



RESEARCH ARTICLE - ENGINEERING

Boosting Li-Ion Battery Pack Lifespan with Active On-Load Balancing

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Article Info.	Abstract
<i>Article history:</i> Received 21 March 2023 Accepted 02 July 2023 Publishing 31 December 2023	Due to the repeated cycles of charging and discharging, battery manufacturers cannot ensure perfect cell balance. Cell balancing is considered essential for equalizing each battery cell to the same state of charge level in a series configuration. Lithium-ion (Li-ion) batteries can be damaged or have their lifespan decreased by improper discharge processes. This study investigates battery balance during discharge by analyzing the state of charge (SoC) and current distribution of a 3-cell battery pack based on a multi-transformer shared flyback converter (F-C) under varying load conditions. A balanced approach is employed to control individual cells using a dedicated switch for each cell during the discharge process. The results indicate that the proposed active balancing method can enhance the Li-ion pack's balancing capacity while reducing the disparity in residual energy among the battery cells. The unique contribution of this research lies in the active balancing approach, which offers efficient and effective battery management during discharge. This approach provides crucial insights for the future development of improved battery systems. Therefore, Given the linearly decreasing target SoC, the average error over all time points is approximately 4.29%.

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1. Introduction

Li-Ion batteries are in increased demand in various energy storage applications, such as electric vehicles, electric bikes, and photovoltaic off-grid installations. Therefore Li-ion batteries possess several benefits, including high energy and energy density, minimal self-discharge, a lengthy lifespan, and no memory effect [1, 2]. It is used widely in various energy storage applications. However, a single cell's voltage is only 3.6V, so to provide the required high voltage must be connecting multiple cells in series.

The balancing techniques are classified into two types of balancing methods passive and active [3]. The passive balancing technique dissipates the excess charge as heat from the unbalanced cell by using a switch shunting resistor for each cell and dissipates the deviation energy as heat energy between cells. Active balancing uses energy-storage elements, such as transformers, inductors, and capacitors, to transfer energy from high-voltage battery cells to low-voltage battery cells, which has a balancing technique with the advantages of low energy loss and equalizing the voltage efficiency of battery cells by transferring charge. This method uses energy storage elements as external energy storage to transfer energy between the cells [4]. In battery systems, cell imbalance is fairly common.

Therefore, maintaining battery balance is crucial because only the lowest-charge cell in a serially connected battery pack discharges quickly to empty. Batteries connected in series will have less capacity and lifespan as a result. If the battery is unbalanced, it could potentially put the device or even human personnel in danger [5]. This paper primarily introduces an F-C-based active balancing circuit that prevents energy loss or a storage element to move energy from cell packs and reduces balancing time.

This research makes a notable contribution by introducing an innovative active balancing method for the discharge process of Li-ion batteries. This strategy not only enhances battery performance and lifespan but also provides insights into battery behavior during discharge. The findings have significant implications for the design and performance of battery systems, offering an effective solution to the issue of cell imbalance in Li-ion batteries.

Nomenclature & Symbols			
PCB	Passive Cell Balancing	F-C	Flyback Converter
ACB	Active Cell Balancing	N_1	Number of Turns in The Primary
BMS	Battery Management System	N_2	Number of Turns in The Secondary
SoC	State of Charge	V_o	Output Voltage
DoD	Deep of Discharge	V_s	Input Voltage Source
Li-ion	Lithium-Ion	C	Capacitance
Li-Po	Lithium-Ion Polymer Battery	f	Switching Frequency
PWM	Pulse Width Modulation	ΔV_0	Ripple Voltage
V _{gs}	Voltage Gate to Switch	D	Duty Cycle
SoC_{max}	The Maximum State of Charge of The Cell	U_i	The Relative Amount to Maximum Capacity
SoC_i	State of Charge of The Particular Cell	I_{Disch_i}	The Discharge Current of a Particular Cell
PID	Proportional, Integral, and Derivative	I_{ref}	Reference Current

2. Literature Review

In several previous pieces of research on balancing strategies, the authors have used various methods to address cell balancing. For instance, In [6], the authors used a Flyback Converter (F-C) for the cell balancing method, employing external energy storage to transfer energy between cells. However, the non-uniform turn proportions of the secondary winding leakage inductance led to unequal secondary winding voltages, leaving room for improvement. The authors in [7], proposed a charge equalizer using a multi-winding transformer with simple control and soft-switching. It eliminated the need for choke inductors, and the method presented demonstrated potential in terms of efficiency, but its applicability was limited due to higher component count and limited scalability. Similarly, the method proposed in [8], achieved cell balancing but at the expense of voltage imbalances caused by multi-winding effects. The individual cell control method is a solution to this issue. It uses a single F-C and an adjusted filter to control the frequency of each cell, achieving equal cell balancing.

The article [9] highlighted previous research on cell balancing methods for F-Cs with multi-winding, including individual switches and passive and active balancing techniques. Recent research has focused on developing more cost-effective, efficient, and compact methods like generalized filters. The proposed method in the article represented an innovative and promising approach to cell balancing built upon previous research in the field. And despite promising developments, the paper falls short in terms of practical implementation.

The study in [10] highlighted a high balancing efficiency of 89.4% but did not address how to deal with more extensive battery strings. The equalization was achieved based on forward conversion for one group of windings. In [11], the author discussed using a flyback transformer as a storage element for energy conversion in active cell balancing. A multi-output flyback DC/DC converter prototype was built and tested with an 8Ah manganese lithium battery pack. The balancing effect was observed in experimental Li-ion batteries, and potential improvements were suggested for the version. However, the research did not provide a comprehensive review of existing active balancing methods and their limitations, leading to the potential overlook of some existing solutions.

