the first-order ECM. The single RC branch is modeled by the following first-order ODE, where V1 is the polarization voltage across the RC branch:

$$dV1/dt = -V1 / (R1C1) + I / C1 \quad (3.1)$$

The terminal voltage of the cell,Vt, measured at the cell terminals is described by the algebraic equation:

$$Vt = VOC(SOC) - I\ R0 - V1 \quad (3.2)$$

The sign convention adopted is that discharge current I is positive. Under this convention the ohmic resistance and the polarization voltage will reduce the terminal voltage in discharge phase, and increase the terminal voltage during charge phase. R0, R1, and C1 are typically not fixed constants; they depend on both the state of charge and temperature, and may be determined by conducting experiments like pulse discharge and fitting the results or recursive least-square methods.

3.2.2 State of Charge Estimation

Perhaps the most important variable to be estimated for a battery management system is the State of Charge (SOC) -which is the ratio of the battery's current capacity to its nominal capacity. Because direct measurement is not possible with currently available sensor technologies, this estimation must rely on algorithms that integrate the voltage, current, and temperature of the battery. The most commonly used algorithms include the Coulomb counting method, and the Extended Kalman Filter (EKF) that combines the Coulomb counting method with voltage-based correction utilizing the ECM model.

Coulomb counting method, also called ampere-hour integration method, is defined as follows:

$$SOC(t) = SOC(t0)\ t0t\ [\ I()/\ Qc]\ d \qquad (3.3)$$

where t0 is the time at which estimation starts,SOC(t0) is the initial SOC at t0, I is the instantaneous current at time (positive in discharge) and Qc is theCoulombic capacity in Ampere hour(usually close to 1 for LI-ion batteries). For discrete time, this expression is modified to:

$$SOC[k] = SOC[k-1] - I[k-1]/Qn \qquad (3.4)$$

wherek is the index for the current instant of time, t is the time step andQnis the normal capacity in Ampere hour. Coulomb counting is a computationally efficient method that suits low-power implementation, but due to cumulative errors from noise, offsets and inaccurate estimation of the initial SOC, an EKF is generally utilized to provide more accurate and consistent SOC estimations.

A summary of the key variables and parameters utilized in the first-order ECM and SOC equations developed above can be seen in the Table 3.1.

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 capacitance	F
Q_n	Nominal battery	Ah

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

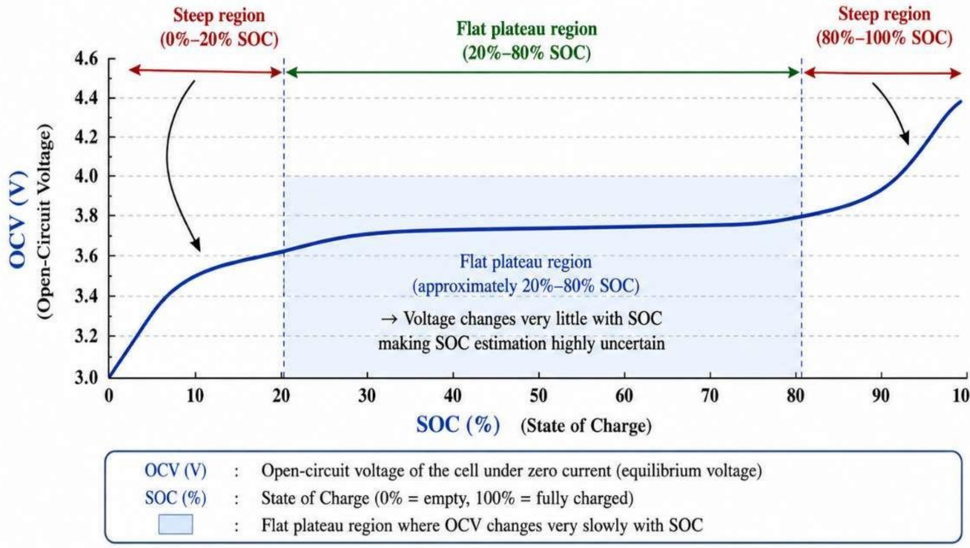


Figure 3.2: Typical nonlinear OCV–SOC relationship for a lithium-ion NMC cell

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.

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.

One key characteristic of Li-ion cells that is problematic for SOC estimation is the nonlinear nature of the OCV-SOC curve. The open circuit voltage has relatively flat plateaus over wide SOC ranges (approximately 20-80% for NMC chemistry as shown in Figure 3.2), where even a large change in SOC only leads to a slight change in OCV. In this plateau region the OCV is a poor indicator of SOC, and even small voltage measurement errors yield large SOC uncertainties. At the extremities of the SOC range the curve steepens, providing higher observability, but at the cost of indicating a region of potential Li-plating and rapid aging. This non-linearity requires current integration combined with voltage based correction.

The model and equations described in this section represent the heart of the state estimation algorithm that this work implements as the BMS state estimator. In the following section the architecture of the complete BMS is described; including the sensing front-end, embedded state estimation algorithms, and protection/balancing functions which together enable a complete battery management solution.

3.3 Battery Pack Configuration

In real world applications a single Li-ion cell seldom generates a pack voltage or capacity required for the target load. High power density systems such as Electric vehicles, grid-scale energy storage, or industrial systems require pack-level voltages and capacities that are many orders of magnitude greater than that of a single cell, which is typically rated between 3.0V-4.2V and is approximately some amp-hours in capacity. In order to meet these pack requirements, multiple cells are interconnected using one of two topologies (although more exotic configurations also exist), series connection or parallel connection. In most practical systems a combination of both is used. However, any such interconnection introduces undesirable effects relating to mismatch between individual cells, which the BMS must account for.

3.3.1 Series Connection

The positive terminal of one cell is connected to the negative terminal of another, to create a loop through each cell in turn, such that current only flows through one cell at a time.When cells are connected in series, the total voltage of the pack is multiplied by the number of series connected cells; the capacity however remains the same as that of the individual cell. For a string of n s cells connected in series the total pack voltage can be approximated as:

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

Where V i is the voltage across the i-th cell in the series string, and V nom is the nominal voltage of a single cell (assuming for now all cells have identical voltages). As current flows only through one cell at a time, the capacity of a series connected string is equivalent to that of a single cell-this arrangement allows for an increase in total pack voltage without an increase in total pack energy capacity. The result of this is that the lowest capacity cell within the series string will define the current limit for discharge, and will also reach the upper voltage limit first for charging, making them a potential source of energy inefficiency or even a hazard.

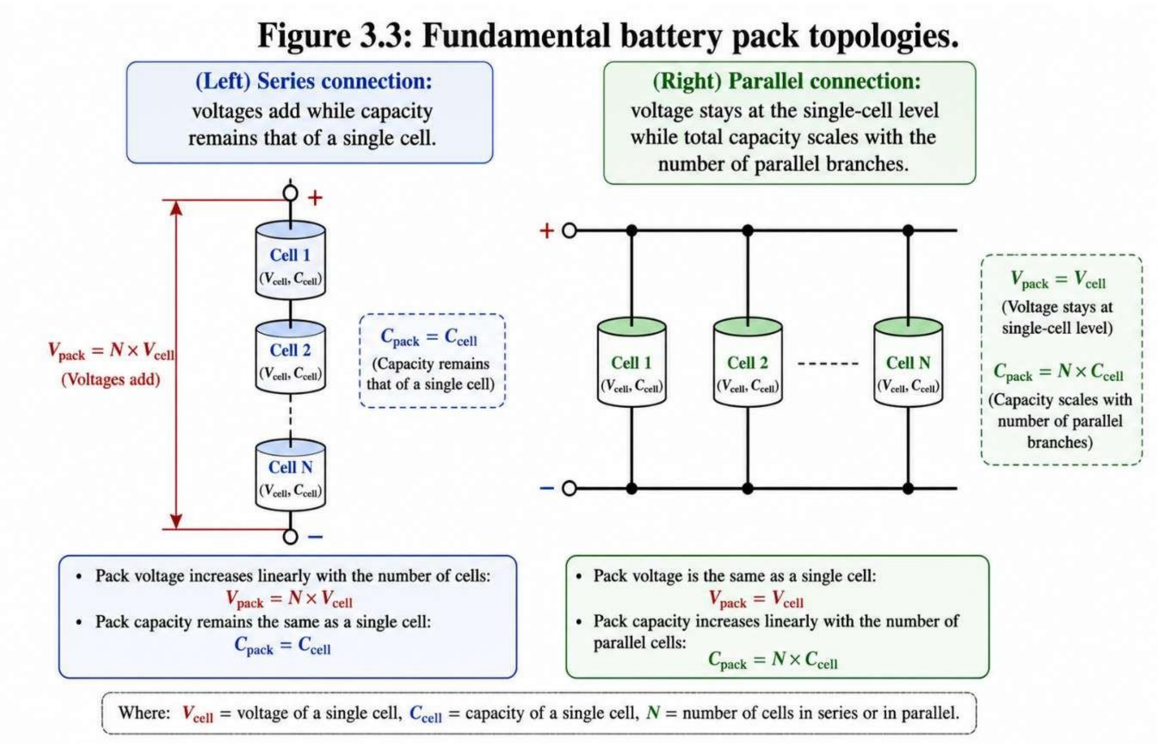


Figure 3.3: Fundamental battery pack topologies. (Left) Series connection: voltages add while capacity remains that of a single cell. (Right) Parallel connection: voltage stays at the single-cell level while total capacity scales with the number of parallel branches.

3.3.2 Parallel Connection

In parallel connection all positive terminals are joined and all negative terminals are joined together. This means all cells in parallel feel the same voltage, so the pack voltage remains that of a single cell, but the total pack capacity increases with the number of parallel connected cells. For n p cells connected in parallel:

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

As all cells are tied to the same voltage they must share equal voltage across them. However this means that current will distribute among cells in proportion to their own conductance: ideal evenly, but more likely, slightly unequally depending on the differences in the internal resistances of the cells within the string. It is less straight-forward to measure individual cell currents within a parallel group, requiring current sensors dedicated to each cell, and increasing costs and complexity, as compared to the series connected cells which are simply at different positions within a single string and thus have only a single common current flowing through them.

In a "real" battery pack the system will be a combination of both, denoted as n p n s, for example 4P10 S. This arrangement provides high voltage due to the 10S structure and high capacity due to the 4P cells and significantly reduces the effective internal resistance of each series cell, which is key for this application.

3.3.3 Cell Mismatch and Its Consequences

Despite manufacturing each Li-ion cell to have identical specifications, there will always be a degree of variation between any two cells. This variation arises from manufacturing variations in Electrode coating, separator porosity, electrolyte filling volumes, tab connections etc and is what leads to individual cells having slightly differing capacities, resistances, and self-discharge rates even at the moment of manufacture. As cells age, differences in their internal resistances and capacities evolve at different rates:cells that operate at higher temperatures within the pack, cells that are consistently driven closer to full charge and full discharge cycles, and cells subject to greater stress will decay faster than cells that operate in a "less taxing" manner, further adding to the inherent imbalance in cell states.

