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Design and Implementation of a Converter-Based Active Battery Cell Equalization System for Electric Vehicles

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Abstract: Battery cell balancing is one of the key functions of the Battery Management System (BMS) used in Electric Vehicles (EVs), as it enhances the battery performance while prolonging the battery life as well as providing safety. Battery cells connected in series have different parameters like internal resistance, temperature, and aging effects, which cause the state of charge to be different. This results in the battery capacity being less efficient and can cause battery degradation or safety issues. This paper discusses the different battery cell balancing techniques used in the battery management system. These techniques include passive balancing, switched capacitor equalizers, inductive equalizers, transformer equalizers, and DC–DC converter equalizers. A MATLAB/Simulink model is used to implement the different battery cell balancing techniques and their simulation results compared. A battery cell equalization system based on the Ćuk converter is designed for the battery cells of the Electric Vehicle. Simulation results show that the proposed system balances the charge of the battery cells efficiently with the least time and highest efficiency compared to the other battery balancing techniques.

Keywords: Battery Management System (BMS), Electric Vehicle Batteries, Cell Balancing, Active Balancing, Passive Balancing, Ćuk Converter, Battery Equalization, MATLAB/Simulink.

I. INTRODUCTION

The use of electric vehicles has gained popularity as a cleaner source of energy in the modern world. The performance and reliability of EVs are highly dependent on the battery pack. The battery pack is composed of several cells in series and parallel configuration. Due to the differences in the characteristics of the cells in the battery pack, the cells are subjected to various charge levels during the charging of the battery pack. This results in the cells being out of balance in terms of the state of charge and voltage[1]. Over charging the battery cells results in thermal runway and fire. Over charging and under charging the battery cells in series configuration result in the performance being limited. The battery cells are subjected to imbalance in the state of charge and voltage. This results in the battery pack having limited capacity and the over charging and over discharging of the battery cells during the charging and discharging of the battery pack respectively. Therefore, the cell balancing is a critical function of the Battery Management System (BMS).

The primary purpose of the Battery Management System (BMS) is cell balancing. Equalizing the charge distribution during charging and discharging is the goal of cell balancing. The distortion of the battery The literature has presented a number of balancing strategies, which can be broadly categorized into passive and active balancing approaches. Active methods redistribute energy among cells, whereas passive methods release excess energy as heat. Because of their increased efficiency and better use of energy, active balancing techniques are favored for electric vehicle applications. For better battery pack performance, this study explores various cell balancing techniques and suggests an active equalization circuit based on a Ćuk converter.

Numerous balancing strategies that fall into the general categories of active and passive have been proposed in this literature. Because of their high efficiency and energy consumption, active balancing techniques are preferred for electric vehicles. While the active method redistributes the energy among cells, the passive method releases excess energy as heat. For better battery pack performance, the study suggests an active equalization circuit based on a Ćuk converter.

II. LITERATURE REVIEW

Cell balancing is essential to enhancing the longevity, safety, and efficiency of lithium-ion battery packs used in electric vehicles (EVs), it has collected a lot of attention from researchers. Variations in internal resistance, capacity fading,

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temperature gradients, and manufacturing tolerances among individual cells all contribute to cell imbalance. These differences result in an uneven distribution of charges, which lowers the battery pack's usable capacity and may lead to individual cells being overcharged or overdischarged. Therefore, to maintain consistent state-of-charge (SOC) across cells, effective cell balancing techniques are needed.

Initial research classified balancing methods into passive and active categories. Resistors are used in passive balancing methods to get rid of extra energy from higher-voltage cells. These methods are easy to use and don't cost much, but they aren't very efficient because they lose energy as heat. They aren't good for high-power EV applications. Active balancing methods, on the other hand, use capacitors, inductors, or power converters to move energy between cells. This makes the system energy-efficient and speeds up the balancing process.

Recent studies have concentrated on enhancing the efficiency and reducing cell balancing time of various topologies. [1] studied active cell balancing methods for electric vehicles, sorting them by the path of energy transfer and the layout of the circuit. Their research examined different DC–DC converter-based balancing circuits and illustrated that converter-based approaches offer enhanced efficiency and accelerated balancing time relative to passive methods.

