

Article

Advanced MPC-Based Bidirectional Equalization for Energy Balancing in Series-Connected EV Battery Cells

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Abstract

Cell imbalance in series-connected battery packs, typically caused by repeated charge–discharge cycles, negatively impacts capacity, lifespan, and safety in electric vehicle (EV) applications. To address these issues, effective and reliable cell balancing is critical for maintaining battery performance and ensuring consistent energy delivery. Conventional balancing approaches often face drawbacks such as inefficient charge redistribution, limited control of energy flow, and slower response. Although bidirectional equalization strategies reduce the risks of overcharging and overdischarging, challenges remain in achieving high balancing speed, superior energy efficiency, and reduced circuit complexity. This study introduces an active bidirectional cell-to-cell equalization strategy based on a multi-winding transformer topology, where energy is directly transferred from higher-voltage to lower-voltage cells through flyback operation. A time-sharing control algorithm guided by initial state-of-charge (SoC) optimizes the sequence and prevents unnecessary transfers, while an advanced Model Predictive Control (MPC) scheme further enhances dynamic regulation, efficiency, and robustness of the balancing process. The proposed system is validated using MATLAB/Simulink 2019b and real-time hardware-in-the-loop testing with the OPAL-RT OP5700 platform, demonstrating superior equalization speed and energy utilization compared to conventional techniques.

Keywords: multi winding transformer; flyback converter; active balancing; series-connected cells; cell-to-cell equalization; time-sharing

1. Introduction

The rapid growth of electric vehicles (EVs) and renewable energy has created an urgent demand for efficient and dependable battery management systems (BMS). To ensure battery safety and long lifespan, modern BMS must integrate power electronics, bidirectional charge–discharge control, constant-voltage regulation, reverse-current protection, and reliable cell-balancing strategies. Key challenges include sustainability, reusability, and long-term availability of battery systems [1]. Lithium-ion batteries (LIBs) are particularly attractive due to their high energy and power density, long lifespan, low self-discharge rate, pollution-free operation, and absence of memory effects [2]. However, since their nominal single-cell voltage is only about 3.6 V, multiple cells must be connected in series to meet application-level voltage requirements. This series arrangement introduces mismatches in cell behavior caused by variations in internal resistance, self-discharge, and capacity during manufacturing or operation [3]. Such imbalances can lead to overcharging



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or overdischarging of individual cells, resulting in reduced usable capacity, faster degradation, and potential thermal runaway [4]. To counter these issues, balancing strategies are required to equalize state-of-charge (SoC), extend battery life, and maintain safe and efficient operation [5].

Balancing approaches are broadly categorized into dissipative (passive) and non-dissipative (active) methods. Passive balancing employs resistors to shunt excess charge, releasing it as heat, which makes the method simple and cost-effective but inherently inefficient and thermally limiting [6]. In contrast, active balancing redistributes charge among cells using inductors, capacitors, or transformers, thereby conserving energy and improving system efficiency [7]. Passive approaches are often implemented with resistors and diodes to adjust SoC, but they waste energy and operate independently for each cell [8]. Active balancing, however, enables cooperative energy sharing between cells through DC–DC converters, avoiding energy dissipation as heat and increasing the usable capacity of the pack [9]. These active circuits employ energy-storage elements, such as inductors and capacitors, to move energy from high-SoC cells to low-SoC cells, offering significant performance advantages [10].

Among active balancing designs, the single charge equalizer using a multi-winding transformer (SCEMT) has been investigated for its accuracy in series-connected LIBs [11]. It transfers equalization currents across overcharged cells to the entire pack, allowing rapid charge redistribution [12,13]. However, this method requires voltage sensors for every cell, increasing overall cost and size. Switch selection in SCEMT-based systems also adds control complexity, though it reduces the need for bulky passive elements. Other approaches, such as switched-capacitor systems and buck–boost converters, also facilitate energy transfer. Yet, they suffer from long equalization times, high cost, or inefficiencies when large SoC differences exist between non-adjacent cells [14,15]. Direct cell-to-cell equalization has been proposed to solve these issues by using inductors or transformers to transfer energy between any two cells, achieving fast balancing. Nonetheless, only two cells can typically be balanced at once due to control limitations [16,17]. In practical modules, such as a six-cell pack, differences in charging and discharging rates create further SoC mismatches, reducing usable pack capacity and accelerating aging of the weakest cell. Flyback converter-based balancing circuits have therefore been introduced, which provide isolated charge transfer among cells. Yet, their effectiveness depends on the choice of duty ratios, balancing sequence, and control logic. Battery packs are utilized in fuel–cell hybrid cars as well as battery electric vehicles to sustain vehicle operation during abrupt load fluctuations, absorb regenerative braking energy, and offer transitory power assistance. Therefore, battery subsystems utilized in fuel–cell hybrid cars may likewise have cell-level SoC imbalance. Therefore, maintaining usable battery capacity and preventing individual cells from prematurely exceeding their voltage and SoC limits depend on effective balancing. The suggested active equalization technique can be used for battery packs utilized in fuel–cell hybrid vehicle applications, even though the current study concentrates on EV battery cells.

Recent studies have placed greater emphasis on precise SoC estimation and sophisticated data-driven approaches for EV battery systems. These methods are especially pertinent to active cell balancing since determining high- and low-SoC cells relies on dependable SoC data. Recent methods for estimating SoC that combine hybrid techniques and machine learning have shown promise in enhancing SoC tracking across different battery operating conditions. In this study, SoC data serves as the governing variable for detecting the imbalance state and establishing the energy-transfer sequence, whereas the MPC controller manages the converter's duty cycle.

Alongside battery electric vehicles (EVs), battery energy storage systems are utilized in fuel cell vehicles (FCVs) for transient power support, capturing regenerative braking energy, and assisting vehicle performance during quick load changes and cold-start situations. The battery pack in an FCV experiences continual charging and discharging cycles, which can result in variations in the state of charge (SoC) among cells connected in series. This type of imbalance at the cell level can diminish the effective usage of the battery pack and influence its power output capability. Recent studies have also explored sophisticated energy management techniques for fuel-cell hybrid vehicles to enhance battery usage and overall system performance [17]. Consequently, efficient cell balancing is important not only for EV battery systems but also for battery packs utilized in FCV applications. Even though this study emphasizes a series-connected electric vehicle battery setup, the suggested active balancing method could possibly be adapted for other hybrid battery uses, such as fuel cell vehicles.

To address these challenges, this study proposes a multi-winding transformer-based active bidirectional cell-to-cell equalization method. Unlike conventional designs, it allows multiple cell pairs to balance simultaneously and directly, eliminating the limitation of proximity-based approaches. Compared with cell-to-pack-to-cell methods, it prevents scenarios where the same cell is charged and discharged simultaneously, thereby enhancing efficiency, safety, and lifetime. Its bidirectional capability also ensures flexible and efficient energy flow between cells. In static comparisons, the proposed design demonstrates superior balancing speed and efficiency compared to traditional flyback-based systems. Simulation results for a six-series-cell configuration confirm that this strategy enables rapid equalization, improved charge utilization, and longer pack life. By leveraging a multi-winding transformer and optimized control, the system offers a compact, scalable, and energy-efficient balancing solution well-suited for EV battery applications.

This work's primary contribution is the coordinated integration of a multi-winding bidirectional flyback equalization circuit, SoC-based time-sharing method, and MPC-based duty-cycle management, rather than only the use of a multi-winding transformer. The suggested method divides the imbalance state into three balancing modes after first identifying the high- and low-SoC cells. In order to prevent needless energy transfer and simultaneous charging and discharging of the same cell, the time-sharing method chooses the order in which the cells engage in energy transfer. The MPC controller then uses the anticipated SoC response and balancing required to calculate the converter duty cycle. Therefore, rather than only the multi-winding transformer, the integrated topology-control architecture and coordinated energy-balancing mechanism are what make the proposed work new."

The following is a summary of this work's main contributions:

1. For battery cells linked in series, a multi-winding transformer-based active bidirectional cell-to-cell flyback equalization architecture is created.
2. To identify the source and target cells as well as their energy-transfer sequence, a SoC-based three-mode time-sharing technique is presented.
3. To reduce the anticipated SoC mismatch while restricting the converter control action, an MPC-based duty-cycle control technique is created.
4. MATLAB/Simulink R2019b (The MathWorks, Inc., Natick, MA, USA) and real-time HIL simulation utilizing the OPAL-RT OP5700 (OPAL-RT TECHNOLOGIES, Montréal, Québec, Canada) platform are used to validate the suggested approach.

2. Structure of Balancing System

The proposed design uses a multi-winding transformer to create an active, bidirectional flyback equalization system for battery cells connected in series. Each cell connects to its own transformer winding through MOSFET switches. This setup allows energy to move

directly from a cell with a higher state of charge to one with a lower state of charge. By controlling the MOSFET switches, you can manage both the direction and order of energy transfer. This approach combines direct cell-to-cell energy transfer with a shared multi-winding magnetic core. Three main types of variations between cells are linked in series based on the differences in SOC between cells in a series-connected cell configuration. For a better understanding, this cell imbalance technique is explained with an example as follows: Figure 1a depicts the highest cell. Figure 1b shows some high and low cells; the lowest cell is illustrated in Figure 1c. This paper proposes an active cell-balancing system with three equalization modes that may correct various imbalances and increase balancing accuracy. Balancing among six cells with unequal SoC requires decisions that go beyond simple voltage-based rules. If conventional strategies such as “highest voltage to lowest voltage” are used, energy transfer may not be efficient, and repeated switching can stress the converter. Likewise, meta-heuristic methods like Genetic Algorithm (GA) or Particle Swarm Optimization (PSO) are computationally heavy for real-time balancing of six cells, even though they can be used offline for converter design or controller tuning.