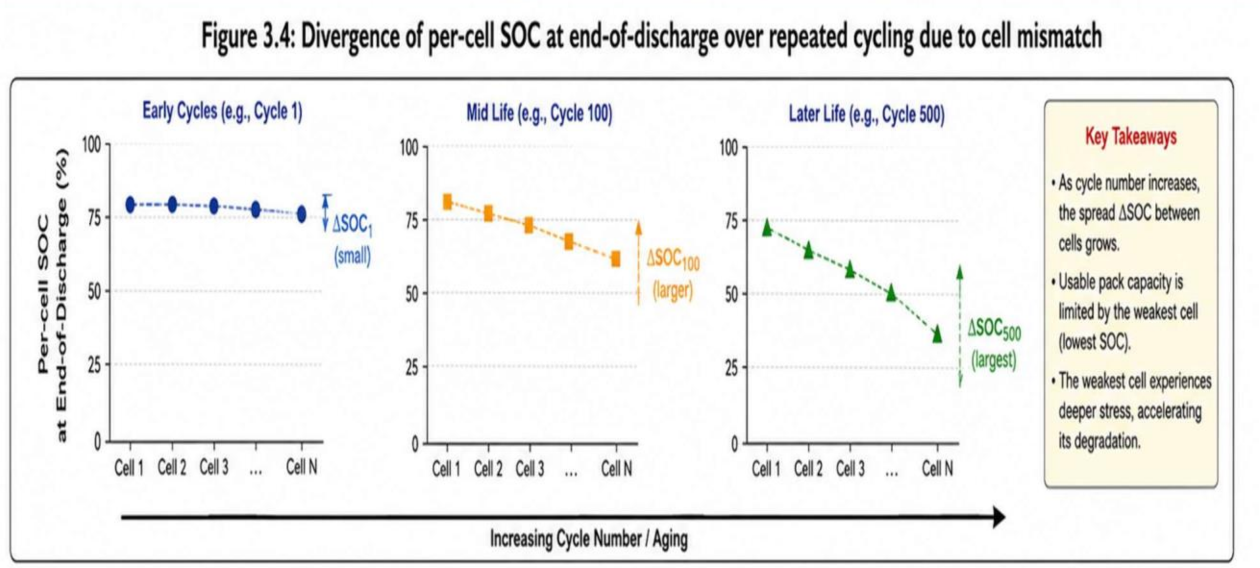


Figure 3.4: Divergence of per-cell SOC at end-of-discharge over repeated cycling

The result of cell mismatching in a series connection is that the cell states will never be identical over the entire charge/discharge cycle, even if they begin the cycle with identical SOC. With identical current through each cell in series, all cells lose/gain exactly the same amount of charge, and are thus equally effective in increasing/decreasing their SOC. However, as mentioned, capacity differs, and thus capacity removal and generation is different. With repeated cycling the imbalance in cell SOC increases. If this imbalance is not corrected by cell balancing, then one cell will reach either the upper voltage limit, or the lower voltage limit, forcing the entire cell string to stop charging or discharging respectively at the earliest opportunity to avoid damage to that cell, regardless of the current SOC of the other cells in the string.

3.4 BMS Architecture

The intelligent electronic subsystem that monitors, protects, and optimizes the behavior of a battery pack over its operational life is known as a Battery Management System. This device functions as an interface to the battery, feeding real-time state information to the host controller while at the same time enforcing safe operating parameters under all conditions. A state-of-the-art BMS can be broken down into four functional layers that are, despite their categorization, in continuous communication with each other: a sensing front-end, a central controller and estimation engine, a cell balancing circuit, and a protection system. Measurement data flows up from the sensing layer and the control signal to cell balancing and protection systems flows down from the controller. Measurement data is sensed by the sensing front end and passed up to the central controller that generates the necessary balancing commands and trips to the protection system. A control signal is passed down from the protection system to control the main contactors which isolate the pack.

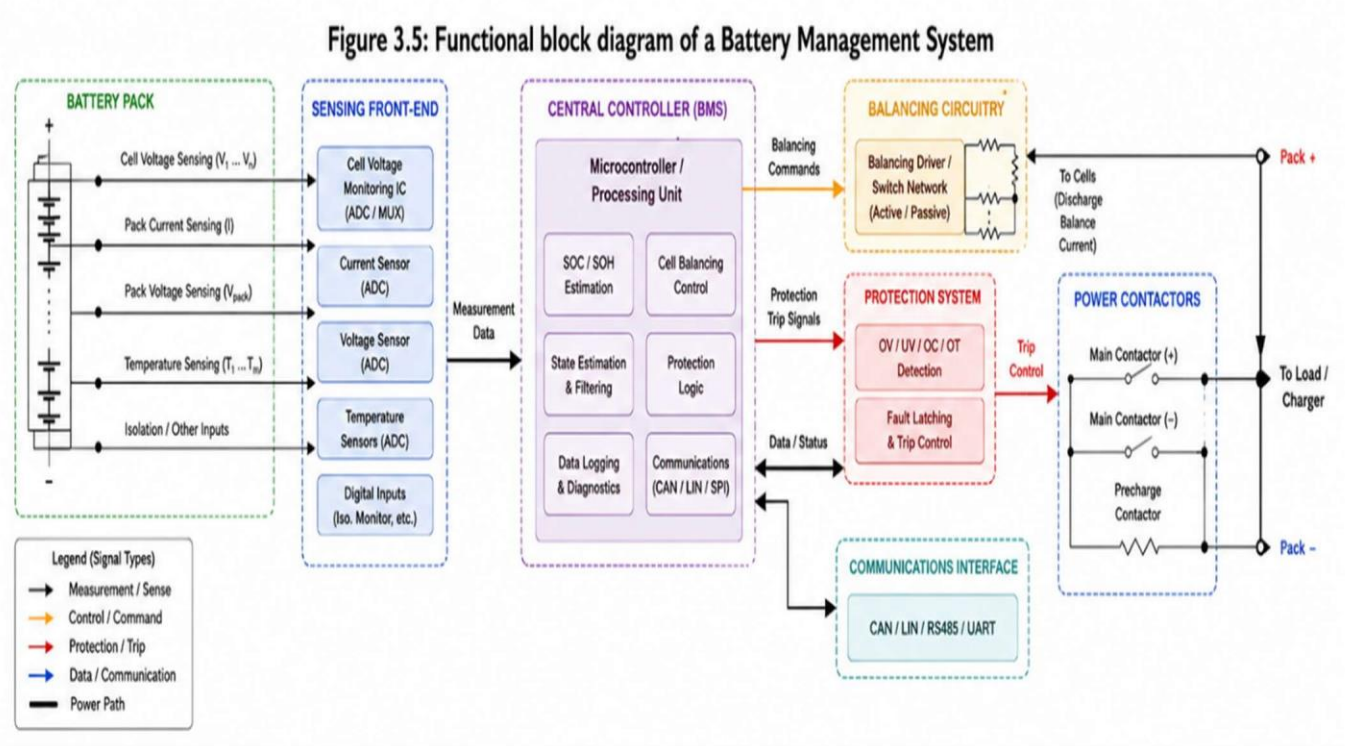


Figure 3.5: Functional block diagram of a Battery Management System.

3.4.1 Sensing Front-End

The sensing front-end is the first level of sensing within the BMS and has the job of converting electrical quantities- voltage per cell, pack current, and temperature- into digitized signals that can be processed by the main controller. When sensing voltages across each individual cell within a series string, the most critical value required to protect against over/undervoltage and detect SOC mismatches is the precision measurement of the cell voltage. Through specialized ICs, they sample cell voltage with resolutions from 0.5 to 2 mV and sampling rates of a few Hz. Pack current is measured either with an accurate Hall-effect transducer or a Shunt resistor. Higher accuracy requires smaller resistor values, leading to higher power dissipation. Negative temperature coefficient (NTC) thermistors placed at strategically important locations within the battery- either near the cells, bus bars or power electronics- provide the temperature readings to the sensing front end. Since the performance of electrochemical cells depends heavily on temperature and the likelihood of degradation greatly increase at elevated temperatures, temperature readings must be precise to support an accurate SOC estimation as well as a reasonable thermal management.

3.4.2 Central Controller

The central controller is the heart of the BMS, performing state estimation and control tasks. It receives input data from the sensing front-end and executes complex algorithms- such as coulomb counting, extended Kalman filtering or observers- in real time in order to obtain SOC, SOH and remaining useful life values. In addition to state estimation, the main controller implements the algorithms for the cell balancing function, generating balancing signals at appropriate times. The controller also enforces operating parameters by comparing current and future state values against a set of safety thresholds and issuing tripping commands to the protection system when thresholds are exceeded. It can send and receive data from a host system through a serial connection, typically Controller Area Network (CAN) communication in automotive and industrial systems, in order to share its state estimation information with the host system.

3.4.3 Cell Balancing Circuit

The balancing circuit is responsible for equalizing SOC levels across cells in the series string, reducing charge imbalances between cells. This may either be achieved passively, by bypassing an overcharged cell with a resistor, or actively, using a switching network to transfer charge between cells. Passive balancing is very simple and cheap, but suffers from inefficient transfer of charge from high SOC to low SOC cells where charge is instead dissipated as heat. Active balancing transfers energy from the high SOC to the low SOC cell via inductors or capacitors, such as an inductor based, fly capacitor or small DC-DC converter, which achieve 80 to 95% efficiency. The optimal balance technique depends on cell imbalance, cost constraints and expected thermal performance**.**

3.4.4 Protection System

The protection system's primary function is to keep the pack operating within safe electrical and thermal parameters, as irreversible damage or potentially dangerous situations can arise from over/under voltage and over current. Specifically, it monitors over voltage (OVP), under voltage (UVP), over current (OCP), short circuit detection (SCD), over temperature (OTP), and under-temperature charging (which can trigger lithium plating and permanently reduce battery life). If any of these conditions are detected, the main contactors within the battery pack are immediately opened, physically isolating the battery pack from the rest of the system. Protection against these faults are divided between hardware and software. Hardware protection using simple analog comparators offers extremely rapid response times of microseconds but is limited to simpler fault detections while software based protection using more complex algorithms takes a slightly longer response time, often with some tolerance for transients, to allow for more elaborate logic. The use of both methods assures some level of safety even if the software should malfunction**.**

CHAPTER 4

DESIGN OF CELL BALANCING METHODS

4.1 Resistive Cell Balancing Method

One of the simplest and common methods of BMS cell balancing is called resistive cell balancing or passive balancing. In this method, extra energy from cells with high voltage or high state of charge (SOC) is lost as heat via resistors. The goal of this balancing process is to make sure all cells within the battery have almost similar voltage and SOC levels when charging and discharging. Each cell in a lithium-ion battery does not function exactly in the same way owing to different factors like manufacturing tolerance, different temperatures, and aging effects. With time, there will be some cells with high voltages and other with low voltages. This creates an imbalance that results in reduced battery efficiency, decreased battery life, and safety concerns. Resistive balancing solves this issue by discharging the cells with high voltages until all cell voltages are balanced.

4.1.1 Working Principle

In the resistive balancing technique, the resistance is introduced to each cell of the batteries via a controlled switch such as MOSFET. Once the voltage of a specific cell exceeds the predetermined threshold, the switch for the same cell is ON. In this case, the current will flow through the resistor, and thus the excess energy from the selected cell is converted into heat energy.The balancing process takes place until the voltage differences between the cells get minimized.

Balancing current through the resistor can be obtained via Ohm’s law:

Where Ibis the balancing current, Vcellis the cell voltage, and Rbis the balancing resistor.