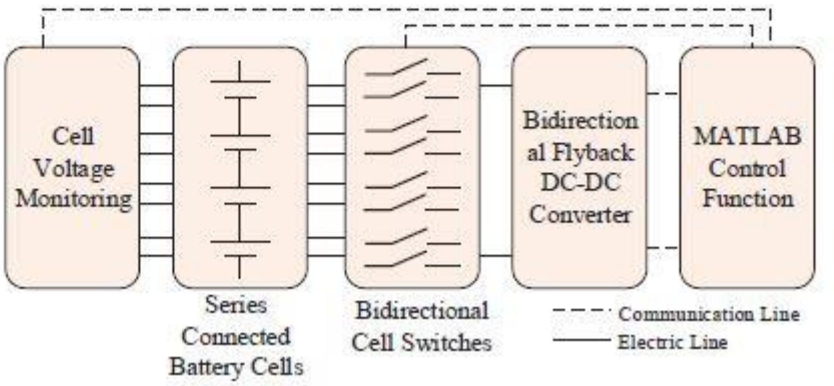

Fig. 1 Set up of Equalization Circuit

Inductor-based equalization methods have received a lot of attention because they can move large amount of energy between cells. Venkatasatish [4]. suggested a multi-inductor active balancing system with SOC-based control for lithium-ion battery packs. The proposed topology significantly reduced balancing time compared to conventional methods, while maintaining high efficiency as shown by simulation results and hardware-in-the-loop results.

[3] suggested a multi-cell-to-multi-cell (MC2MC) active balancing method that uses buck-boost converters and clustering algorithms for battery packs. Their findings indicated that adaptive control strategies, when integrated with state of charge (SOC) estimation, can enhance balancing efficiency and decrease equalization time by facilitating energy transfer between non-adjacent cells.

Recent research has investigated hybrid balancing strategies that integrate various balancing methodologies. [5] came up with a new way to balance the duty cycle that combines duty cycle control with energy transfer from cell to pack. For large battery packs used in electric vehicles, the proposed method cut down on the time it takes to equalize the SOC by a lot compared to standard duty-cycle balancing methods.

There are many types of active balancing circuits, but DC–DC converter-based equalizers have recieved a lot of attention because they are very efficient and easy to control. Ćuk converter-based balancing circuits, in particular, let energy flow in bidirectional with little current ripple and a lot of energy transfer capacity. Previous research has shown that modified Ćuk converter circuits[6] can balance several cells with fewer switching devices while still being very efficient and equalizing quickly.

Even through these improvements, battery equalization systems still have some problems to solve, such as making the circuits more complicated, designing the control algorithm, and finding the right amount of time to balance large battery packs. Hence research is still focused on making converter topologies better, cutting down on the number of parts, and coming up with smart control strategies to make balancing work better.

This paper examines and simulates various cell balancing techniques, including passive balancing, switched capacitor equalizers, flyback converters, and DC–DC converter-based methods, using MATLAB/Simulink. An active balancing

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circuit based on a Ćuk converter is recommended and tested for a lithium-ion battery pack with eight cells. The suggested topology seeks to attain expedited balancing time, enhanced efficiency, and a diminished component count relative to traditional balancing techniques[7].

III. PROBLEM STATEMENT

Lithium-ion battery packs for electric cars are made up of several cells that are connected in series or parallel to get the right voltage and capacity. But because of differences in how they are made, temperature gradients, internal resistance, and aging, each battery cell usually has different voltage and State-of-Charge (SOC) levels when it is charging and discharging. This imbalance makes the battery pack less effective and may cause some cells to reach over-charge or over-discharge conditions sooner than others.

This kind of imbalance has a big effect on how well the battery works, how safe it is, and how long it lasts. In the worst cases, cell imbalance can cause thermal runaway, loss of capacity, and early battery failure. In Battery Management Systems (BMS), it is very important to keep the same SOC and voltage across all battery cells.

Standard passive balancing methods waste extra energy as heat through resistors, which makes them less efficient and costs energy. Active balancing methods are more efficient because they move energy between cells. However, many existing topologies have problems like more complicated circuits, more parts, slower equalization speeds, and more complicated control algorithms. So, making a battery cell balancing system that is fast, efficient, and has low losses is still a big problem for modern electric vehicle battery packs.

IV. RESEARCH GAP

There has been a lot of research on battery cell balancing techniques, however there are still some problems with the ones that are already out there:

1. Low Efficiency in Passive Balancing: Passive balancing methods emits extra energy as heat, which makes them less energy-efficient and puts more stress on the batteries in high-capacity EVs.