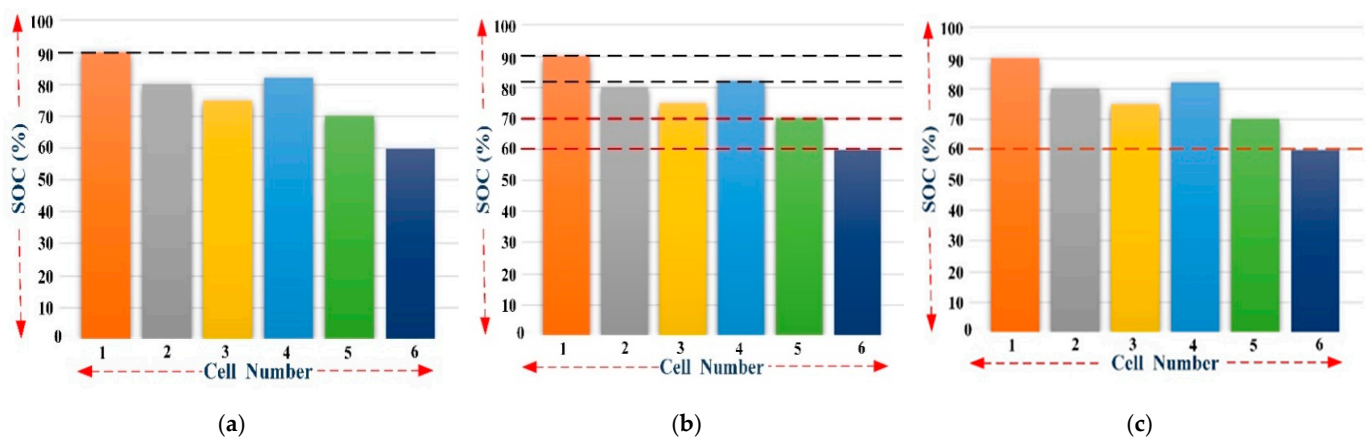


Figure 1. Types of series-connected imbalanced cells. (a) The highest one, (b) some high and low, and (c) the lowest one.

Figure 2 depicts the proposed balancing system structure. There are three ways to balance: one high cell, one low cell, and some high and low cells. Some cells are made with high-balance modes and some with low-balance modes to deal with abnormalities. The balance circuit is a bidirectional flyback converter with a multi-winding transformer, which is controlled by the advanced MPC controller. An ampere-hour integration method is employed to measure each cell’s SOC instantly. The SOC values of each cell were compared and examined, followed by the MPC controller turning the MOSFETs OFF and ON using the PWM drivers. Two MOSFETs are connected in series with each of the two alternate transformer windings that are placed within each of the cells. By altering the ON-OFF configuration of 2 MOSFET, energy can enter either way, providing energy that flows both ways. It is required that high-energy cell discharge take place on the transformer’s left side for simplicity of control. Low-energy cell charging occurs on the transformer’s right side.

MOSFETs S_{A1} and S_{C1} switch ON when energy moves from the transformer’s left side to its right side. In contrast, MOSFETs S_{B1} and S_{D1} switch off when this occurs. Together, the switches on S_{A1} and S_{C1} and the diodes on S_{B1} and S_{D1} ensure that current flows in just one way and does not return to the side of the cell with a higher SOC. The 2 MOSFETs are disabled/OFF on the right-hand winding circuit of the transformer. When a high-energy cell has to be discharged; otherwise, they are turned OFF in the turning circuit on the left. The complexity of the MOSFET drive circuit, as well as the number of control signals, is significantly reduced by controlling all MOSFETs using a pair of PWM signals that work

well together. High flexibility allows the equalization circuit to achieve cell-to-cell equality for every type of cell.

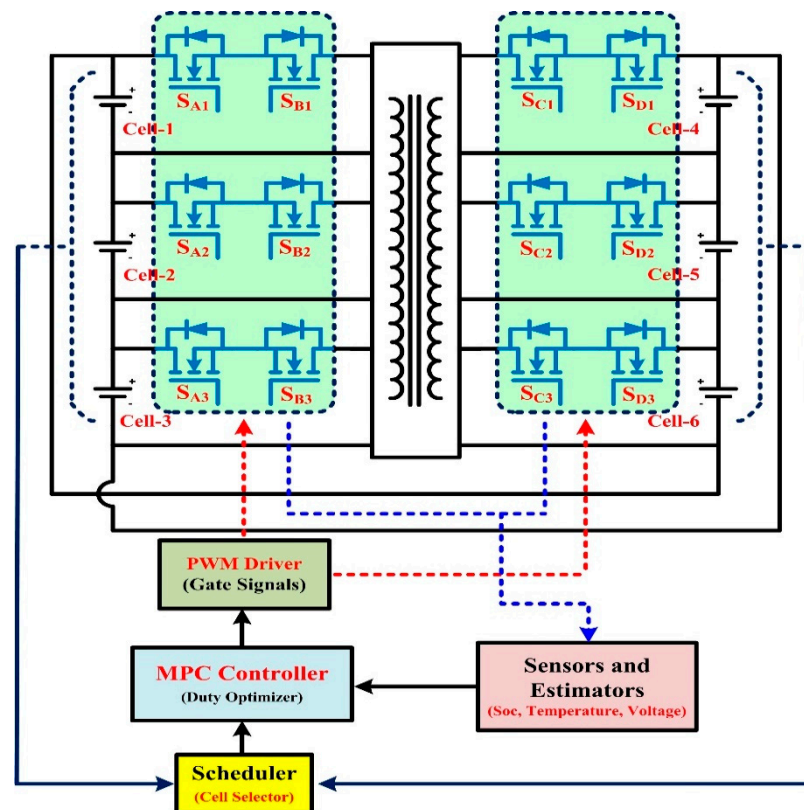


Figure 2. Schematic diagram of proposed equalization topology.

Practical Scalability of the Multi-Winding Transformer

While the suggested six-cell layout shows that the cell-to-cell balancing concept is feasible, expanding the topology to a full EV battery pack presents practical difficulties for the multi-winding transformer's design and production. For an N_C -cell battery string, an increase in the number of transformer windings and controlled switching interfaces is necessary. As a result, the magnetic component's physical size, inter-winding capacitance, leakage inductance, insulation needs, and winding arrangement complexity all rise. Maintaining homogeneous magnetic coupling among a large number of windings is similarly hard and may result in differential energy-transfer characteristics across various cells. To reduce copper loss, core loss, and temperature rise, proper winding arrangement, conductor selection, insulation coordination, core selection, and thermal management are also necessary. Therefore, it might not be the most practical solution to directly extend a single transformer to a large number of battery cells. For longer battery strings, a modular design with several multi-winding transformer units may be taken into consideration. Therefore, the six-cell configuration employed in this work is regarded as a proof-of-concept platform for testing the suggested balancing method; future research will focus on optimal transformer design and modular scaling for bigger EV battery packs.

3. Equalization Circuit Working Principle

The magnetic flux core must be resized to reduce every switching cycle accompanied by electromagnetic interference, since this research employs a multi-winding transformer-based bidirectional flyback DC converter. In the discontinuous current mode (DCM), each switching cycle reconfigures the magnetic flow, efficiently avoids electromagnetic

saturation, increases energy efficiency, and releases all the energy that has been stored in the transformer inductor.

In this work, the flyback converter is considered to operate predominantly in discontinuous conduction mode (DCM) under the selected switching frequency, transformer inductance, and duty-cycle conditions. Therefore, the switching-cycle analysis presented in this section is based on DCM operation. The equalization circuit transmits energy from Cell-1 to Cell-2, and its operation is discussed below using Cell-1 and Cell-2 as examples, as illustrated in Figure 3, and supposing that $SOC1 > SOC2$. The following presumptions are made to simplify the analysis. During a switching cycle, the cell terminal voltage stays constant, disregarding parasitic characteristics of parts and circuits.

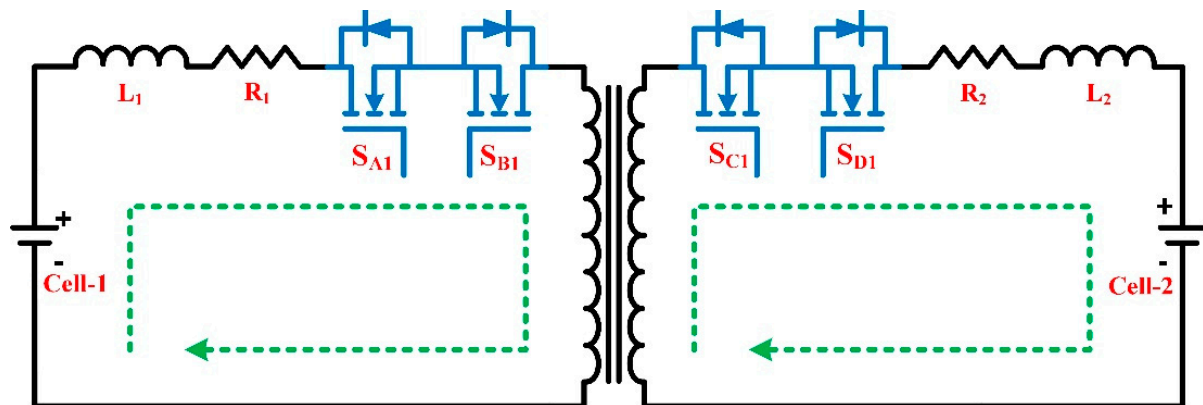


Figure 3. Cell-1 to Cell-2 energy transmission principle.