As seen from the formula above, the balancing current is inversely proportional to the resistance value. The lower the resistance, the higher the balancing current, and vice versa.The power dissipated in the balancing resistor is given by:

$$\square = \square_{\square}^{\square}\square_{\square} \qquad (\square.\ \square)$$

The same power equation can also be expressed as:

$$\square = \frac{\square_{\square\square\square\square}^{\square}}{\square_{\square}} \qquad (\square.\ \square)$$

where □ represents 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 the charging process, the BMS system constantly checks the voltage of each individual cell. In the case that a certain cell hits the maximum voltage level before other cells, the balancing resistor, which is attached to this cell, becomes operational. By doing so, it discharges the surplus electricity from the cell, while the other cells keep getting charged.

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

$$\square = \square_{\square}\square \qquad (\square.\ \square)$$

where □ is the discharged charge, $\square_{\square}$ is the balancing current, and □ is the balancing time.

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

$$\square\square\square = \square\square\square_{\square} - \frac{\square}{\square_{\square}}\int \square(\square)\,\square\square \qquad (\square.\ \square)$$

where $\square\square\square_{\square}$ is the initial state of charge, $\square_{\square}$ is the nominal battery capacity, and $\square(\square)$ is the balancing current over time.

Terminal Voltage Equation

The battery terminal voltage is:

$$\square_{\square\square\square\square\square\square\square\square} = \square_{\square\square} - \square\square_{\square\square\square} \qquad (\square.\ \square)$$

Where:

- $\square_{\square\square}$ = Open circuit voltage
- □ = Cell current
- $\square_{\square\square\square}$ = Internal resistance

Power Dissipation in Resistor

- Energy is dissipated as heat:
- $\square_{\square} = \square^{\square}_{\square}\square_{\square}$
- Alternative form:
- $\square_{\square} = \frac{\square^{\square}_{\square\square\square\square}}{\square_{\square}}$

Energy Loss During Balancing

Energy dissipated over balancing time:

$$\square_{\square\square\square\square} = \square_{\square}\square \qquad (\square.\ \square)$$

Where:

- □= Balancing duration

Voltage Difference Between Cells

Voltage imbalance:

$$\Delta\square = \square_{max} - \square_{min}\ldots\ldots\ldots\ldots\ldots\ldots(4.7)$$

Balancing starts when:

$$\square\square > \square\square_{\square\square\square\square\square\square\square\square\square}$$

4.1.3 MATLAB simulation

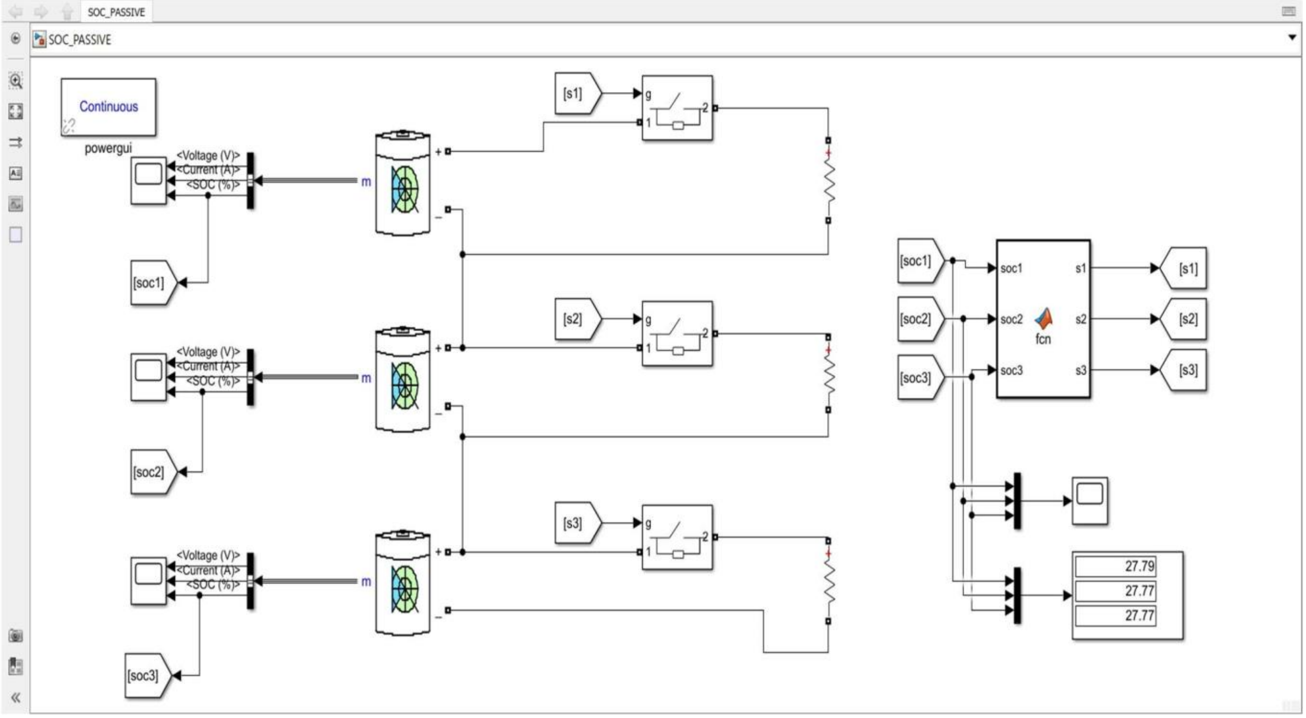


Fig : 4.1 MATLAB/SIMULATION Resistive cell balancing

4.1.4 Advantages of Resistive Balancing

Resistive balancing is a straightforward, inexpensive, and easy-to-implement technique in real battery applications. Fewer elements and control circuitry are required as opposed to active balancing techniques. Due to its simplicity and effectiveness, passive balancing is commonly employed in portable devices, electric bicycles, and affordable batteries for electric cars.

4.1.5 Limitations of Resistive Balancing

While resistive balancing is easy to implement, there are a few downsides associated with it. First of all, resistive balancing entails a certain amount of energy waste since the extra energy goes into heating up the batteries instead of transferring it into weaker ones. Additionally, a cooling mechanism would have to be implemented as well to handle the heat produced by the system. On top of that, resistive balancing is significantly slower than other balancing strategies, such as active balancing.

4.2 Switched Capacitor Balancing

$$□_□(□) = □_□\,(□ - □^{-\frac{□}{□□}}) \qquad (□.\,□)$$

where $□_□(□)$ is the capacitor voltage at time □, $□_□$ is the source voltage, □ is the equivalent resistance, and □ is the capacitance.

During discharging, the capacitor voltage decreases according to:

$$□_□(□) = □_□\,□^{-\frac{□}{□□}} \qquad (□.\,□)$$

where $□_□$ 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

Charge transfer in switched capacitor balancing involves the transfer of electrical charge from one battery cell to another via the capacitor. In case two adjacent cells have different potentials, the capacitor will automatically charge from the cell having a higher voltage to the cell having lower voltage. The process of balancing takes time that varies with capacitance, frequency, and potential difference.

In the beginning, the capacitor charges from the cell with a high voltage using the equation:

$$□ = □□ \qquad (4.10)$$

where □ is the stored charge, □ is the capacitance, and □ is the capacitor voltage.

The energy stored in the capacitor is given by:

$$□ = \frac{□}{□}□□^{□} \qquad (□.\,□□)$$

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:

$$□(□) = \frac{□□}{□}\,□^{-\frac{□}{□□}} \qquad (□.\,□□)$$

where □□ is the voltage difference between cells and □ 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:

$$□_{□□□} = □□□□ \qquad (□.\,□□)$$

where □ is the switching frequency, □ is the capacitance, and □□ 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

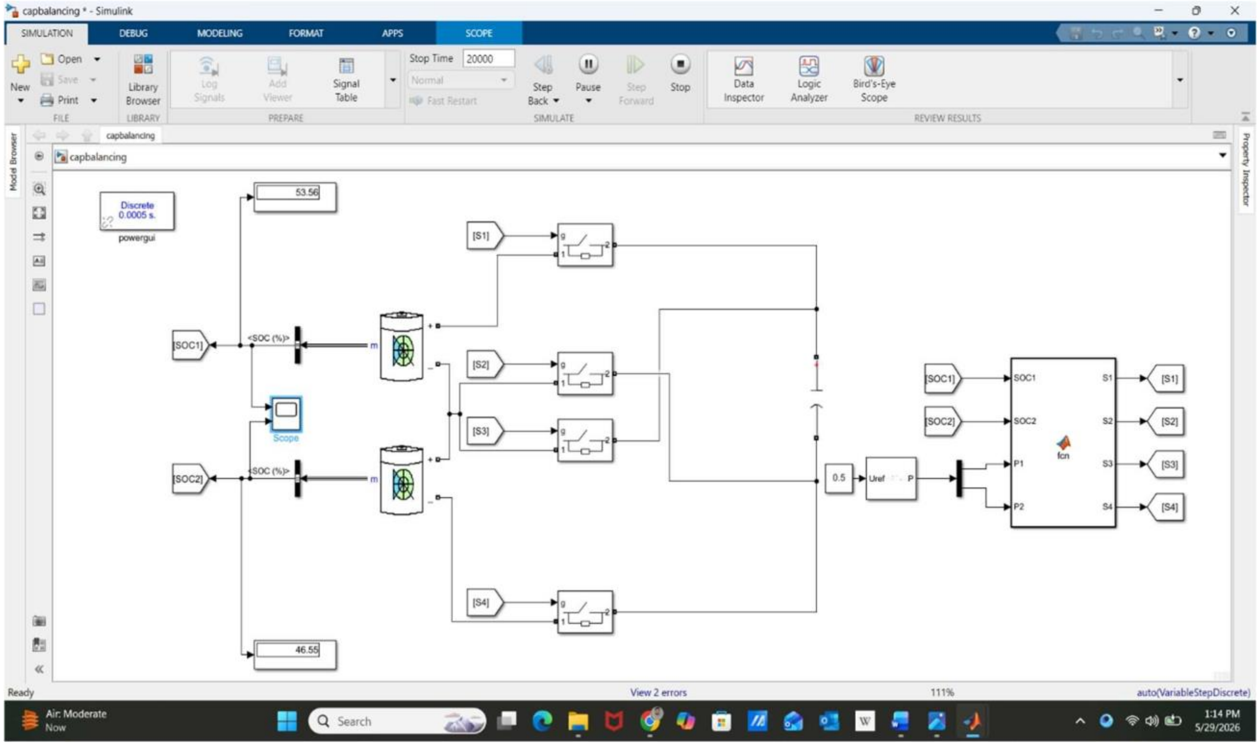


Fig : 4.2 MATLAB/SIMULATION Capacitive cell balancing

4.2.3 Performance of Capacitor-Based Balancing

Capacitive balancing results in higher efficiency than resistive balancing since energy moves from one cell to another, but it is not lost as heat. The design of this circuit is simple, and there is no need for any magnetic parts like inductor-based techniques. Capacitive balancing ensures moderate balancing time at a reasonable cost.

Nevertheless, switched capacitor balancing involves only neighboring cells and, therefore, takes longer time when balancing batteries with many cells. Moreover, the balancing current is determined by the capacitance and frequency. In spite of that, capacitor balancing is widely used in the medium power range due to its effectiveness.

4.2.4 Advantages of the Capacitor-Based Balancing Method

One aspect that distinguishes the capacitor balancing method from the traditional passive balancing approach is the significant increase in efficiency. For example, the balancing circuit shown in figure 4.2.3 shows that when there is an excess charge in one cell compared to other, it is transferred by charging the capacitor which is connected to that cell. Then, the same capacitor with charged by a cell, then discharged to a cell with deficiency of charge. In contrast to a conventional passive method where dissipated into heat. The efficiency of energy transfer, as seen in this method, is higher thus saving unnecessary energy losses. This is vital especially for batteries used in electric vehicles and renewable energy sources.