2. A lot of parts in active balancing circuits: Active balancing circuits, like transformer-based and multi-switch DC–DC converters, need a lot of switches and magnetic parts, which makes the system more expensive and complicated.

3. Slow Equalization Speed: Capacitor-based balancing methods take longer to get the charge equalized due to slow energy transfer rates.

4. Complicated Control Strategies: Advanced converter-based balancing systems is hard to put into practice due to complicated control algorithms and precise switching coordination.

Limited Comparative Analysis:
Numerous studies failing to deliver a thorough comparison of passive and active balancing methods under equivalent simulation conditions; concentrate on a singular balancing technique

V. CONTRIBUTION TO THIS WORK

In order avoid these gaps in research, this paper suggests and tests an active battery cell balancing method that uses a Ćuk DC–DC converter topology. The primary contributions of this research are:

- Making an active equalization circuit based on a Ćuk converter with fewer parts and better energy transfer efficiency.
- Assessment of balancing efficacy regarding equalization duration, power dissipation, and circuit intricacy.

The proposed method will enhance battery pack efficiency and decrease balancing time, all while preserving a functional and scalable architecture appropriate for electric vehicle applications.

VI. PROPOSED METHOD: ĆUK CONVERTER-BASED ACTIVE CELL BALANCING

There are many ways to balance, and one of them is Cuk converter balancing, which works quickly. Voltage differences can happen in a battery pack during charging and discharging cycles. To make a series-connected battery pack more

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balanced, an equalization circuit based on a Ćuk converter is suggested. The circuit lets battery cells send and receive energy in both directions while keeping the current ripple low.

The suggested topology uses n switches and (n+1) inductors to keep an n-cell battery pack in balance. This setup needs fewer parts than traditional methods that need (2n−1) switches.

The traditional Cuk balancing method needs (2n-1) switches for n cells, but the new method only needs (n) switches and n+1 inductors for n cells. This cuts down on both the number of parts and the amount of energy that is wasted, as shown in Figure 1. This circuit does a good job of balancing eight cells in a battery string that is set up in a series [11]. It has a buck-boost feature that is made possible by a simple pulse width modulation (PWM) with a 50% duty cycle. There are two main phases in the operational framework. In the first phase, switches Q1, Q3, Q5, and Q7 are turned on, while the other switches stay off. In the next step, switches Q2, Q4, Q6, and Q8 are turned on while the other switches are turned off.

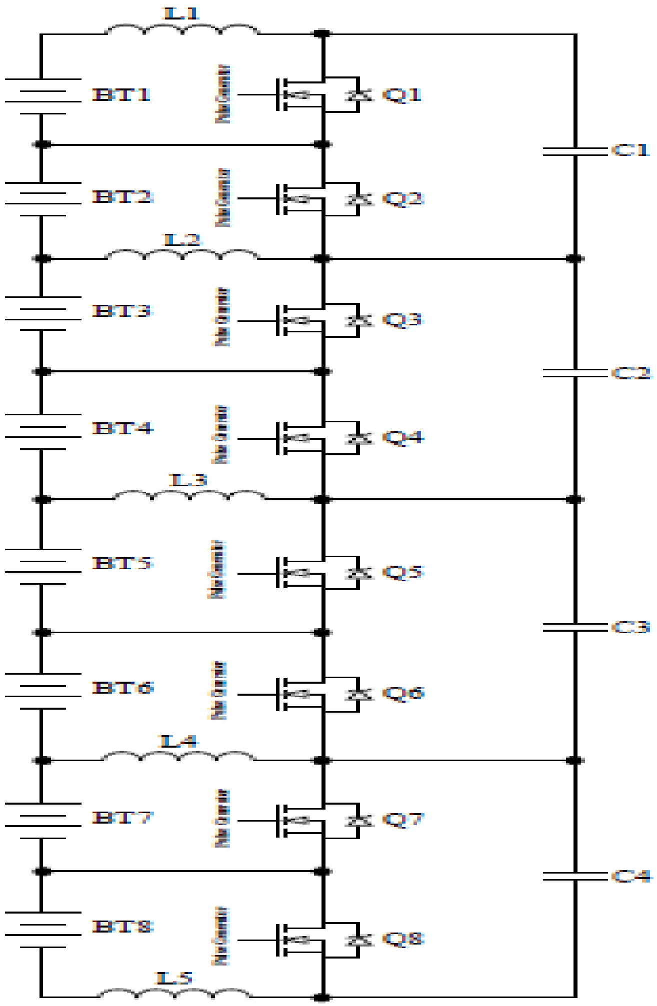

Fig. 2 Schematic of the proposed Cuk converter balancing circuit [11]

The circuit operates in two switching stages:

Stage 1
Switches Q1, Q3, Q5, and Q7 are turned ON while the remaining switches are OFF.