The transformer serves as a means of transferring energy. Both the secondary and primary loops of the transformer are switched ON alternately during the equalization phase. There are two distinct working modes. Where “T” is the switching time and δ is the PWM duty cycle. Figure 4 illustrates the fundamental Cell-1 to Cell-2 energy transfer waveform. A transformer is in mode 1 [0 DT]: S_{A1} is ON and S_{C1} , S_{B1} , and S_{D1} are all OFF, which results in Cell-1 discharging and energy being stored in the primary inductor. The primary winding is positive on the top side and negative on the lower side. The circuit model that corresponds to the Cell-1 discharge loop is shown in Figure 5.

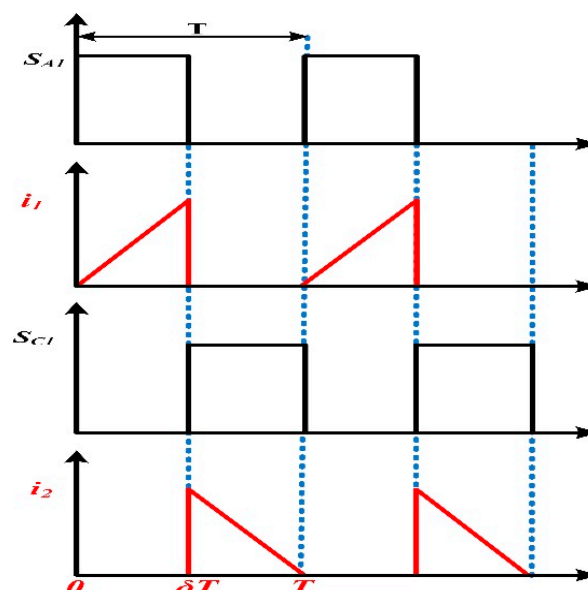


Figure 4. Cell-1 to Cell-2 transfer of energy waveform from.

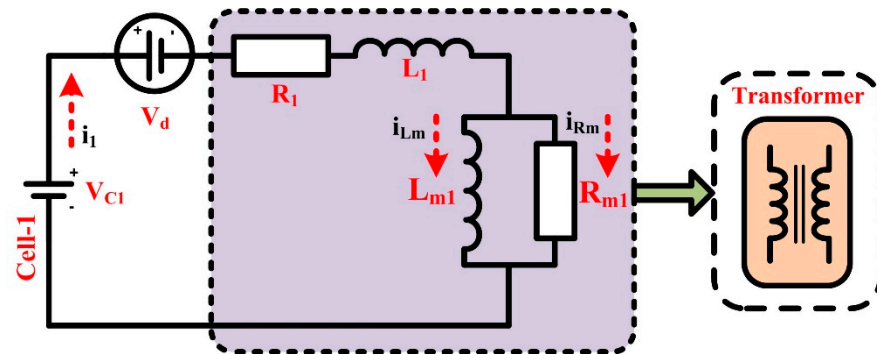


Figure 5. Equivalent circuit of the discharging loop for Cell-1.

Figure 5 depicts the following: V_{C1} represents the voltage of Cell-1; L_{m1} , R_{m1} , and L_1 represent the primary magnetization resistance, leakage inductance, and inductance of the winding, respectively; R_1 stands for the primary loop's equivalent resistance and V_d for the MOSFETs' voltage drop. Kirchhoff's current and voltage laws can be utilized to identify the positive direction of the current in Figure 5.

$$i_1 R_1 + V_d + L_1 \frac{di_1}{dt} + i_{Rm} R_{m1} = V_{C1}$$

$$L_{m1} \frac{di_{Lm}}{dt} = i_{Rm} R_{m1}$$

$$i_1 = i_{Rm} + i_{Lm} \quad (1)$$

$E_{V_{C1}}$ denotes the energy produced by Cell-1, $E_{L_{m1}}$ denotes the energy consumed by the transformer's primary winding, and E_{V_d} , E_{R1} , E_{L1} , and $E_{R_{m1}}$ define the energy lost by MOSFETs as well as the primary loop's equivalent resistance, the leakage inductance, and the primary winding's equivalent resistance to magnetization. By the principle of energy conservation,

$$E_{V_d} = \int i_1 V_d dt$$

$$E_{R1} = \int i_1^2 R_1 dt$$

$$E_{R_{m1}} = \int i_{Rm}^2 R_{m1} dt$$

$$E_{L1} = \frac{1}{2} L_1 i_1^2$$

$$E_{L_{m1}} = \frac{1}{2} L_{m1} i_{Lm}^2$$

$$E_{V_{C1}} = E_{V_d} + E_{R1} + E_{L1} + E_{L_{m1}} + E_{R_{m1}} \quad (2)$$

Iron and copper losses are neglected under ideal circumstances. The primary winding current i_1 is given by Equation (3).

$$i_1 = i_{Lm} = \frac{V_{C1} - V_d}{L_1 + L_{m1}} t (0 < t \leq \delta T) \quad (3)$$

When $t = \delta T$, i_1 achieves its maximum value, which is i_{1max} , which is as follows:

$$i_{1max} = i_{Lma} = \frac{V_{C1} - V_d}{L_1 + L_{m1}} \delta T \quad (4)$$

This process results in a linear rise in magnetic flux when the transformer core becomes magnetized by the primary current. The rise $\Delta\phi^+$ is

$$\Delta\phi^+ = \frac{V_{C1}}{N_p} \delta T \quad (5)$$

Transformer primary winding turns are N_p , and stored energy in the transformer is

$$E_{L_{m1}} = \frac{(V_{C1} - V_d)^2 \delta^2 T^2}{2L_{m1}(L_1 + L_{m1})^2} \quad (6)$$

S_{C1} is activated, S_{A1} , S_{B1} , and S_{D1} are all disabled, and Cell-2 is charging in Mode 2 [DT T]. The electromotive force induced by the primary winding is produced by its inductance, which has a positive polarity in the downward direction and a negative polarity in the upward direction. The positive-polarity electromotive force is at the top, and the negative polarity is at the bottom and is generated by the secondary winding via magnetic coupling. This is due to Cell-2 being charged by the inductance of the transformer's secondary winding. Figure 6 shows the equivalent circuit for the Cell-2 charging loop. V_{C2} represents Cell-2 voltage in the model depicted in Figure 6; L_{ma2} and R_2 represents the secondary loop's equivalent inductance and resistance, respectively, and V_{d2} represents the voltage drop of the MOSFET. From Kirchhoff's voltage law, we may also find the current direction.

$$i_2 R_2 + V_{C2} + V_{d2} = L_{ma2} \frac{di_2}{dt} \quad (7)$$

where $E_{V_{C2}}$ = energy that Cell-2 absorbs, $E_{L_{ma2}}$ = energy that the transformer's secondary winding releases and $E_{V_{d2}}$ and E_{R_2} are the energy that MOSFETs lose and the secondary loop's corresponding resistance, respectively, observing the energy-saving concept.

$$\begin{aligned} E_{R_2} &= \int i_2^2 R_2 dt \\ E_{V_{d2}} &= \int i_2 V_{d2} dt \\ E_{V_{C2}} &= \int i_2 V_{C2} dt \\ E_{L_{ma2}} &= E_{V_{d2}} + E_{R_2} + E_{V_{C2}} \end{aligned} \quad (8)$$

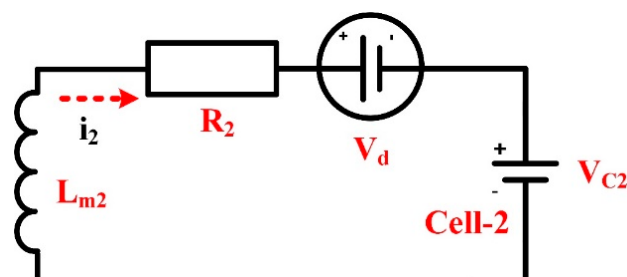


Figure 6. Equivalent circuit to the discharging loop for Cell-2.

The declining slope of the secondary inductor current under ideal circumstances is

$$\frac{di_2}{dt} = \frac{V_{C2} - V_{d2}}{L_{ma2}} \quad (9)$$

The secondary winding current is at its maximum as follows:

$$i_{2\max} = \frac{N_P(V_{C1} - V_d)}{N_S(L_1 + L_{\text{ma1}})} \delta T \quad (10)$$

The number of secondary winding turns is N_S . The secondary loop current is polarized in the opposite direction throughout this operation, demagnetizing the transformer's iron core and causing a linear drop in magnetic flux.

$$\Delta\phi^- = \frac{V_{C2}}{N_2} (1 - \delta) T \quad (11)$$

4. Balancing Control Scheme

When equalization is complete, the SOC of each cell should, in an ideal scenario and without accounting for the energy loss of circuit elements, be equal to the average SOC of the batteries (SOC_R). In this study, the batteries' unbalanced states are divided using SOC_R as a reference value, and the related equalization techniques are developed for the various unbalanced states. According to the electrical characteristics and circuit component parameters, a certain margin can be established above and below the SOC_R in real applications. For real-time operation with six cells, Model Predictive Control (MPC) is the most effective choice. The upper-level scheduler identifies which cell has the highest SoC (source) and which has the lowest SoC (target) and determines the balancing sequence. Then, the lower-level MPC controller calculates the optimal duty cycle for the flyback converter, predicting how energy transfer will affect the voltages and currents in the next few steps. The cost function minimizes the difference in SoC across the six cells, while penalizing losses and ensuring thermal and electrical safety.

$$\text{SOC}_R = \frac{1}{N_C} \sum_{i=1}^{N_C} \text{SOC}_i \quad (12)$$

4.1. MPC Weighting Parameter Selection

The relative weighting of the MPC was selected, and responsibility was assigned for the weighting of the cell deviation. Reducing the SoC mismatch is given more attention when Q is higher; however, an overly high number could lead to aggressive control action. Similarly, increasing the value of R results in smoother control actions but may slow down the balancing response. After repeated tuning and adjustment, $Q = 100I$ and $R = 0.01I$ were selected as suitable weighting matrices for the proposed balancing system, as presented in Table 1. These values offer a suitable balance between SoC convergence and gradual duty-cycle variation and were preserved during both the simulation and real-time validation. Here, I is the identity matrix corresponding to the number of controlled cells.