Another way in which capacitor balancing is better than other methods is through the alternative switched capacitor balancing circuits designs. For these circuits only electronic switching devices such as MOSFETs and capacitors are used unlike passive balancing circuits where magnetic devices are essential. The lack of inductors in the design greatly simplifies control and increases the compactness of the circuit. Capacitive balancing systems offer better thermal behavior than resistive systems. During charge transfer from cell to cell with capacitor, not much heat energy is lost and hence there is no increased temperature in the circuit. A reduced circuit temperature has a positive implication for battery life as the thermal stresses on the cells are greatly minimized. A low temperature circuit also means that less power will be consumed during operation as cooling power is drastically reduced or is completely eliminated. It is also worth noting that the balancing speed is improved significantly compared to passive balancing systems. Continuous flow of charges from cell to cell speeds up balancing and this is dependent on either the capacitance or the switching frequency.

With this approach, there is no complex control logic to initiate the energy transfer between neighboring cells, as this process relies solely on the potential differences that exist between the cells. This therefore makes the system more robust while significantly reducing the processing power needed by the battery management system.

A key advantage of capacitor balancing circuits is their excellent scalability, allowing their application on multi-celled lithium-ion batteries. Given that they are compact and relatively inexpensive, such systems find great applications in mid-power devices such as e-scooters,energy storage systems and hybrid vehicles.

4.2.5 Limitations of the Capacitor-Based Balancing Method

Although the capacitive balancing method offers numerous advantages over its passive counterpart, there are still several disadvantages to consider. Firstly, it is important to mention that these balancing methods generally take longer to balance large batteries. The cell-to-cell charge transfer with a switched capacitor balancing circuit occurs mainly between adjacent cells; hence, voltage imbalances in cells located further away would require a multi-step charge transfer.

Secondly, it is necessary to discuss the limiting balancing current capacity. As demonstrated, energy transfer is dependent on the value of the capacitor and also the frequency of switching, indicating that there are certain limitations imposed on the achievable balancing current values.

The balance process is also greatly affected by capacitor ESR and switching losses of the semiconductor components. Although there is some improvement in energy efficiency compared to passive methods, there are unavoidable energy losses resulting from the two aspects mentioned above. Furthermore, the control circuit will become increasingly complex for larger battery packs due to the additional number of switches that are needed for each capacitor along with the intricate synchronization of controls to manage correct charge transfer. For instance, in a multi-celled pack where a large number of capacitors would be incorporated into the design, the increased complexity of this switched circuit would be highly difficult to manage.

38 The capacitor balancing method also struggles in energy transfer over long distances; i.e., the cell with the highest energy level cannot directly transfer energy to the cell with the lowest energy level particularly if the cells are located far from one another in the battery pack. Additionally, the capacitor voltage stress that occurs during the repeated charge and discharge cycles of balancing, tends to reduce the lifespan of the capacitor. High frequency switching leads to generation of EMI, as well as switching noise.

If the difference between voltages of cells is small then the transfer current would become smaller, hence the balancing speed is significantly reduced in the last stage of the balancing process.

However, compared with other active balancing methods it can still be regarded as one of the most common and effective techniques of balancing given its relatively reasonable performance/price ratio.

4.3 Single Inductor Balancing

36 The single inductor balancing system incorporates just one inductor and several switches to manage the energy exchange among battery cells. In essence, it involves charging an inductor using each battery cell and then discharging the charged inductor to a lower voltage cell over time.

When a switch is turned ON initially, energy flows into the inductor and is then stored in its magnetic field. Once the charge in the inductor reaches a predetermined level, the switch is turned OFF and a second switch is turned ON to discharge the energy held in the magnetic field of the inductor into the low voltage cell.

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

$$\square_{\square} = \square \frac{\square\square}{\square\square} \qquad (\square.\ \square\square)$$

where $\square_{\square}$ is the voltage across the inductor, □ is the inductance, and $\frac{\square\square}{\square\square}$ 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:

$$\square = \frac{\square}{\square}\square\square^{\square} \qquad (4.15)$$

where □ is the stored magnetic energy, □ is the inductance, and □ 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 principle behind energy transfer in inductor balancing depends on electromagnetic energy storage and switching. In case of the selection of the cell with the higher voltage, the balancing circuit switches the inductor with the high voltage cell. Gradually, the current increases in the inductor with the accumulation of the magnetic energy.

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

$$\square(\square) = \frac{\square}{\square}\square \qquad (\square.\ \square\square)$$

where □ is the source voltage and □ 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 $\square_{\square}$ is the initial inductor current and □ is the equivalent resistance in the discharge path.

The transferred charge during balancing is given by:

$$\square = \int \square(\square)\square\square \qquad (\square.\,\square\square)$$

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:

$$\square_{\square\square\square} = \frac{\square\square\square\square}{\square} \qquad (\square.\,\square\square)$$

where □□is the voltage difference between cells, □is the duty cycle, □is the switching period, and □is the inductance.

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

4.3.2 MATLAB Simulation

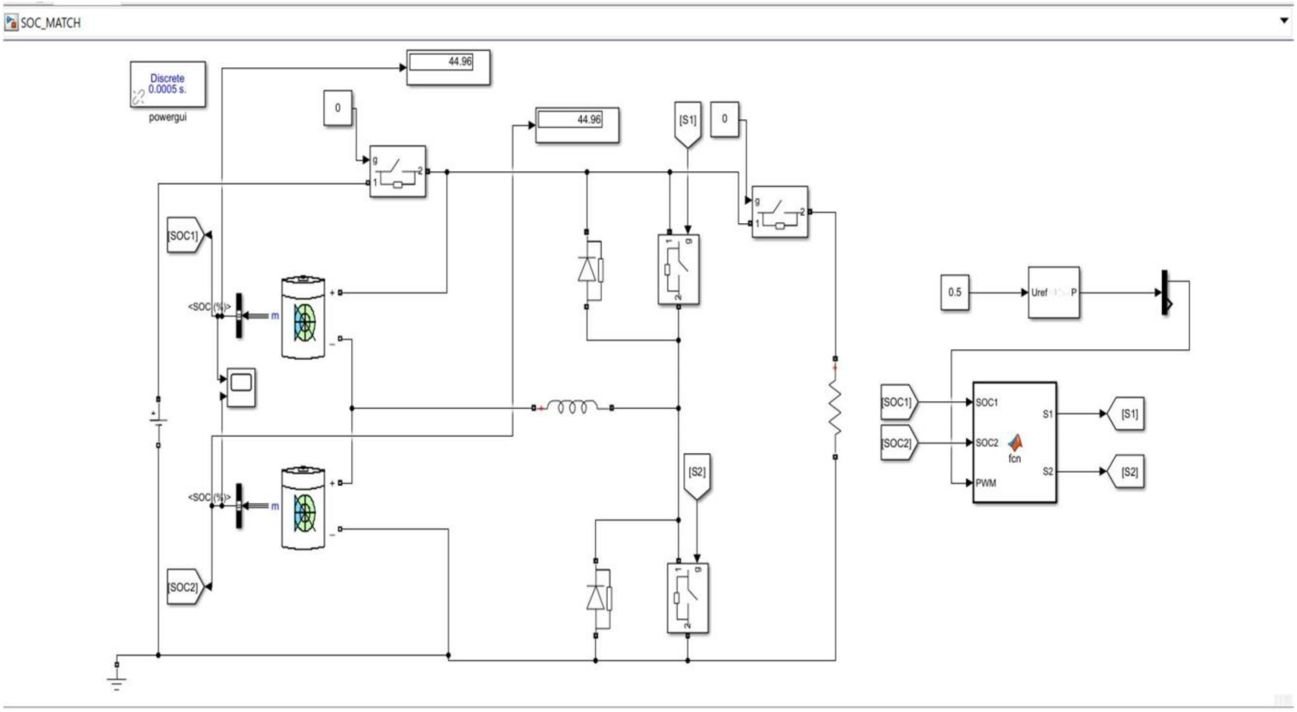


Fig : 4.3 MATLAB/SIMULATION Inductor cell balancing

4.3.3 Converter Operation

The inductor balancing circuit works on the same principle as a DC-DC converter. Balancing control monitors the voltages of each individual cell and decides which cells need power transmission. Converter functioning involves two phases - the first phase is energy storage while the second one is energy transmission.

In energy storage phase, the switch attached to the cell having higher voltage is turned on, so that energy starts accumulating in the inductor. In energy transmission phase, the source switch is turned off, and the switch connected to the target cell gets turned on.

The duty cycle of the converter is defined as:

$$\square = \frac{\square_{ON}}{\square} \qquad (4.19)$$

where $\square_{ON}$ is the ON time of the switch and $\square$ is the total switching period.

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

$$\square_{o} = \frac{\square}{1-\square}\square_{in} \qquad (4.20)$$

where $\square_{o}$ is the output voltage and $\square_{in}$ 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:

$$5 = \frac{\square_{out}}{\square_{in}} \times 100\% \qquad (4.21)$$

where 5 is efficiency, $\square_{out}$ is useful transferred power, and $\square_{in}$ is input power.

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

4.3.5 Fast Balancing

The inductor-based balancing circuit has higher balancing speed than resistive and capacitive balancing circuits. Because the inductor has a better capacity to transfer power, it can achieve higher balancing current. It also has the capability to transfer the energy from one cell to another very far cell; thus the overall balancing process speed is increased in a large battery pack. Fast balancing is required when a large battery pack is used in applications like EVs to increase charging efficiency.

4.3.6 Complex Control

Though the inductor-based balancing circuit has higher efficiency and speed, its controlling circuit is more complex compared to other balancing techniques. The proper synchronizing switching time, current path, duty cycle and protective circuits must work correctly so that energy can be transferred in safe manner from the circuit. In this type of circuit, the sensors, gate drivers and other advanced switching algorithms must be in harmony for balanced current. Any switching failure can create over current, voltage spike or Electromagnetic Interference (EMI). The simultaneous switching of the transistors can create a short circuit path for the cell to be charged. While switching at high frequency, both the switching and magnetic core losses play a significant role.

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

As opposed to the resistive balance, the inductor balance uses substantially less power since the energy is being reallocated rather than heated. The amount of energy lost is very low and hence optimum performance of the battery is achieved. The amount of thermal generation is low thus less need for cooling and longer life.

Compared to the capacitor balance, the inductor balance enables for more faster redistribution of energy and higher balancing currents. Whilst capacitor balance can only balance two neighbouring cells, inductor balance can redistribute from non-neighbouring cells. This is far more effective in large unbalanced battery systems.

The inductor balance shows good scalability of performance with higher power usage systems. For that reason it is widely used in electric transport, aerospace systems, and also in renewable energy.

4.3.8 Limitations of Inductor-Based Balancing

Despite many advantages, there are also a few disadvantages for balancing systems based on inductors. The first disadvantage is the complex system structure. For the purpose of balancing cells, the system should consist of inductors, power switches, current sensors and controllers. It is clear that the implementation of such system is more complicated than the cell balancing using capacitor or resistor.

It is necessary to mention that the implementation cost of such system is relatively high because the inductor and the special switchers should be used. Besides, inductors are bulky and heavy compared to capacitors.

The next problem concerns with the high frequency switching which results in the disturbance of the surrounding electrical devices via the emission of electromagnet waves. Additional filters or shield should be introduced to prevent such disturbance.