Stage 2
Switches Q2, Q4, Q6, and Q8 are turned ON while the remaining switches are OFF.

Pulse Width Modulation (PWM) with a duty cycle of 50% controls the switching operation

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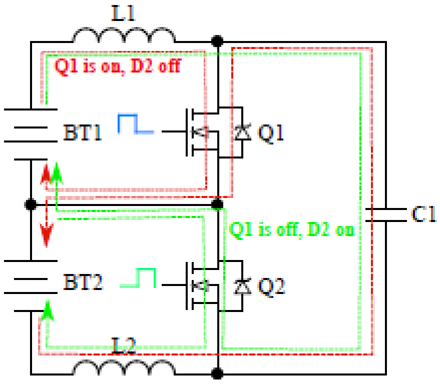

Fig.3 Simplified Cuk converter circuit with two cells

In order to simplify the design consider sub circuit having two cells and switching devices Q1 and Q2. When Q_1 turns ON; Q_2 will be OFF

$$Vcell1 = L1\frac{di_{L1}}{dt}$$

$$V_{cell2} = -L_2 \frac{di_{L1}}{dt} + V_{C1}$$

Expression for average inductor current can be obtained from charge balance of C1 as

$$i_{L1}(1-D)T_s - i_{L2}DT_s = 0$$

Where D is duty cycle and Ts is switching frequency. The average inductor current for L1 and L2 can be expressed as

$$i_{L1} = [\frac{1}{2}(\frac{V_{\text{cell1}}}{L_1}D^2 + \frac{-V_{C1}+V_{\text{cell1}}}{L_1}(1-D)^2)]T_s$$

$$i_{L2} = [\frac{1}{2}(\frac{V_{C1}-V_{\text{cell2}}}{L_2}D^2 + \frac{-V_{\text{cell2}}}{L_2}(1-D)^2)]T_s$$

VII. MATHEMATICAL MODELLING OF THE ĆUK CONVERTER BALANCING CIRCUIT

The proposed battery equalization system utilizes a Ćuk DC–DC converter topology to transfer energy between cells in a series-connected battery pack. The converter enables both directional energy transfers while maintaining continuous current in both inductors, resulting in low current ripple and improved balancing efficiency.

The simplified Ćuk converter used for cell balancing consists of following inductors (L_1 and L_2), a coupling capacitor (C1), a switch (S), and a diode (D).

The Ćuk converter operates in two switching states within a switching period T_s.

1) <u>Mode 1: Switch ON (0< t< DT_s)(0 < t < DT _s)(0< t< DT_s)</u>

When the switch S is turned ON:

- The diode becomes reverse biased.
- Inductor L1 stores energy from the source battery.
- Capacitor C1 transfers energy to the output stage through L_2.

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The inductor voltage equations are

$$V_{L1} = V_{in}, V_{L2} = -V_C$$

The inductor current variations are

$$\frac{di_{L1}}{dt} = \frac{Vin}{L1}$$

$$\frac{di_{L2}}{dt} = -\frac{Vc}{L2}$$

2) Mode 2: Switch OFF (DTs<t<Ts)(DT_s < t < T_s)(DTs<t<Ts)

When the switch is OFF:

- The diode conducts.
- Energy stored in L_1 is transferred to capacitor C_1.
- Inductor L_2 supplies energy to the load cell.

The voltage equations become

$V_{L1} = V_{in} - V_C$

$V_{L2} = V_C - V_o$

The corresponding current equations are

$di_{L1}/dt = (Vin - V_C) / L_1$

$diL2/dt = (VC - Vo) / L_2$

TABLE I DESIGN SPECIFICATION

Parameter	**Value**
Switching Frequency	100 kHz
Inductor Value	10 µH
Capacitor Value	100 µF
Cell Voltage Range	3 – 3.8 V
Sampling Time	2 µs
Duty Cycle	50%

VIII. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink models were developed to simulate different cell balancing techniques including passive balancing, switched capacitor equalizers, flyback converters, and the proposed Ćuk converter equalizer.