Table 1. Selected MPC weighting parameters.

Parameter	Purpose	Selected Value
Q	Penalizes SoC deviation	$100I$
R	Penalizes duty-cycle variation	$0.01I$
N_P	Prediction horizon	10
N_C	Control horizon	3
T_S	Sampling time	5 ms

The chosen weighting parameters remained unchanged for all the documented simulation and OPAL-RT real-time validation outcomes.

4.2. MPC-Based Duty-Cycle Control

The lower-level Model Predictive Control (MPC) is employed to determine the optimal duty cycle of the bidirectional flyback converter according to the instantaneous SoC distribution of the series-connected cells. The average SoC of the cells is considered as the balancing reference. For the initial SoC values of 65%, 70%, 75%, 80%, 85%, and 90%, the reference SoC is 77.5%. The discrete-time SoC prediction model is expressed as

$$SOC_i(k+1) = SOC_i(k) + \frac{\eta_i I_i(k) T_s}{Q_i} \quad (13)$$

where $SOC_i(k)$ is the SoC of cell i at sampling instant k , $I_i(k)$ is the balancing current, Q_i is the cell capacity, T_s is the sampling time, and η_i represents the charging or discharging efficiency. The SoC tracking error is defined as

$$e_i(k) = SOC_i(k) - SOC_R \quad (14)$$

where SOC_R is the reference SoC. The MPC predicts the future SoC response for candidate duty-cycle values and minimizes the predicted SoC mismatch together with unnecessary variations in the control signal. The objective function is defined as

$$J = \sum_{j=1}^{N_p} \|SOC(k+j) - SOC_R\|_Q^2 + \sum_{j=0}^{N_c-1} \|\Delta d(k+j)\|_R^2 \quad (15)$$

where $N_p = 10$ is the prediction horizon, $N_c = 3$ is the control horizon, $Q = 100I$ is the SoC-error weighting matrix, $R = 0.01I$ is the duty-cycle variation weighting matrix, and d is the PWM duty cycle. The relatively high SoC weighting gives priority to cell equalization, while the duty-cycle variation penalty limits unnecessary control action.

The ideal duty cycle is determined by examining the expected SoC response related to the viable candidate duty-cycle values. For every candidate value, the MPC assesses the anticipated SoC deviation throughout the prediction horizon and analyzes the cost function specified in (17). The candidate yielding the lowest possible cost is chosen as the ideal duty cycle. Only the initial control action is executed, and the optimization process is repeated at the subsequent sampling instant with the revised SoC values.

The duty cycle and balancing current are constrained as

$$0.05 \leq d(k) \leq 0.5 \quad (16)$$

$$|I_i(k)| \leq 3A \quad (17)$$

And the predicted SoC is restricted to the allowable range

$$0 \leq SOC_i(k) \leq 100\% \quad (18)$$

The voltage constraint is

$$3.0 \leq V_i(k) \leq 4.2 V \quad (19)$$

The transformer magnetic flux is constrained by the selected turns ratio, inductance, switching frequency, and duty ratio. A detailed numerical flux constraint is reserved for physical transformer design because the present study uses a real-time converter model. Thermal limits are represented indirectly through the allowable balancing current in the present model; detailed device-temperature constraints require thermal component models and are considered for future hardware validation.

At every sampling instant, the controller evaluates the predicted SoC response for the candidate duty-cycle values, calculates the corresponding cost function, and selects

the feasible duty cycle associated with the minimum cost. Only the first control action is applied to the PWM generator, after which the cell states are updated, and the optimization is repeated. This receding-horizon procedure enables the balancing duty cycle to adapt continuously to the changing SoC difference between the source and target cells.

The batteries' cell count is n . As an example, consider six series-connected cells, and define $SOC_{maxA} > SOC_{maxB} > SOC_{minB} > SOC_{minA}$.

When $Z = 0$, $SOC_{maxA} > SOC_R > SOC_{maxB} > SOC_{minB} > SOC_{minA}$

$Z = 1$, $SOC_{maxA} > SOC_{maxB} > SOC_R > SOC_{minB} > SOC_{minA}$

$Z = 2$, $SOC_{maxA} > SOC_{maxB} > SOC_{minB} > SOC_R > SOC_{minA}$ (20)

The highest balancing mode is represented by 0, some high and low balancing modes are represented by 1, and the lowest balancing mode is represented by 2, respectively. Figure 7 displays the suggested balancing method's entire flowchart.

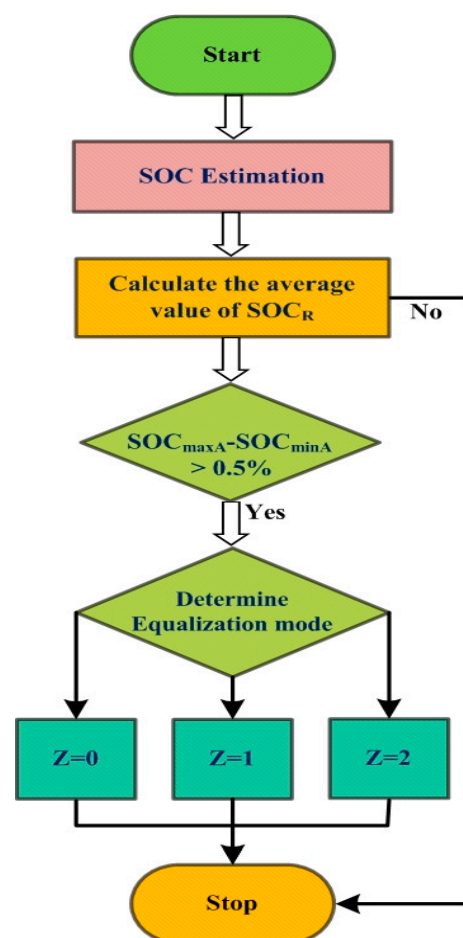


Figure 7. The proposed balancing method overall flowchart.

In the mode of the highest balancing case, $Z = 0$ is the balancing mode used when $SOC_{maxA} > SOC_R > SOC_{maxB} > SOC_{minB} > SOC_{minA}$. When using this mode to balance the load, $Cell_{maxA}$ is associated with the transformer's primary side, while $Cell_{maxB}$, $Cell_{minB}$, and $Cell_{minA}$ are all on the secondary side, attached. To prevent the same cells from being charged and discharged at the same time during the equalization process, which shortens battery life, this work aims to tightly regulate both the discharging and charging activities of cells. Energy is balanced at $Z = 0$ when $Cell_{maxA}$ discharges energy and $Cell_{minA}$ charges energy.

The appropriate MOSFETs are gradually activated to supply power to the energy-absorbing cells. At the outset of the equalization procedure, $Cell_{maxA}$ transmits energy to $Cell_{minA}$, while $Cell_{maxB}$ and $Cell_{minB}$ are in a wait state. When the SOC of $Cell_{minA}$ exceeds that of $Cell_{minB}$, the matching MOSFET of $Cell_{minB}$ turns on, and $Cell_{minB}$ begins charging at the same pace as $Cell_{minA}$. The matching MOSFET of $Cell_{maxB}$ turns on when SOC_{min} equals SOC_{minB} and SOC_{maxB} , and $Cell_{maxB}$ begins absorbing the energy generated by $Cell_{maxA}$ at a similar rate to $Cell_{minB}$ and $Cell_{minA}$. If, and only if, $SOC_{minA} = SOC_{minB} = SOC_{maxB} = SOC_{maxA}$, then equalization is complete. Figure 8a displays the control flow diagram for this operation. The basic waveforms of the $Z = 0$ equalization mode are depicted in Figure 9a. $Cell_{maxA}$, $Cell_{maxB}$, $Cell_{minB}$, and $Cell_{min1}$ all have their balancing currents, which are respectively denoted by i_{maxA} , i_{maxB} , i_{minB} , and i_{minA} .