At last, the losses resulted from high frequency switching, the conduction as well as switching loss of power switches should be taken into account, though the efficiency of this technique remains to be high.

Another aspect that complicates the system, is the control algorithm. Algorithms used for inductor based balancing techniques are more complicated to design, and precise synchronization of the switching signals. This would involve higher computational power and more complexity to real-time battery management.

CHAPTER 5

RESULTS AND PERFORMANCE EVALUATION

5.1 Resistive (Passive) cell balancing MATLAB/Simulation Setup

Resistive active cell balancing, available in MATLAB/Simulink, is a straightforward and efficient algorithm for the study of battery pack components' active cell active balancing. The simulation enables the analysis of voltage balancing behavior, the simultaneous equalisation of SOCs, balancing current and energy loss. Power dissipation of balancing resistors is the primary disadvantage of this method due to other drawbacks of its simplicity, it is not suitable for large variety of systems.

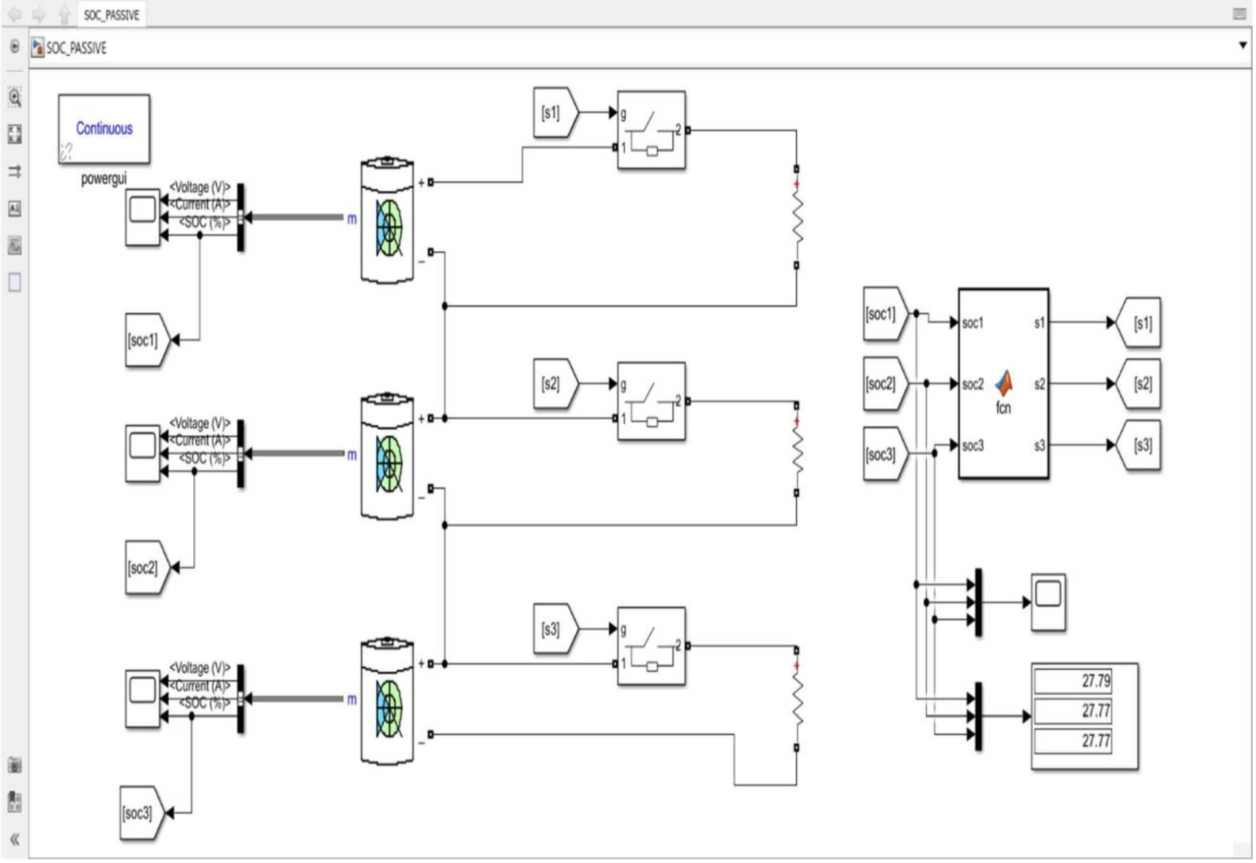
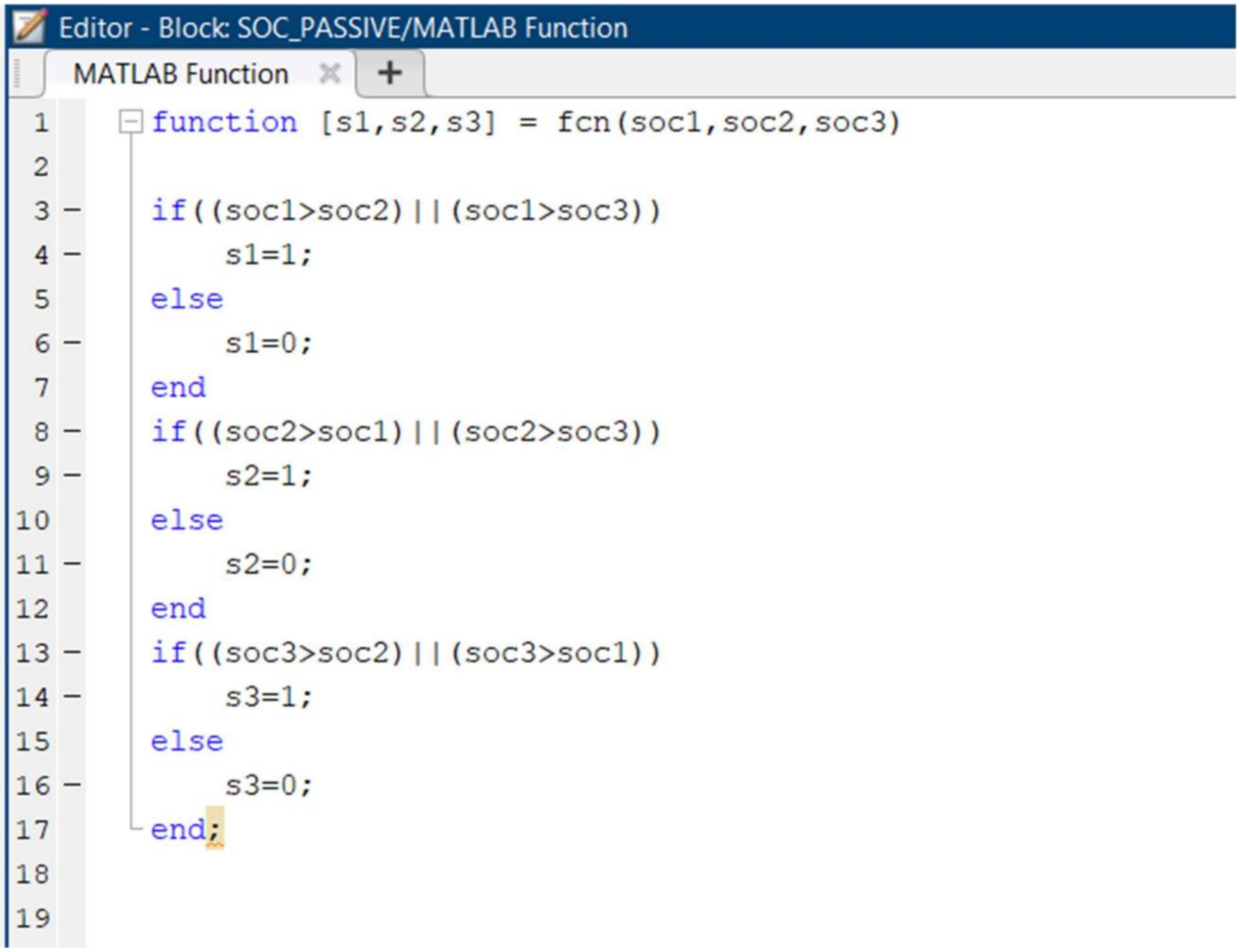


Fig : 5.1 MATLAB/SIMULATION Resistive cell balancing

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. It checks the remaining cells in the battery pack, and compares the SOC of each cell continuously to the other cells in the pack. When the SOC of a particular cell is higher than cells of any other, the switching signal is turned HIGH ($s1 = 1$, $s2 = 1$ or $s3 = 1$). This HIGH signal turns