Simulation results show that:

• Passive balancing has high energy loss.
• Capacitor-based balancing provides moderate equalization speed.
• Inductor-based methods improve efficiency.
• The proposed Ćuk converter balancing circuit achieves the fastest equalization with minimal power loss.

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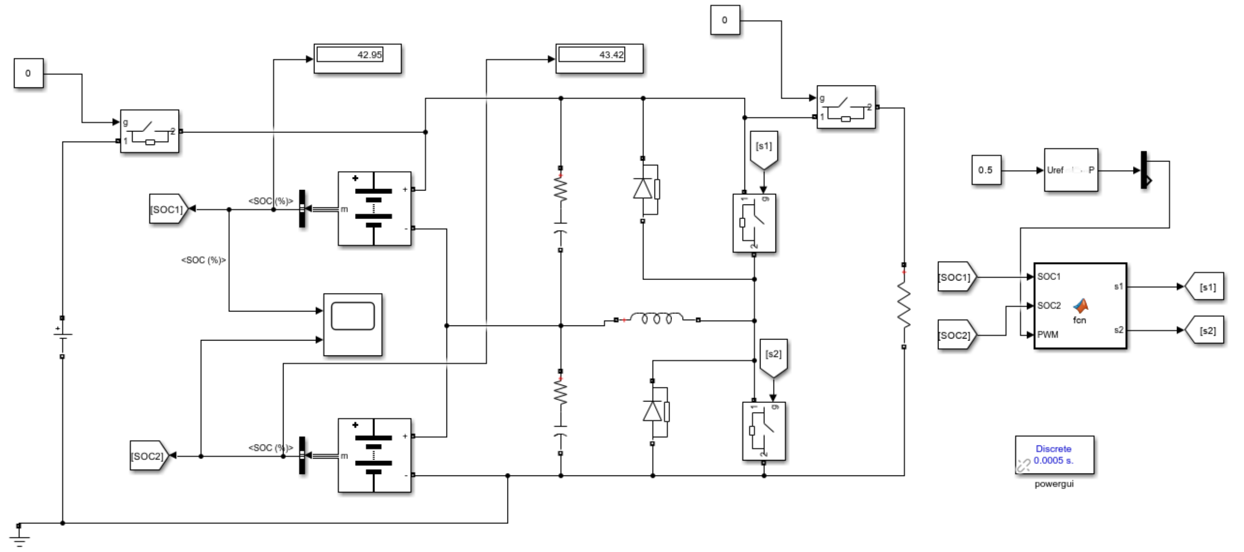
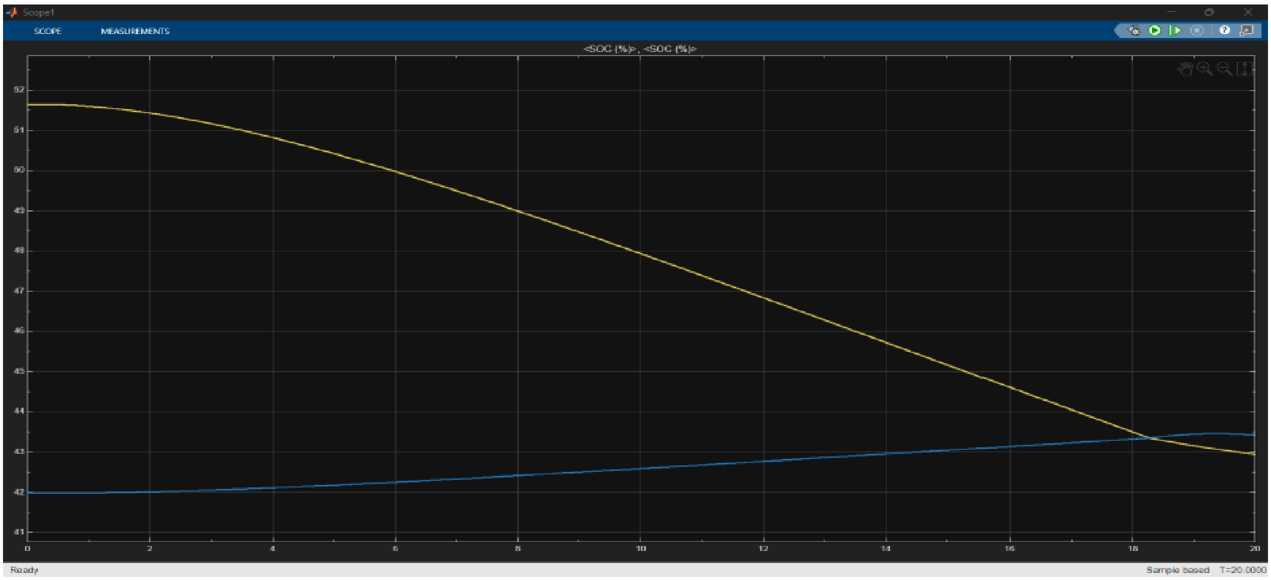