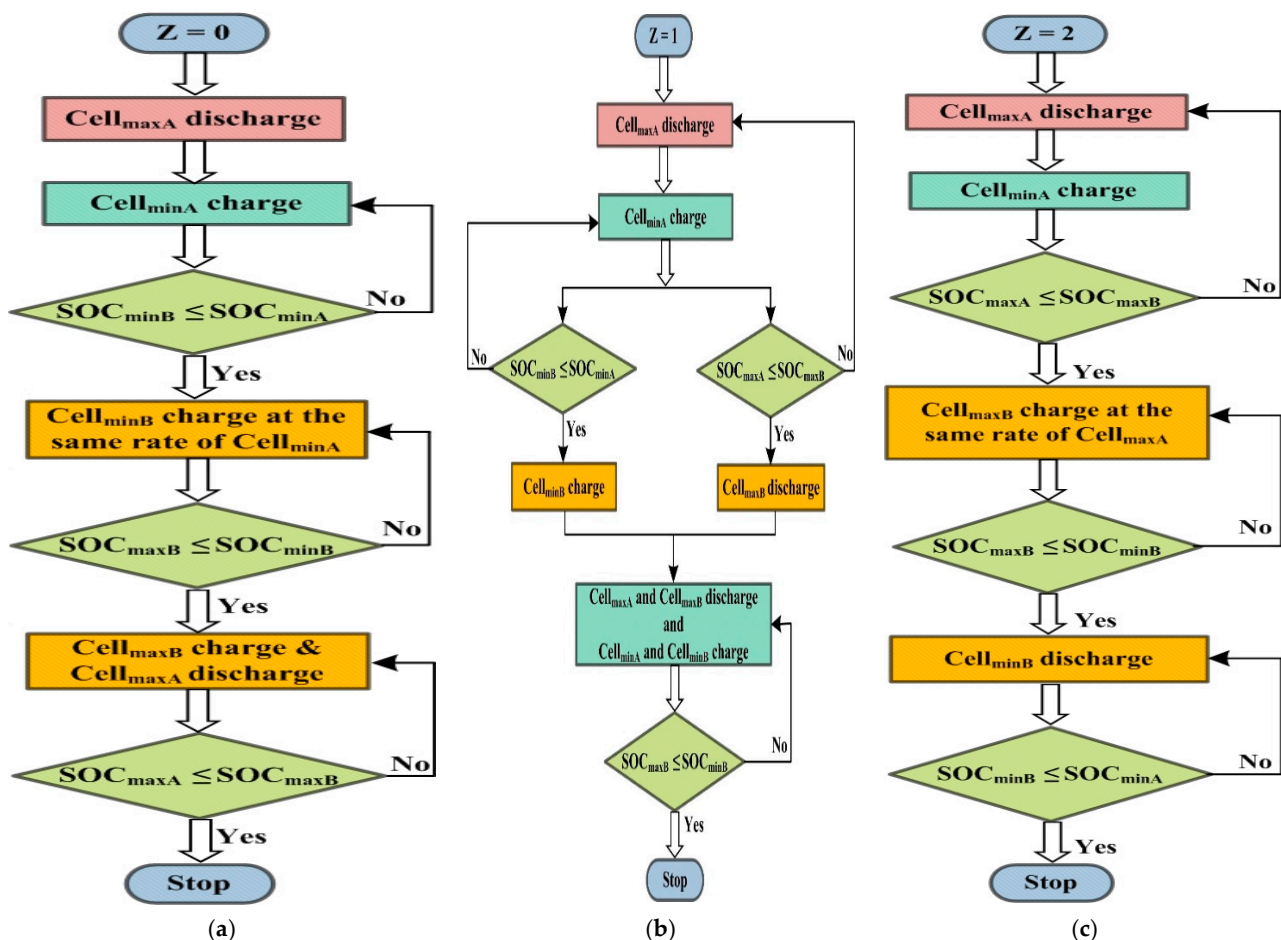


Figure 8. Equalization mode flowchart. (a) $Z = 0$, (b) $Z = 1$, (c) $Z = 2$.

In mode of some high- and low-balancing cases, the $Z = 1$ balancing mode is used when $SOC_{maxA} > SOC_{max2} > SOC_R > SOC_{minB} > SOC_{minA}$. $Cell_{maxA}$ and $Cell_{maxB}$ are attached to the transformer's secondary side, while $Cell_{minB}$ and $Cell_{maxA}$ are coupled to its primary side. When $Z = 1$ is achieved, $Cell_{min2}$ and $Cell_{minA}$ only absorb energy, while $Cell_{maxA}$ and $Cell_{maxB}$ only release energy. $Cell_{maxA}$ transmits energy to $Cell_{minA}$ in the process of equalization, while $Cell_{maxB}$ and $Cell_{minB}$ are in a state of waiting. As the energy of $Cell_{maxA}$ is transferred, the SOC of $Cell_{maxA}$ gradually decreases. When $SOC_{maxB} = SOC_{maxA}$, $Cell_{maxB}$'s matching MOSFET turns on and begins to release energy at the same rate as $Cell_{maxA}$. For $Cell_{minA}$, SOC is also still rising at the same time. When $SOC_{minA} = SOC_{minB}$, $Cell_{min2}$ matching MOSFET turns on and begins to charge at the

same pace as $\text{Cell}_{\min A}$. Energy is transferred from $\text{Cell}_{\max B}$ and $\text{Cell}_{\max A}$ to $\text{Cell}_{\min B}$ and $\text{Cell}_{\min A}$ when $\text{SOC}_{\min A} = \text{SOC}_{\min B}$ and $\text{SOC}_{\max B} = \text{SOC}_{\max A}$. Balancing stops when $\text{SOC}_{\min A} = \text{SOC}_{\min B} = \text{SOC}_{\max B} = \text{SOC}_{\max A}$. Figure 8b displays the control flow diagram for it. The essential waveforms for the $Z = 1$ equalization mode are shown in Figure 9b.

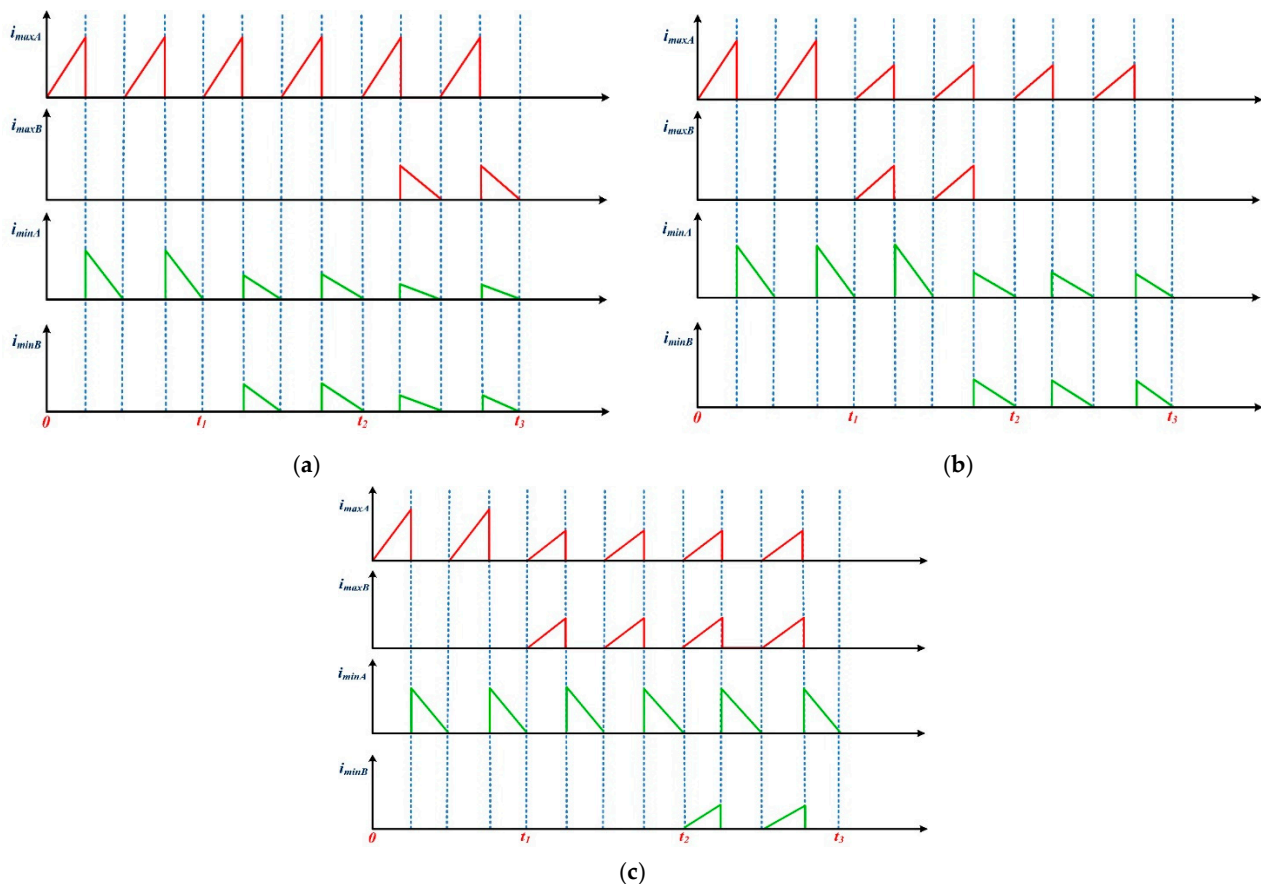


Figure 9. Equalization mode waveforms. (a) $Z = 0$, (b) $Z = 1$, (c) $Z = 2$.

In the low-balancing mode case, when $\text{SOC}_{\max A} > \text{SOC}_{\max B} > \text{SOC}_{\min B} > \text{SOC}_R > \text{SOC}_{\min A}$, the $Z = 2$ balancing mode is activated. To achieve this delicate balancing act, $\text{Cell}_{\min A}$ is wired to the secondary side of the transformer, while $\text{Cell}_{\max A}$, $\text{Cell}_{\max B}$, and $\text{Cell}_{\min B}$ are linked to the primary. $\text{Cell}_{\max A}$ and $\text{Cell}_{\min B}$ only emit energy, whereas $\text{Cell}_{\min A}$ only takes it in, during the $Z = 2$ balancing phases. The appropriate MOSFETs are progressively activated to power the energy-releasing cells. $\text{Cell}_{\max A}$ transfers energy to $\text{Cell}_{\min A}$ at the beginning of the equalization process, while $\text{Cell}_{\max B}$ and $\text{Cell}_{\min B}$ are waiting. When $\text{SOC}_{\max B}$ equals $\text{SOC}_{\max A}$, $\text{Cell}_{\max B}$ begins to discharge at the same pace as $\text{Cell}_{\max A}$, as the SOC of $\text{Cell}_{\max A}$ keeps decreasing. When the matching MOSFET for $\text{Cell}_{\min B}$ is on and $\text{SOC}_{\max B} = \text{SOC}_{\max A} = \text{SOC}_{\min B}$, $\text{Cell}_{\min B}$ begins releasing energy at the same rate as $\text{Cell}_{\max B}$ and $\text{Cell}_{\max A}$. The equalization process is complete when $\text{SOC}_{\min A} = \text{SOC}_{\min B} = \text{SOC}_{\max B} = \text{SOC}_{\max A}$. Figure 8c displays a flowchart of its control.