ON the balancing switch of the balancing cell and excess energy is dissipated via the balancing resistor. If soc1>soc2, then switch s1 discharges Cell 1 if soc1>soc3, then switch s1 discharges Cell 1 or else if soc1<soc2 and soc1<soc3, then nothing. Likewise, this argument holds when handling Cells 2 and 3. If a cell's SOC is lower than the highest, its switching signal will be LOW (0) and the balancing circuit will be OFF. It allows for a switching sequence, whereby the cascaded cells with higher SOC values are discharged in a sequential manner until they have sufficiently equal SOC values in order to minimize the cell imbalance of 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;
```

Fig:5.2 Switching sequence code for Resistive cell balancing

5.1.2 MATLAB Simulation result/Resistive cell balancing SOC Match

The first SOC matching simulation result shows the balancing behaviour of 3 battery cells starting with different SOCs. Initially the cells are simulated with SOC amounts of 60%, 55% and 40% respectively, which puts the battery pack severely out of balance. Due to the continuous monitoring of the difference in SOC by the balancing controller, the switching sequence is triggered for cells that are more highly charged.The balancing controller constantly monitors the difference in SOC, and triggers the switching for the higher charged cells as a result of the monitoring. The cells with higher SOC begin to discharge slowly and the lower SOC cell remains at its level and slowly changes. This results in all the SOC curves gradually being drawn to each other. Final values of the SOC are around 28%, indicating that out of balance policy reduced the mismatch between SOC of cells. The result shows the effectiveness of the balancing to have a uniform charge distribution and to ensure battery pack uniformity during discharging operation.

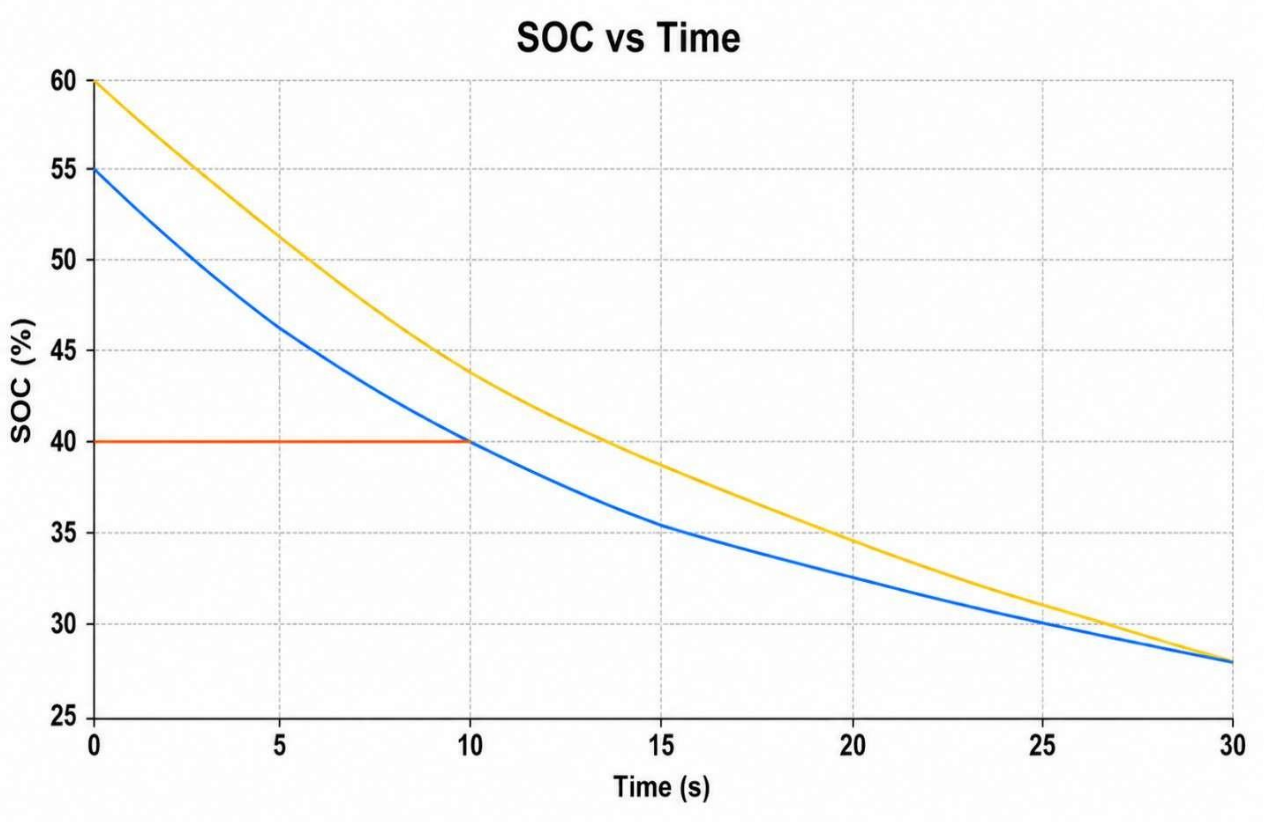


Fig : 5.3 Simulation Result SOC match with Resistive cell balancing

5.2 Capacitor (Active) cell balancing MATLAB/Simulation Setup

The active cell balancing system is built in MATLAB/Simulink to investigate the transfer of energy between cells of Lithium-ion battery (LIBs) with different states of charge (SOC). The approach was to use several battery cells in series using MOSFET switching circuits that act as switched capacitors. The balancing controller constantly kept an eye on the difference of voltage between neighbouring cells and operated the switching devices to movecharge from higher voltage cells to the lower voltage cells via the capacitors. The evaluation of balancing performance comprised different battery models, capacitor elements, switching logic, voltage sensors, and SOC estimation elements in the simulation. Unlike the passive balancing this method reduces the amount of wasted energy into heat being generated as the excess energy is distributed between the cells.

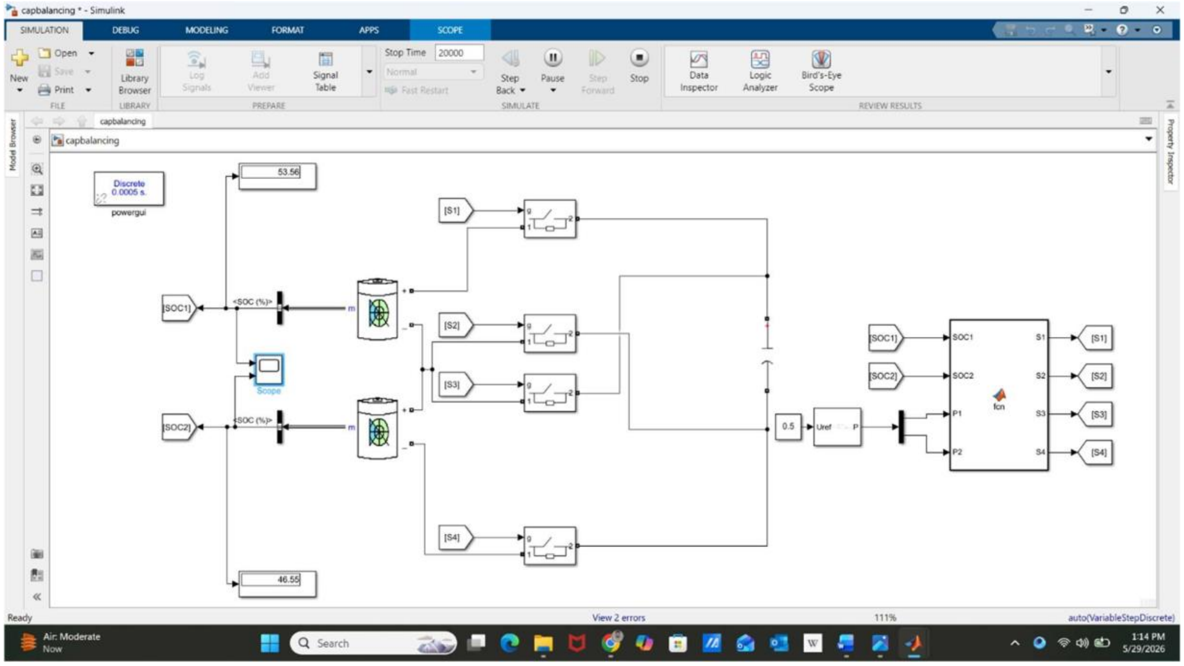
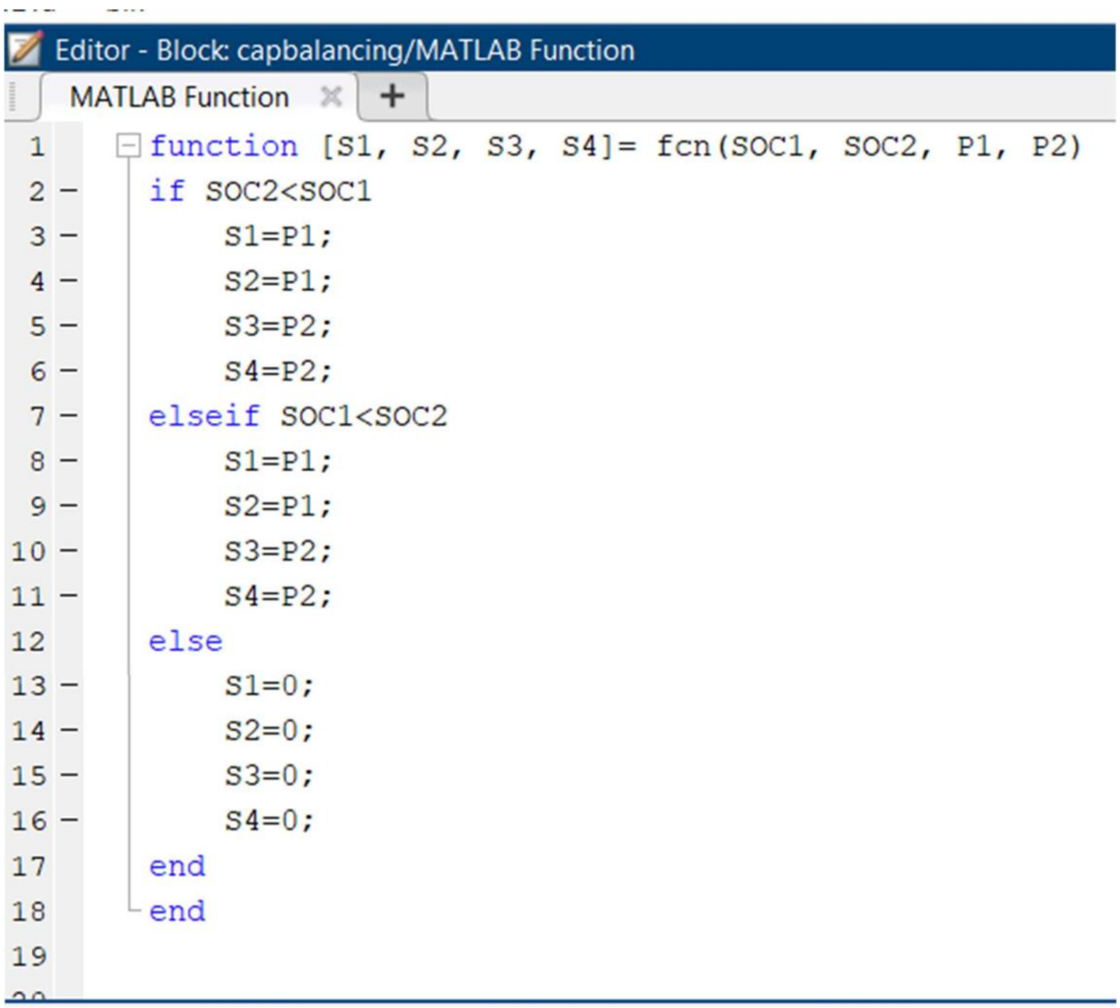


Fig : 5.4 MATLAN/SIMULATION Capacitor cell balancing

5.2.1 Switching sequence

The MATLAB function determines the sequence in which the active cell balancing control switches the cells to perform active cell balancing by comparing the SOC of two cells. If SOC2 < SOC1, then switches S1 and S2 are on with the signal P1 and switches S3 and S4 are on with the signal P2, thereby enabling the flow of energy from the high SOC to low SOC. The same switching action applies in this way too when SOC1 is less than SOC2, the cells are switched against each other. All switches hereafter obtain 0 values when both SOC values are the same, thus ending the balancing process (S1=S2=S3=S4=0). This switching logic also causes a gradual energy redistribution between the batteries and promotes uniformity of the battery SOC.