Figure 3 Simulink Model for Inductor based Battery Equalization



The results confirm that the proposed converter-based approach provides improved energy efficiency and faster balancing compared to traditional techniques.

TABLE II RESULTS

	Shunting Resistor	Switched Capacitor	Buck-boost Converter	Proposed
Equalization type	Passive	Active	Active	Active
Equalization time	Satisfactory	Satisfactory	Excellent	Excellent
Execution	Excellent	Very Good	Very Good	Excellent
Control	Very Simple	Medium	Complex	Complex
Power loss	High	Low	Negligible	Negligible
Cost	Very Cheap	Cheap	Costly	Medium
Size	Excellent	Good	Good	Very Good

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I/V Stress	Nil	Low	Low	Low
Advantages	Cheap, simple, small size	Simple control, bidirectional, low stresses	Good equalization time, easy modularized design bidirectional	Excellent equalization time, bidirectional easy modularized design, high power application
Disadvantages	Less efficient, Heat problem, Slow speed, Low power application	Slow Speed required more switches	Costly, Complex control	Complex control

IX. CONCLUSION

Battery cell balancing is very important for making electric vehicle battery systems work efficiently and safer. This study examined various balancing techniques and proposing a Ćuk converter-based active equalization circuit for lithium-ion battery packs.

The simulation results show that the proposed topology is superior to passive and traditional active balancing methods because it balances faster, loses less power, and uses energy more efficiently. So, the proposed method is good for EV battery systems that need a lot of power.

In the future, the focus will be on putting intelligent control algorithms into action and testing the proposed balancing system's hardware.

REFERENCES

[1]. Ashraf A., " Review of cell balancing schemes for EV battery management systems", Energies, 2024; 17: 1271.
[2]. Wu, Hongxia, et al. "Multi-Cell-to-Multi-Cell active equalization method based on k-means clustering and battery pack SOC estimation." International Journal of Electrochemical Science 19.6 (2024): 100588..
[3]. Venkatasatish, R., and C. Dhanamjayulu. "Design and implementation of an inductor based cell balancing circuit with reduced switches for Lithium-ion batteries." Scientific Reports 14.1 (2024): 28691.
[4]. Khan, Neha, et al. "A novel active cell balancing topology for serially connected Li-ion cells in the battery pack for electric vehicle applications." Scientific Reports 14.1 (2024): 18600.
[5]. Ouyang, Quan, et al. "A unified model for active battery equalization systems." IEEE Transactions on Control Systems Technology (2024).
[6]. Darwish, Ahmed. "A bidirectional modular cuk-based power converter for shore power renewable energy systems." Energies 16.1 (2022): 274.
[7]. Dam, Shimul K., and Vinod John. "A selection switch based cell-to-cell battery voltage equalizer with reduced switch count." 2019 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, 2019.
[8]. Baughman, Andrew C., and Mehdi Ferdowsi. "Double-tiered switched-capacitor battery charge equalization technique." IEEE Transactions on Industrial Electronics 55.6 (2008): 2277-2285.
[9]. Darwish, Ahmed. "A bidirectional modular cuk-based power converter for shore power renewable energy systems." Energies 16.1 (2022): 274.
[10]. Lee, Yuang-Shung, et al. "Battery equalization using bi-directional Cuk converter in DCVM operation." 2005 IEEE 36th Power Electronics Specialists Conference. IEEE, 2005.
[11]. F. Moghaddam and A. Van den Bossche, "A Battery Equalization Technique Based on Ćuk Converter Balancing for Lithium Ion Batteries," 2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST), Thessaloniki, Greece, 2019, pp. 1-4