Figure 9c illustrates the waveforms for the $Z = 2$ equalization mode, where cells with higher state of charge (SoC) consistently discharge while cells with lower SoC continuously receive charge. This process is managed through a time-sharing mechanism, ensuring that no single cell is charged and discharged simultaneously during balancing. The order of balancing is determined by the initial SoC values, allowing the control logic to remain simple yet precise. Equalization is terminated once the difference between charging and discharging cells reaches a defined threshold, which provides an adaptive adjustment feature. Energy losses in circuit components are also considered when setting this termination

criterion, making the approach more realistic. Current flow is regulated by tuning the MOSFET duty cycle, with a fixed discharge duty of 0.5 applied in this study. Furthermore, as the number of participating cells on both the primary and secondary windings increases, the balance loop shifts more significantly during the equalization process, highlighting the system's dynamic nature.

5. Simulation Results and Analysis

An equalization model with six cells connected in series is constructed to assess the effectiveness of the balancing method proposed in this paper. The simulated battery model and MOSFETs are used in the model to simulate the power circuit. An embedded MATLAB program has been employed to develop the Adaptive MPC controller. The simulation experiments for static equalization, charge, and discharge equalization are each carried out. The static equalization simulation experiments are evaluated in depth in this paper. Table 2 displays specific features of the simulation model. Compared to conventional topologies for static equalization that use flyback converters [18–20]. The SOC values for cells (1–6) are shown in Table 3 below.

Table 2. MPC controller parameters.

Parameter	Value
Sampling time T_s	5 ms
Switching frequency	10 kHz
Prediction horizon N_p	10
Control horizon N_c	3
SoC weighting Q	100I
Duty-cycle variation weighting R	0.01I
Minimum duty ratio	0.05
Maximum duty ratio	0.50
Maximum balancing current	3 A
Initial nominal duty	0.50

Table 3. Simulation parameters.

Parameters	Ratings
Cell rated Voltage	3.6 V
Cell rated Capacity	6.5 Ah
Switching Frequency	10 kHz
Primary winding Inductance	48 μ H
Secondary winding Inductance	48 μ H
Turns ratio of the transformer	1:1
PWM duty cycle	50%
MOSFET Voltage drop	0.6 V
Sampling time	5 ms

A six-cell series-connected setup is chosen as a typical testing platform to validate the suggested equalization topology and control approach. The suggested balancing idea is not inherently limited to six cells; nevertheless, raising the cell count necessitates more

voltage/SoC sensing channels, switching devices, transformer windings, and balancing states. Thus, the six-cell setup is regarded as a proof-of-concept verification, whereas expansion to larger battery strings is viewed as a prospective evolution.

Table 4 Presents the initial SOC values of the cells, while Table 5 Summarizes the cell-balancing with different control strategies with Runtime SOC values. Figure 10 illustrates the cell SOC variations under balancing conditions, with subfigures (a–f) showing the increasing and decreasing SOC trends, (g) depicting the cells without balancing, and (h) illustrating the cells with balancing. (a–f) cells increasing and decreasing for the balancing condition, (g) cells without balancing, and (h) cells with balancing.

Table 4. SOC values of cells at the initial stage.

Cell No:	Initial Values of SOC (%)
Cell-1	65%
Cell-2	70%
Cell-3	75%
Cell-4	80%
Cell-5	85%
Cell-6	90%

Table 5. Cell-balancing control strategies.

Control Strategies	SOC Value of Cell (%)	Runtime SOC Value (%)
The highest value of the cell	90%	87.5%
High & low values of cells	80%, 85% & 70% & 75%	77.5%, 87.4% & 67.5%, 77.4%
The lowest value of the cell	65%	67.4%

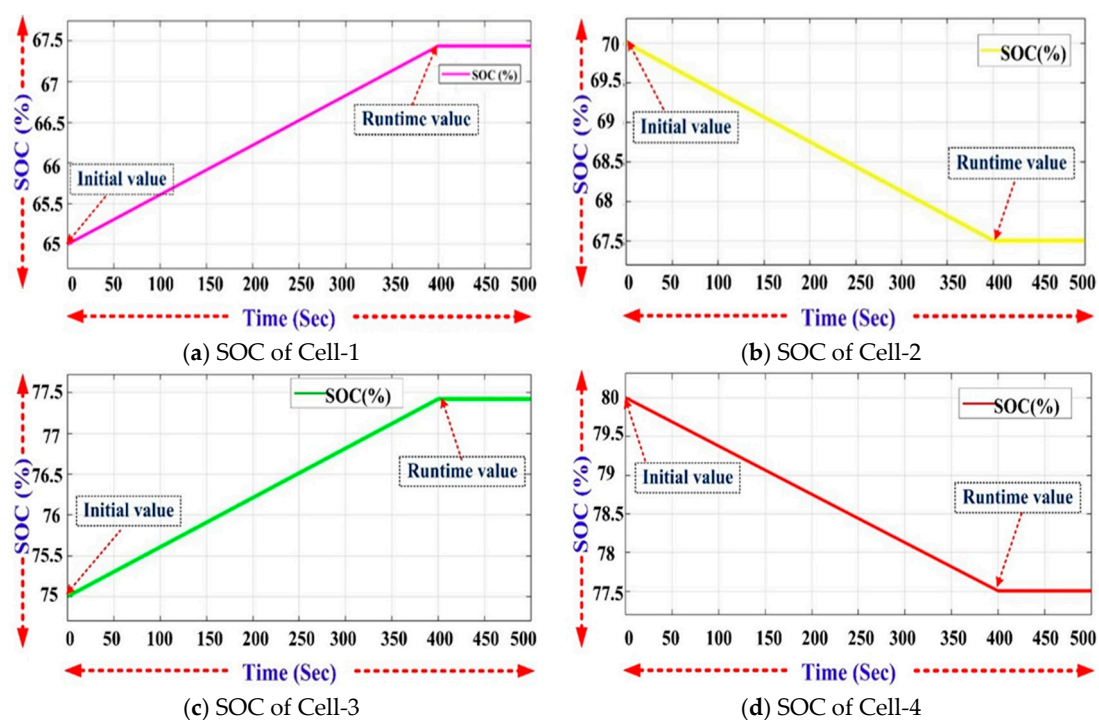


Figure 10. Cont.

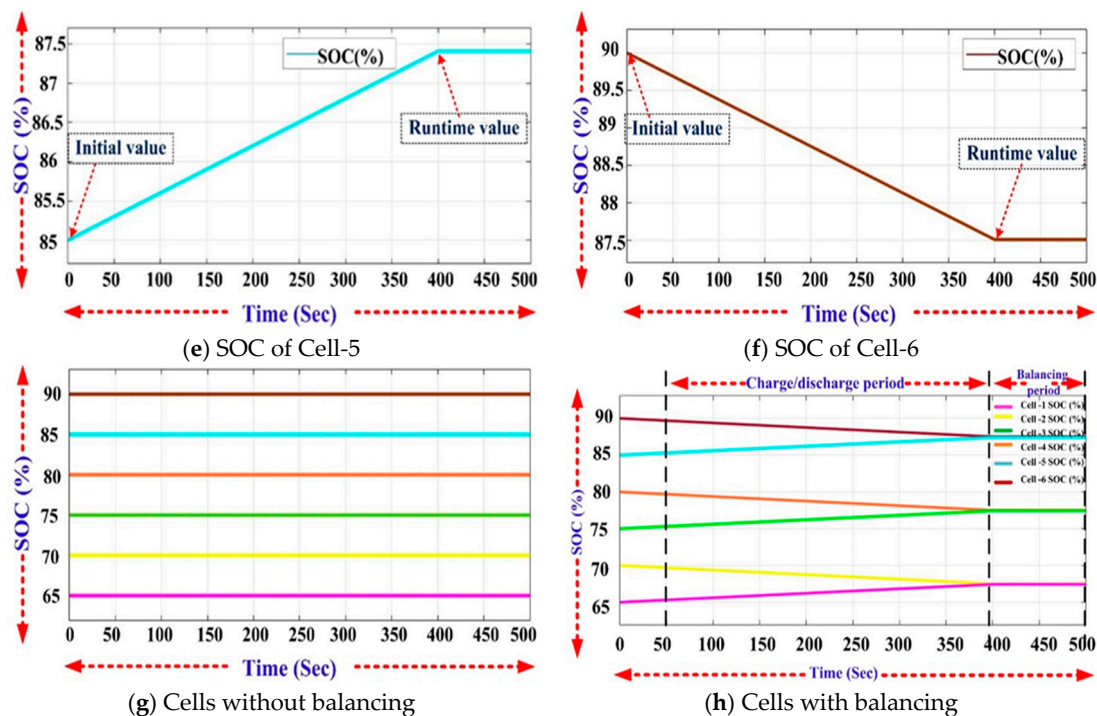


Figure 10. (a–f) Cells are increasing and decreasing for the balancing condition. (g) Cells without balancing; (h) cells with balancing.