```
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
```

Fig: 5.5 Switching sequence code for Capacitor cell balancing

5.2.2 MATLAB Simulation result/Resistive cell balancing SOC Match

The graph demonstrates capacitive cell balancing where over time the State of Charge (SOC) of 2 battery cells will converge. At first, Cell 1 will be around 60% SOC and Cell 2 about 40% SOC. The switched capacitive process balances the energy between the two cells and the energy of the yellow curve is transferred to the lower charged cell, gradually reducing its curve and raising the blue curve. After some time, both the SOC curves converge at almost 50%, which is equivalent to a successful cell balancing. This approach ensures power is fed efficiently, decreases power loss, and achieves good battery pack uniformity.

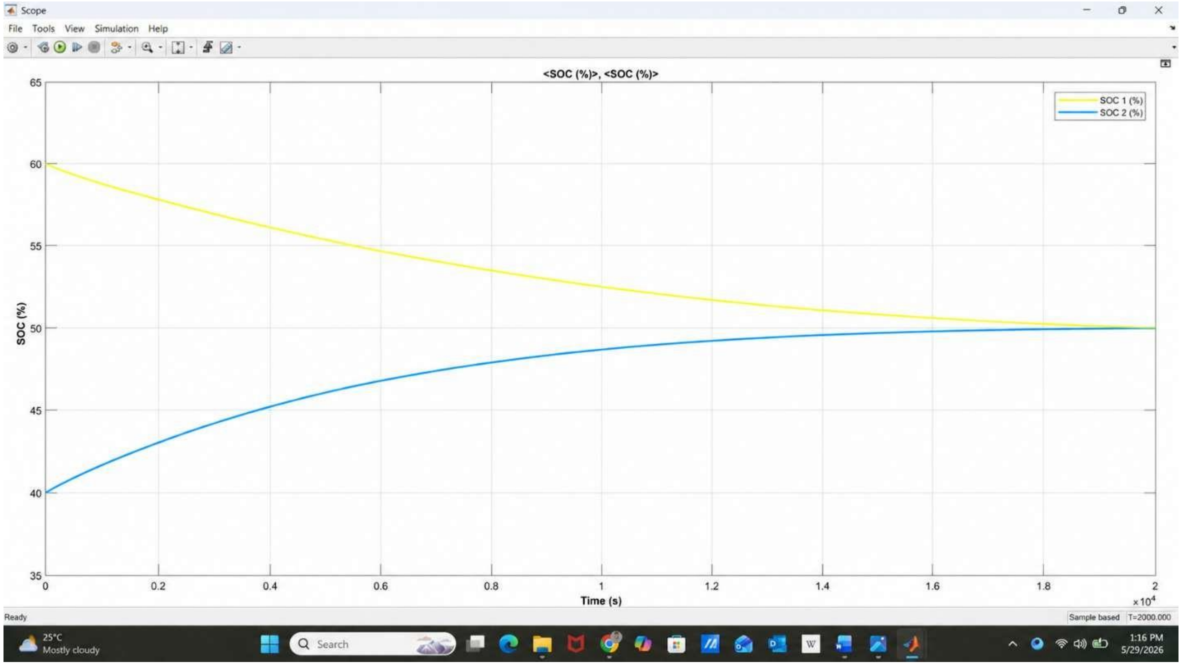


Fig : 5.6 Simulation result SOC Match with Capacitor cell balancing

5.3 Inductor (Active) cell balancing MATLAB/Simulation Setup

The MATLAB/Simulink model design for inductor active cell balancing is designed to investigate an inductor and controlled switching circuit to transfer energy from a higher charged cell to a lower charged cell. This simulation uses a battery pack made from several lithium-ion cells, a single inductor, a lithium-ion controller and switches. The controller continually checks the State of Charge (SOC) and cell voltage of each individual battery cell. When a voltage difference is found, the energy stored in the inductor will be switched from the cell of higher energy to the lower energy cell. The simulation is created using the components in Simulink including the following blocks: battery models, inductor, PWM pulse generators, MOSFET switches, voltage sensors, and the SOC estimation block. Balancing charges and discharging the interval of the inductor, controlled by the balancing algorithm, which provides energy balance distribution between cells. Operating it while the inductor temporarily stores magnetic energy of the high voltage cell and delivers it to the low voltage cell, efficient active balancing with reduced power loss occurs in comparison with passive balancing. Parameters, including balancing current, SOC equalization time, cell voltage difference and energy efficiency, are used to evaluate the performance of the balancing system. This simulation result indicates that the balancing speed of inductor-based balancing turned out to be faster and with higher efficiency, which can be applied in electric vehicle and energy storage applications.

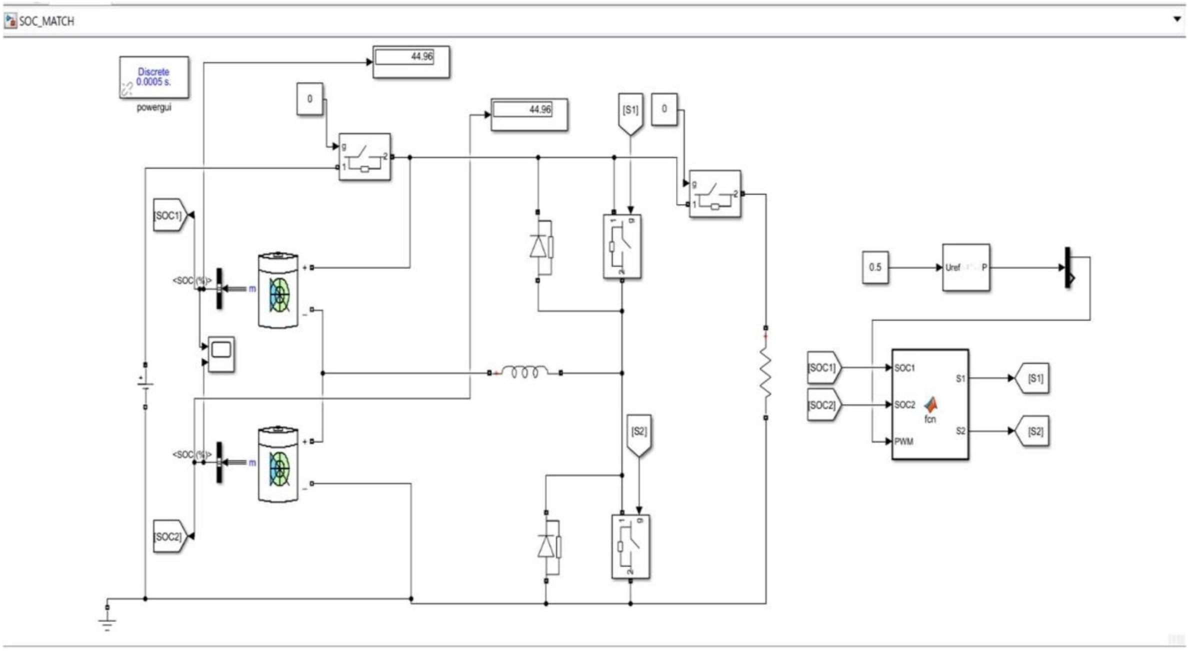
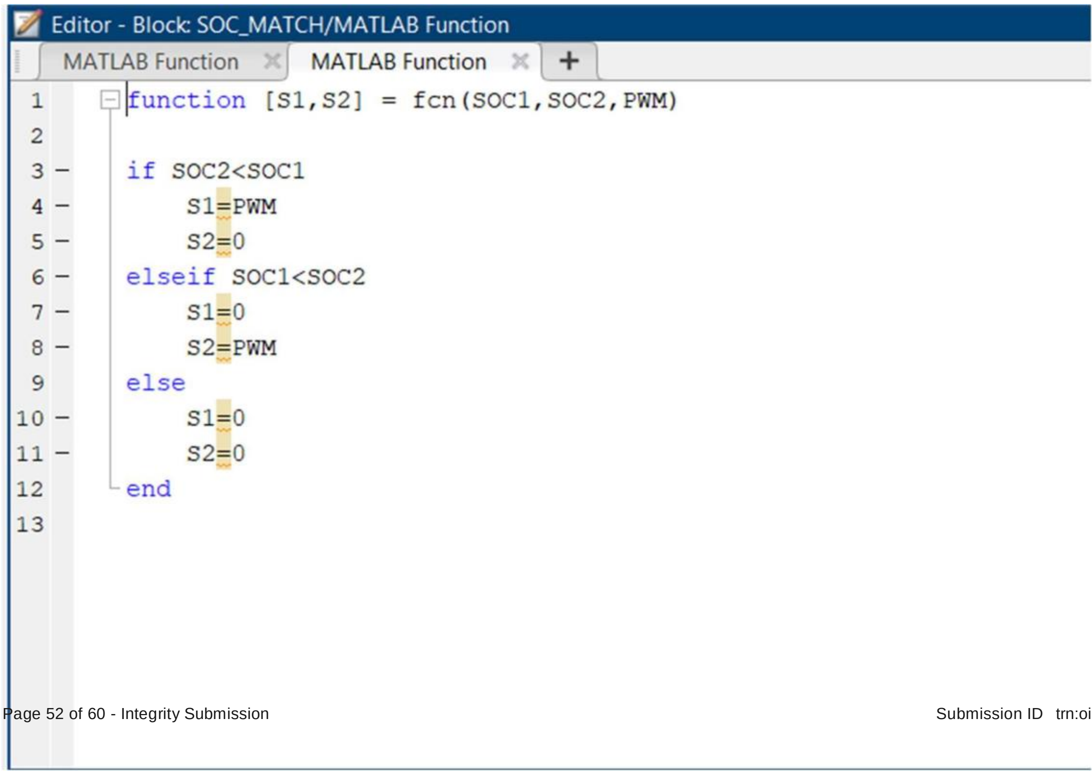


Fig:5.7 MATLAB/SIMULATION Inductor cell balancing

The MATLAB switching sequence is implemented as a comparison of SOC for two battery cells and switching control of S1 and S2 based on this. If SOC1 > SOC2, then S1 is activated due to which energy is transferred from Cell 1 to Cell 2. Likewise, if the SOC2 is unnecessarily high, switch S2 will be ON for the reverse energy transfer. If both values of SOC are the same, both switches stay OFF, which means that there are balanced cells. Switching operation and balancing current is executed with PWM signal.

.