The proposed control strategy is based on the relative SoC distribution of the series-connected cells rather than on a fixed initial SoC pattern. The three balancing modes $Z = 0$, $Z = 1$, and $Z = 2$ are selected according to the instantaneous relationship between the individual cell SoCs and the reference SoC. Therefore, the control logic can accommodate different distributions containing one high-SoC cell, multiple high- and low-SoC cells, or one low-SoC cell. Nevertheless, the detailed simulation and HIL validation presented in this work consider a six-cell configuration with an initial SoC distribution of 65–90%. The effects of different cell capacities, internal resistances, aging conditions, and randomly distributed initial SoCs require additional parameterized simulations and experimental validation and are therefore considered as future extensions.

6. Real-Time Simulation Results and Discussion

The real-time hardware-in-the-loop (HIL) validation of the suggested balancing control approach is provided by the OPAL-RT implementation described in this work. The main purpose of a real-time simulator is to cut down on cost, time, and risk. The main use of real-time simulators is to find a workable solution for electrical drives, grids, power systems, cars, aerospace applications, etc. Real-time simulation models are used to simulate the battery and power-electronic converter, and the OPAL-RT environment is used to assess the control method. The MATLAB/Simulink model and the HIL implementation both have a 5 ms sample interval. The general balancing tendency shown in offline simulation is replicated in the HIL data, with low-SoC cells advancing near the reference value and high-SoC cells going toward the reference SoC. Physical converter-loss measurement and detailed thermal characterization are deemed outside the purview of the current HIL validation as they necessitate a hardware prototype. The OP5700 real-time simulator is shown in Figure 11. The RT-LAB simulation software (v2023.1.0.533; Workbench Version 2023.1) was installed on the host computer. The host PC was linked to the real-time simulator through an Ethernet connection. The real-time simulator's output was seen on a mixed-signal oscilloscope (MSO) through analog output pins and probes.

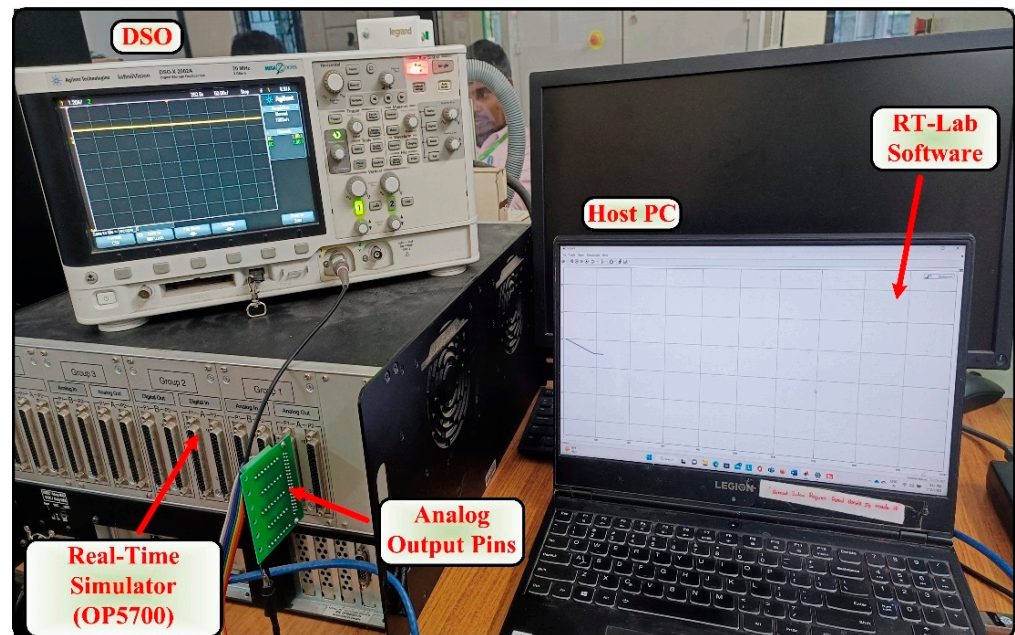


Figure 11. Real-time simulator setup.

6.1. OP5700 Real-Time Simulator Specifications

The OPAL-RT (OP5700) real-time HIL simulator specifications are given in Table 4

6.2. RT-LAB Simulation Module

Before running the proposed model in the real-time simulator, some changes will be made to the MATLAB-Simulink model. The RT-LAB simulation model has two subsystems: the computation subsystem (SM_Subsystem) and the GUI or console subsystem (SC_Subsystem). The MPC controller, DC-Dc converter, selecting switches, batteries, and measuring circuits are grouped to form an SM_Subsystem, and Scopes and displays are grouped to form an SC_Subsystem. For real-time simulation, the discrete mode of simulation, a fixed-step solver, a 5 ms sampling time, and an infinite run time were chosen.

6.3. Results of Real-Time Simulation

The results of the real-time simulation of the proposed topology are shown in the following figures. At first, the SOC values of each cell will be fixed as shown in Table 3. The proposed model was changed so that it would work with RT-LAB software, and after choosing the right solver setup, the model was tested in the OPAL-RT simulator.

The output was viewed on a multi-signal oscilloscope (MSO) by connecting the probe to a suitable analog pin on the simulator. The oscilloscope used for this check has one channel so that the output of the cell can be seen at once. At first, each cell's output can be measured separately. The oscilloscope that is used has a time limit of 50 s per division, so only 500 s of output can be seen at a time. In the proposed topology, the balanced state will be reached in 400 s, so the full balancing waveform cannot be seen. The waveform can be seen as an under-balancing condition and an after-balancing condition. Figure 12 shows that the SoC values of cells 2, 4, and 6 decreased from their initial values toward the reference SoC because their initial SoC values were higher than the reference. Similarly, cells 1, 3, and 5 increased toward the reference value because their initial SoC values were lower than the reference. This is because their SOC values are higher than the average SOC value.

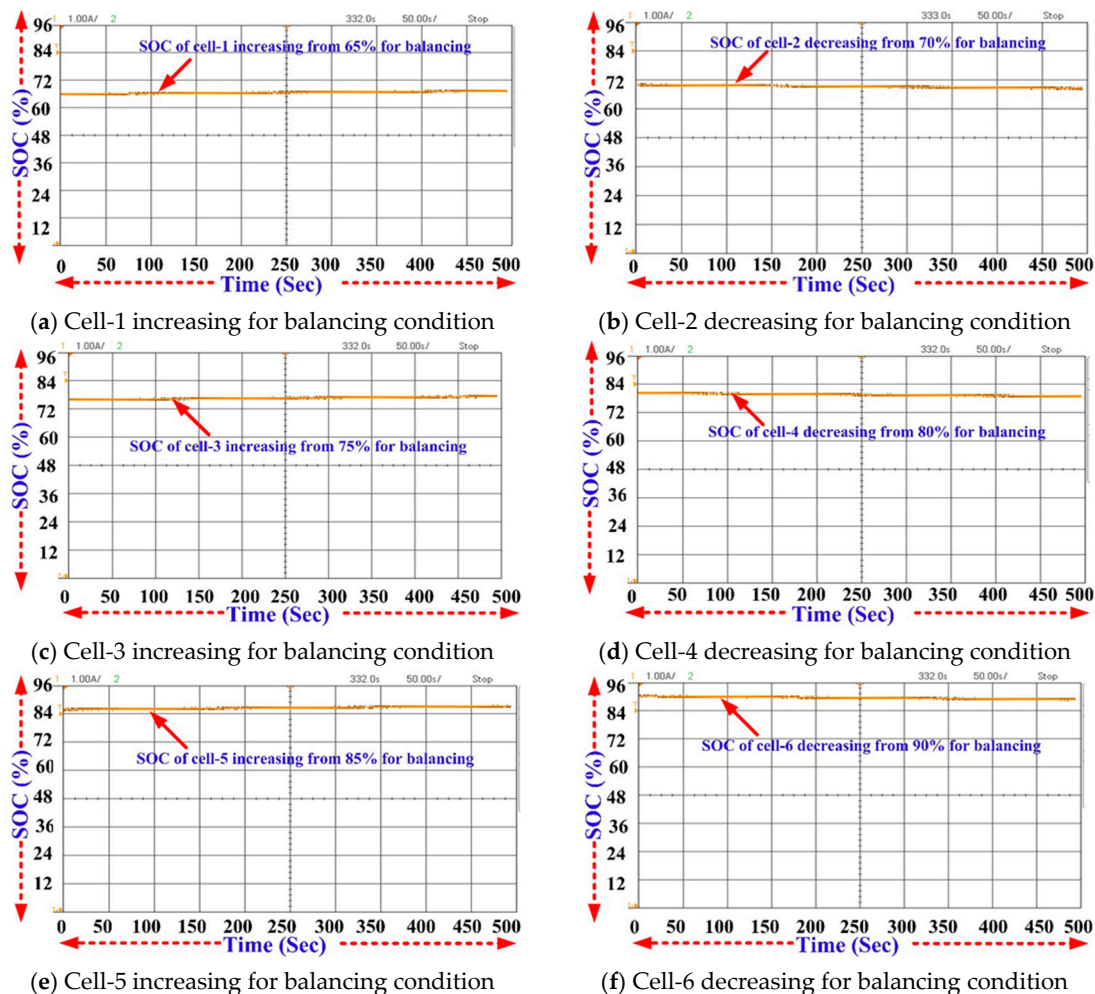


Figure 12. (a–f) Real-time simulation results of cells 1 to 6.

The average SoC of all six cells is consistently used as the reference value throughout the proposed balancing strategy. Therefore,

$$SOC_R = \frac{1}{N_C} \sum_{i=1}^{N_C} SOC_i \quad (21)$$

where $N_C = 6$ represents the number of series-connected cells. For the initial SoC distribution of 65%, 70%, 75%, 80%, 85%, and 90%, the corresponding reference SoC is 77.5%.