```
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

```

Fig:5.8 Switching sequence code for Inductor cell balancing

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

Two battery cells were connected to an inductor based active balancing system. The graph displays the SOV between the two battery cells in the active balancing system. The initial SOC level of one cell is greater, approximately 60%, while the other cell is initially approximately 40%. The balancing process transfers the energy from the higher SOC cell to the lower SOC cell via the inductor circuit. Consequently, the SOC of the lower charged cell slowly rises whilst the SOC of the higher charged cell slowly decreases. The two curves of SOC converge at around 45% for the duration of simulation, this singals that the cells are in a balanced state. The result shows that by using the active balancing system, the charge distribution of these cells was equalized and produced better energy efficiency with less energy lost

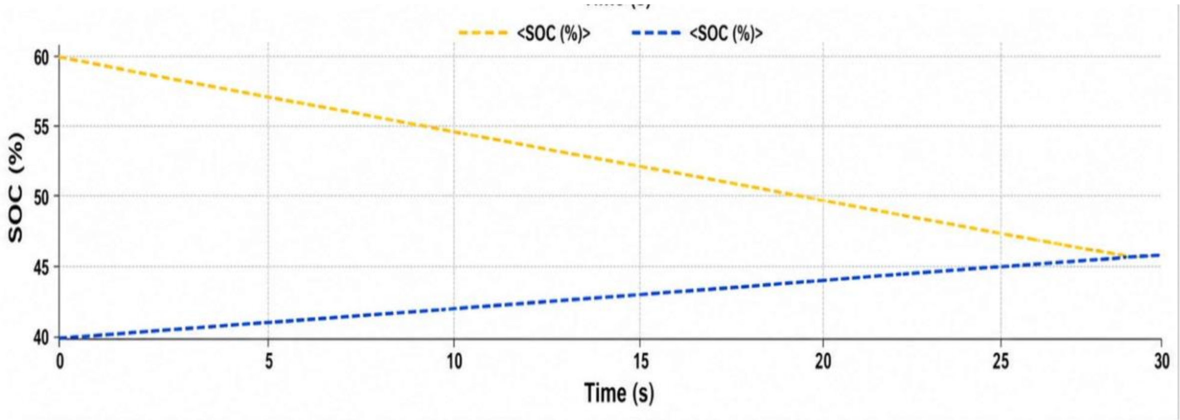


Fig:5.9 Simulation result SOC Match with Inductor cell balancing

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Balancing is an important part of a Battery Management System (BMS), as it ensures balanced State of Charge (SOC) in lithium-ion cells that are arranged in a series configuration. As a result of uneven values of internal resistance, temperature, aging, and production tolerance, there will always be unbalance of cell voltage and State of Charge. Without cell balancing, weaker cells can face overcharge or deep discharge, thereby affecting the overall capacity and cycle life of the battery, besides raising safety concerns. This study focuses on three cell balancing schemes – resistive cell balancing, active cell balancing using capacitors, and active cell balancing using inductors.

6.1.1 Resistive Cell Balancing

Resistive balancing, or passive balancing, is the most basic form of balancing. In this technique, energy from the higher voltage batteries is wasted as heat through resistors until all battery voltages are balanced. The balancing current will be determined by the resistance used in accordance with:

The power dissipated during balancing is:

$$\square = \square^{\square}_{\square\square\square}\ \square \qquad (\square.\ \square)$$

One main strength of the resistive approach is that it has a very simple circuit configuration, low cost of implementation, and simple control process. The approach uses few components and little computation effort, hence appropriate for use in low-cost battery packs. On the downside, the process is very inefficient, owing to the fact that a lot of electrical energy is wasted as heat during the process. This increases the temperature rise within batteries, thereby decreasing their efficiency.

6.1.2 Capacitor-Based Active Cell Balancing

The capacitor-based technique offers a solution for improving the efficiency of the system since it utilizes a system whereby energy is transferred among cells rather than dissipated as heat energy. In the case of the switched capacitor technique, capacitors alternate connection of adjacent cells using switches.

The energy stored in the balancing capacitor is expressed as:

$$\square = \frac{\square}{\square}\square\square^{\square} \qquad (\square.\ \square)$$

The capacitor charging current is approximately:

$$\square_{\square} = \square\frac{\square\square}{\square\square} \qquad (\square.\ \square)$$

As opposed to resistive balancing, the capacitor balancing system uses less energy and experiences less heat due to recycling the energy back into the battery pack. The efficiency is fairly high, while the speed is higher than that in passive balancing. Moreover, it provides quite a compact hardware configuration, as it does not require any magnetic devices like inductors or transformers.

On the other hand, the balancing current depends on the voltage and capacitor size, thus slowing the process down in a big battery pack. The system is more complex as it involves several switches and timing circuits. Furthermore, energy is transferred between adjacent batteries, increasing balancing time in a long string of batteries..

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

6.1.3 Inductor-Based Active Cell Balancing

The active inductor balancing technique is the most efficient among the three active cell balancing techniques that have been studied. This is because the transfer of energy takes place magnetically via inductors or by DC-DC converters without losing much energy.

54

The energy stored in the inductor is:

$$\square = \frac{\square}{\square}\square\square^{\square} \qquad (\square.\ \square)$$

The voltage-current relationship of the inductor is:

$$\square = \square\frac{\square\square}{\square\square} \qquad (\square.\ \square)$$

Inductor balancing is the quickest form of balancing that consumes the least amount of energy because the transfer of energy takes place directly between remote cells without dissipating a lot of power. There is minimal increase in temperature and inductance balancing is ideal for applications in electric vehicles, renewable energy storage system, and large lithium-ion batteries.

Some disadvantages exist even for such a good technique. Its control system is relatively complicated with switching timing necessary. Inductor balancing is expensive since inductors, converters, sensors and switching components at a fast pace are necessary. Higher stress due to switching operation and EMI also exists.

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

Based on the comparative study, it can be deduced that there are certain pros and cons for each type of balancing approach based on its application need.

- Resistance balancing is the most cost-effective method, but it is the least efficient..
- Capacitor balancing is fairly efficient, offers moderate balancing speed, but the circuit design is relatively complex.
- The most efficient and fast balancing is provided by inductor balancing, but at the expense of a much more complicated hardware design.

Results from the use of MATLAB/Simulink indicated that active balancing techniques performed better compared to passive balancing in terms of energy consumption and thermal performance. Inactive balancing techniques, the use of inductors provided the best performance in large batteries while capacitors provided a balanced compromise.

Thus, the choice of balance technique will depend on factors such as battery capacity, efficiency goals, budget issues, balancing speed, and thermal issues within the circuitry. In terms of cost-effective designs, the resistive balancing design is quite viable, but the current trends in vehicles and energy storage favor inductor based balancing designs.

6.2 Future Scope

The advancements of efficient Battery Management Systems (BMS) and cell balancing technology will remain vital areas of study because of the fast proliferation of electric vehicle (EV) usage, renewable energy storage technology, and portable electronics devices. Despite the effectiveness of traditional balancing methods including resistive, capacitive, and inductive balancing techniques, there are certain ways to improve these processes for the future use..

6.2.1 Hardware Implementation of Balancing Systems

The research can further consider the realization of the proposed methods for balancing of lithium-ion batteries from the viewpoint of actual hardware. Theoretical validation of proposed methods is ensured by MATLAB/Simulink simulations, while hardware testing allows assessment of performance under different conditions. Balancing of lithium-ion batteries may be realized by using controllers such as Arduino, DSP, STM32, or FPGA.

In hardware implementation, however, there are other parameters, including switching losses, sensor precision, electromagnetic interference (EMI), heat considerations, and converter efficiency, which need to be taken into consideration. In future research, one may also consider more compact printed circuit board (PCB) design, efficient heat dissipation methods, and power electronics devices.

6.2.2 AI-Based Intelligent Cell Balancing

AI and ML algorithms have been developed that may be used to enhance the performance of battery balancing systems. Traditional methods for achieving battery balancing involve fixed threshold levels, while AI techniques allow for predictions and optimal balancing based on battery dynamics.

The next generation BMS designs may apply neural networks, fuzzy logic, and/or reinforcement learning techniques to provide better estimations of SOC, SOH, temperature changes, and aging. Balancing operations become faster and more efficient when intelligent balancing methods are applied, allowing the selection of the best balancing paths and switching schemes at run-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)

In conventional BMSs, there is wired communication between the battery cells and the controller, which leads to heavy, complex, and difficult-to-maintain systems. In future battery management systems, WBMS will be utilized instead of wired communication through wireless communication technologies including Bluetooth, Zigbee, Wi-Fi, or even wireless CAN communication.

The wireless BMS system would lower wiring harness complexity, increase system flexibility, and facilitate the assembly of batteries in the EVs. Wireless BMS makes it easy to scale up to larger battery packs in use in EVs and renewable energy systems.

Future research directions might include the use of secure wireless communications, low-power sensor networks, and data transmission that is unaffected by any form of signal interference within WBMS systems.

6.2.4 Real-Time Electric Vehicle Applications

With advancements in technology in regards to electric vehicles, the future balancing system will have to work effectively under dynamic driving conditions that involve fast charging, regeneration of brakes, and variable loads. An effective active balancing system could easily integrate with fast charging technologies.

Balancing systems in real time would be able to constantly monitor battery variables such as voltage, current, state of charge, state of health, and temperature. Future research may concentrate on ultra-fast balancing techniques, adaptive control converters, and their implementation within an integrated system that optimizes vehicle energy utilization.

Moreover, the batteries for future electric vehicles would need to have higher energy densities, thereby necessitating improved balancing techniques.

6.2.5 Hybrid Cell Balancing Methods

In hybrid balancing approaches, the strengths of passive and active approaches are combined to give an optimal solution in terms of overall performance. In this approach, active balancing can be implemented when the battery is operating under nominal conditions, while passive balancing is used at the stage of battery equalization.

In future, hybrid architectures can employ both capacitors as well as inductors to enhance balancing capability and scalability without increasing complexity. In such systems, the hybrid controller will determine the best balancing approach based on battery conditions, SOC mismatch, and operating environment.

These hybrid systems are expected to offer superior thermal performance, faster balancing times, and increased battery life.

6.2.6 Overall Future Perspective

The future designs of battery balancers will become highly intelligent, efficient, space-saving, and automated designs due to advancements in battery technology. The use of technologies like artificial intelligence, wireless connectivity, power electronics, and real-time monitoring will increase the safety and efficiency of batteries. Of all other future aspects, intelligent active battery balancing along with real-time monitoring and hybrid energy transfer systems is likely to play a prominent part in future electric vehicles and renewable energy storage systems.

REFERENCES

[1] Zhang, Yongzhi, Rui Xiong, Hongwen He, and Weixiang Shen. "Lithium-ion battery pack state of charge and state of energy estimation algorithms using a hardware-in-the-loop validation." *IEEE Transactions on Power Electronics* 32, no. 6 (2016): 4421-4431.

[2] Sun, Fengchun, Rui Xiong, and Hongwen He. "A systematic state-of-charge estimation framework for multi-cell battery pack in electric vehicles using bias correction technique." *Applied Energy* 162 (2016): 1399-1409.

[3] Cao, Jian, Nigel Schofield, and Ali Emadi. "Battery balancing methods: A comprehensive review." In *2008 IEEE Vehicle Power and Propulsion Conference*, pp. 1-6. IEEE, 2008.

[4] Moo, Chin S., Yao Ching Hsieh, and I. S. Tsai. "Charge equalization for series-connected batteries." *IEEE Transactions on Aerospace and Electronic Systems* 39, no. 2 (2003): 704-710.

[5] Moghaddam, Ali Farzan, and Alex Van den Bossche. "Flyback converter balancing technique for lithium-based batteries." In *2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, pp. 1-4. IEEE, 2019.

[6] Ye, Yuanmao, and Ka Wai Eric Cheng. "An automatic switched-capacitor cell balancing circuit for series-connected battery strings." *Energies* 9, no. 3 (2016): 138.

[7] Pascual, Cesar, and Philip T. Krein. "Switched capacitor system for automatic series battery equalization." In *Proceedings of APEC 97-Applied Power Electronics Conference*, vol. 2, pp. 848-854. IEEE, 1997.

[8] Baughman, Andrew C., and Mehdi Ferdowsi. "Double-tiered switched-capacitor battery charge equalization technique." *IEEE Transactions on Industrial Electronics* 55, no. 6 (2008): 2277-2285.

[9] Yuanmao, Ye, Ka Wai Eric Cheng, and Y. P. B. Yeung. "Zero-current switching switched-capacitor zero-voltage-gap automatic equalization system for series battery string." *IEEE transactions on power electronics* 27, no. 7 (2011): 3234-3242.

[10] Ye, Yuanmao, and Ka Wai E. Cheng. "Modeling and analysis of series–parallel switched-capacitor voltage equalizer for battery/supercapacitor strings." *IEEE journal of emerging and selected topics in power electronics* 3, no. 4 (2015): 977-983.

[11] Shang, Yunlong, Chenghui Zhang, Naxin Cui, and Josep M. Guerrero. "A cell-to-cell battery equalizer with zero-current switching and zero-voltage gap based on quasi-resonant LC converter and boost converter." *IEEE Transactions on Power Electronics* 30, no. 7 (2014): 3731-3747.

[12] Cervera, Alon, Michael Evzelman, Mor Mordechai Peretz, and Shmuel Ben-Yaakov. "A high-efficiency resonant switched capacitor converter with continuous conversion ratio." *IEEE Transactions on Power Electronics* 30, no. 3 (2014): 1373-1382.

[13] Shang, Yunlong, Qi Zhang, Naxin Cui, and Chenghui Zhang. "A cell-to-cell equalizer based on three-resonant-state switched-capacitor converters for series-connected battery strings." *Energies* 10, no. 2 (2017): 206.

[14] Ye, Yuanmao, Ka Wai E. Cheng, Yat Chi Fong, Xiangdang Xue, and Jiongkang Lin. "Topology, modeling, and design of switched-capacitor-based cell balancing systems and their balancing exploration." *IEEE Transactions on Power Electronics* 32, no. 6 (2016): 4444-4454.

[15] Ohno, Takuya, Takahumi Suzuki, and Hirotaka Koizumi. "Modularized LC resonant switched capacitor cell voltage equalizer." In *IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society*, pp. 3156-3162. IEEE, 2014.