6.4. Real-Time Validation and Measurement Window

The real-time waveforms shown in this section were recorded using the existing oscilloscope acquisition window. Given that the entire balancing procedure lasts roughly 400 s, the oscilloscope recording offers a constrained time-frame depiction of the instantaneous electrical parameters. Consequently, the obtainable waveforms are utilized to assess the real-time switching and balancing characteristics of the proposed converter, while the overall balancing progression is analyzed from the simulated SoC paths. The OPAL-RT findings verify that the suggested MPC-based balancing approach can be implemented in real time, and the noted cell-balancing behavior aligns with the simulation outcomes. A comprehensive long-duration experimental waveform would necessitate uninterrupted data recording throughout the entire balancing period and is viewed as a vital enhancement for future experimental confirmation. It is important to highlight that the current OPAL-RT

implementation embodies real-time hardware-in-the-loop validation, with the battery and power-converter models being executed within the real-time simulation framework.

6.5. Practical Implementation Considerations

The OPAL-RT findings shown in this research demonstrate real-time hardware-in-the-loop verification instead of complete power experimental validation utilizing an actual battery pack and converter. In real-world applications, transformer leakage inductance, winding resistance, core losses, parasitic capacitance, magnetic saturation, MOSFET conduction and switching losses, dead-time effects, and temperature-sensitive device parameters can influence the performance of equalization. Sensor noise, measurement bias, ADC quantization error, sampling latency, and SoC estimation inaccuracies can also affect the balancing response. Moreover, differences in cell capacity and internal resistance due to production tolerances and aging may alter the energy-transfer dynamics. These nonideal effects are not completely depicted in the current HIL model and need to be included during future validation of physical prototypes.

7. Comparison with Existing Topologies

Balancing Efficiency Calculation

The balancing efficiency is calculated from the ratio of the energy received by the target cells to the energy supplied by the source cells during the equalization interval. The source and target energies are calculated as

$$E_{source} = \int_0^{t_b} V_{source}(t) I_{source}(t) dt \quad (22)$$

$$E_{target} = \int_0^{t_b} V_{target}(t) I_{target}(t) dt \quad (23)$$

The balancing efficiency is then obtained from

$$\eta_{bal} = \frac{E_{target}}{E_{source}} \times 100\% \quad (24)$$

The calculated efficiency represents the equalization energy-transfer efficiency under the losses represented in the simulation model. Transformer copper loss, transformer core loss, gate-driver loss, and other parasitic losses that are not explicitly modeled are excluded from this value. Consequently, the practical efficiency of a hardware implementation is expected to be lower than the idealized simulated value.

Figure 11 displays the outcomes of a simulation of the proposed design using six series-connected cells. After approximately 400 s, the six cells converge toward the reference SoC and reach the defined balancing condition. Consequently, the proposed topology was balanced in 1800 s, compared to the standard topology [18–20]. Table 6 contrasts the suggested topology with the current topology in terms of several variables, including balancing methods, control platform, converter type, balancing efficiency, and balancing speed. The comparison of various balancing topology parameters as a graphical graph is shown in Figure 13. The charging as well as the discharging systems were developed by considering the structural features that determine each cell's conversion of energy, along with the SOC and its voltage control of balance elements, to enhance the energy uniformity of each cell during the lithium-ion battery pack's operation. Using a bidirectional equalization control technique for lithium-ion batteries depends on the transfer of energy; the sampling time is high, and efficiency is lower compared to the proposed method [21,22]. Comparisons are made between the proposed topology and the existing topology in terms of efficiency and balancing speed. The proposed topology performed better, as shown by

the table and graphic chart. To compare the energy efficiency of the SOC at the beginning and end of equalization, where the efficiency of equalization is calculated, the number of cells is ‘m’, SOC_b is the starting SOC, and SOC_i is the SOC after equalization, charging, and discharging stages with the proposed equalization method. The main advantage of the MPC controller in the proposed system is efficient convergence to a balanced state, even with large SoC mismatches; predictive operation reduces unnecessary switching, improving converter lifetime; constraint handling ensures safe current limits, transformer flux boundaries, and device temperature margins; and adaptability to both continuous and discontinuous conduction modes of the flyback converter. In both the charging and discharging states, it successfully prevents both the overcharging and discharging of cells with various SOC levels, which might enhance the batteries’ overall performance [23,24]. The performance values for the existing methods come from their published studies, which may have used different cell capacities, initial SoC distributions, switching frequencies, balancing currents, and termination criteria. For this reason, Table 6 serves as a benchmark from the literature, not as a direct comparison under identical conditions. The balancing time and efficiency values should be understood in light of the specific conditions used in each reference.

Table 6. Real-time simulator specification.

Product Name	OP5700
Nominal Capacity	100–240 V AC, 50–60 Hz, 8–4 A, 600 W
FPGA (Field-Programmable Gate Array)	Xilinx Virtex 7FPGA on VC707 board
Input/Output connectors	4 panels of 4DB37F connectors
PC interface	Standard PC interface
Hard disk	512 GB SSD
Communication port	16SFP socket, up to 5 Gbps
Monitoring connectors	4 panels of RJ47 connectors
Input/Output lines	256 lines, 8 Analog or digital, 16 or 32 channels

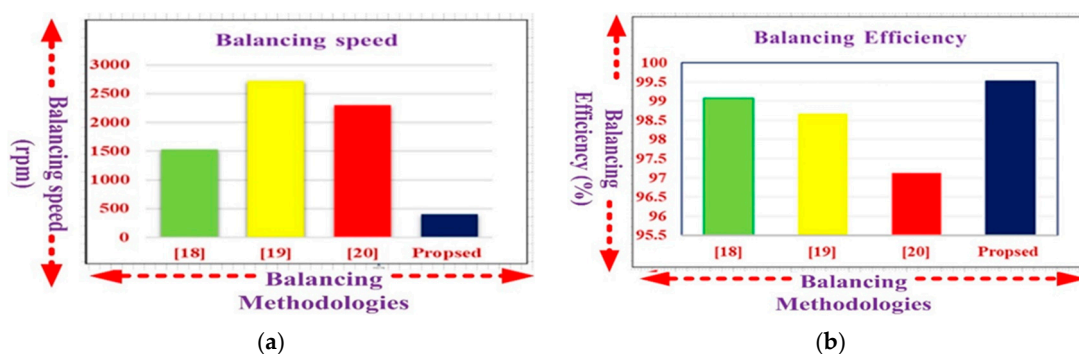


Figure 13. (a,b) Comparison results of balancing speed and efficiency [18–20].

The intricacy of the suggested balancing system is assessed based on the power circuit configuration, switching setup, and controller execution. The multi-winding transformer facilitates direct energy transfer between cells without needing a separate converter for each possible pair of cells. Additionally, the time-sharing method restricts the quantity of concurrently active balancing routes, while the hierarchical control framework distinguishes cell-selection choices from duty-cycle management. As a result, the suggested

system offers a notably reduced controller workload in comparison to balancing methods that need separate control for several balancing converters.

The comparison shown in Table 7 is mainly derived from the performance metrics documented in the relevant literature. It is important to acknowledge that the studies being compared utilize varying battery configurations, initial SoC distributions, switching frequencies, balancing currents, converter architectures, and criteria for balancing termination. Consequently, the stated values should not be regarded as a rigorously regulated quantitative comparison. The table aims to establish a literature-based reference for the proposed balancing method in relation to previously documented techniques. A controlled comparison under the same operational conditions would necessitate comprehensive implementation parameters and simulation models of the chosen reference topology, which are absent from the relevant published literature.

Table 7. Comparison of various cell-balancing topologies.

References	[18]	[19]	[20]	Proposed Method
Converter type	Multi-input and multi-output bidirectional flyback converter	Bidirectional flyback converter	Multiple bidirectional flyback converter	Multi-winding transformer-based active bidirectional flyback converter
Balancing type	Cell to pack—pack to cell	Cell to pack -pack to cell	Cell to cell	Cell to cell
Controlled Platform	Embedded MATLAB function	Microcontroller unit	Field-programmable gate array	Embedded MATLAB unit
Balancing Speed (sec)	1531 s	2727 s	2300 s	400 s
Balancing Efficiency	99.07	98.67	97.12	99.52
Cost	High	Moderate	Low	Moderate
Complexity	High	Moderate	Low	Low
Burden on Controller	High	High	Moderate	Low

Consequently, the balancing time and efficiency metrics documented in the literature need to be understood with regard to the various operating conditions and implementation setups. The suggested approach is assessed mainly through its own simulation and real-time validation outcomes instead of attributing its superiority solely to numerical values reported in the literature.

8. Conclusions

This study proposes an advanced cell-balancing strategy to mitigate state-of-charge (SoC) mismatches in series-connected battery packs for electric vehicle applications. The method combines three equalization techniques to enhance accuracy and adapt to varying imbalance conditions. Central to the design is an active bidirectional equalization circuit employing a multi-winding transformer, which directly transfers energy from the highest-voltage cell to the lowest-voltage cell through coordinated flyback and forward operation. To prevent redundant transfers, a time-sharing control strategy is introduced, with the initial SoC distribution defining the order of balancing, resulting in simplified yet effective control logic. Compared to conventional flyback-based methods, the proposed approach achieves balancing speeds three to four times faster while improving overall energy efficiency. The system's operation and control methodology were validated using MATLAB/Simulink simulations and real-time hardware testing with an OPAL-RT (OP5700) simulator. Results from both platforms were consistent, demonstrating the robustness and real-time applicability of the method. Beyond improved equalization speed, the strategy

offers clear advantages in battery reliability, safety, and service life, making it well suited for advanced battery management systems in electric vehicles. Future improvements may involve integrating refined SoC estimation algorithms to further optimize performance and align with emerging EV requirements.

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