Moreover, the authors in [12] proposed a hierarchical active balancing architecture for series-connected lithium-ion batteries. This architecture grouped battery cells into packs and introduced a top layer to eliminate coupled influence among pack cells. A balancing control based on each cell's State-of-Charge (SOC) and a multi-directional multi-port converter were proposed to deliver energy bi-directionally. The hierarchical active balancing architecture improved the balancing system's performance but did not fully address energy loss and balancing time.

The paper [13] discussed the importance of Battery Management Systems (BMS) in Electric and Hybrid Electric Vehicles for ensuring safety and maximizing battery performance. The authors proposed an active balancing model in MATLAB to redistribute energy among batteries and increase their lifespan. They also presented a custom BMS platform to achieve the necessary battery information for active balancing. Furthermore, the study lacked an in-depth discussion of the practicalities of the proposed model.

In [14] A simulation model was developed for analysis, and an experimental stand confirmed the results. The studied resonant DC-DC converter was applicable for battery management systems, and voltage equalization used an algorithm with different charging currents from each converter. Despite the effort to analyze the significant influence of changing charging currents, it remained unclear how to calculate and control for a suitable half-bridge driver supply. Different charging currents required frequency control of the main switch MOSFET.

3. General Background Theory

The cells' imbalance occurs when there are differences in the SoC or capacity between individual cells in a battery pack. This imbalance can lead to a reduction in the overall performance and lifespan of the battery. It can even cause safety issues if the imbalances become too severe. To address this issue, many battery manufacturers use cell balancing. They adopted different designs to equalize the SoC or capacity of individual cells in a battery pack. Regardless of the balancing technique, battery manufacturers need to ensure that the cells in a battery pack are well-matched in terms of their characteristics and performance. That leads to minimizing the risk of cell imbalances and maximizing the battery's overall performance and lifespan.

3.1. Balancing methodology

Efficient operation and safety of batteries greatly depend on control algorithms, a critical component of which is cell balancing. This process becomes essential when dealing with a battery pack composed of several individual cells connected in series and parallel. Over time, with repeated charging and discharging cycles, the capacity of each cell varies, leading to different states of charge (SoC) for each cell in the pack [15]. This imbalance in SoC can shorten the lifespan of the battery pack, as the charging and discharging process has to halt when the first cell reaches its maximum or minimum SoC, leaving other cells under or overutilized.

To mitigate this issue, the cell balancing technique is employed. Cell balancing aims to ensure that all individual cells within a battery pack reach an almost identical state of charge. Doing so prevents early termination of the charging or discharging process, thus maximizing the utilization and lifespan of all cells in the battery pack. It also avoids potentially dangerous conditions such as thermal runaway, which can occur if charging continues after a cell has reached its maximum voltage [16, 17].

However, achieving efficient cell balancing poses a significant challenge, mainly due to the complex interaction between individual cells' state of charge and the overall performance and safety of the battery pack. To address this, the present study proposes a novel cell-balancing methodology, which will be discussed in the following sections.

3.1.1. Passive Cell Balancing (PCB)

Battery Passive Cell Balancing (PCB) is a technique employed in Battery Management Systems (BMS) to equate the voltage levels of individual cells in a battery pack. Unlike active cell balancing, PCB does not shift the charge among cells actively but utilizes natural processes to achieve cell balancing.

PCB involves connecting passive components like resistors, capacitors, or diodes parallelly with each cell, which act as shunt circuits. When a cell reaches a certain voltage threshold, current flows through these components, diverting the surplus charge from the overcharged cell to the undercharged cell, thus equalizing their voltages.

PCB is less complex and cheaper than active cell balancing as it doesn't need sophisticated electronics or additional power components. However, its effectiveness and efficiency are lower, especially in larger battery packs, due to its reliance on the natural discharge of the overcharged cell. It's typically used in applications with lower energy demands where balancing isn't as critical.

In PCB, the cell with the highest State of Charge (SoC) is connected to a resistor, dissipating extra energy as heat, which leads to the same SoC for all cells. Despite being simple and cost-effective, PCB has limitations, including the pack's capacity restriction by the weakest cell, inefficient energy usage, and extra cooling requirements. Alternatives such as active cell balancing and BMS are developed to address these issues and enhance battery performance and lifespan [18].

3.1.2. Active Cell Balancing (ACB)

Battery Active Cell Balancing (ACB) is a technique employed in Battery Management Systems (BMS) to ensure uniform charging and discharging of all cells within a battery pack. Particularly crucial for Li-ion batteries, ACB maintains optimal performance and prevents safety hazards.

ACB actively monitors each cell's temperature and voltage, adjusting their charge rates to maintain an optimal range. This can involve redirecting excess charge from fully charged cells to undercharged ones or redistributing the pack's stored energy for equal charge levels across cells. This balancing enhances the battery pack's lifespan, improves performance, and minimizes the risk of cell failure or thermal runaway.

In ACB, energy is transferred from the highest SoC cell to the lowest SoC cell via a capacitor, inductor, or DC-to-DC converter. Post-balancing, peak cells will have an SoC equivalent to the pack cells' average, optimizing energy use.

The advantages of ACB include efficient energy transfer between cells and equalized SoC. However, drawbacks include its complex architecture and the added cost of electronics [19, 20]. Fig. 1 illustrates the two primary techniques for balancing batteries: active and passive methods. Both active and passive cell balancing approaches encompass a diverse range of topologies, which can be further categorized into distinct classes. Moreover, Fig. 2 presents a framework for comparing the implementation of different balancing methods, namely passive and active balance techniques. [21, 22]. Because of its ease of use, dependability, and widespread use in industrial applications.

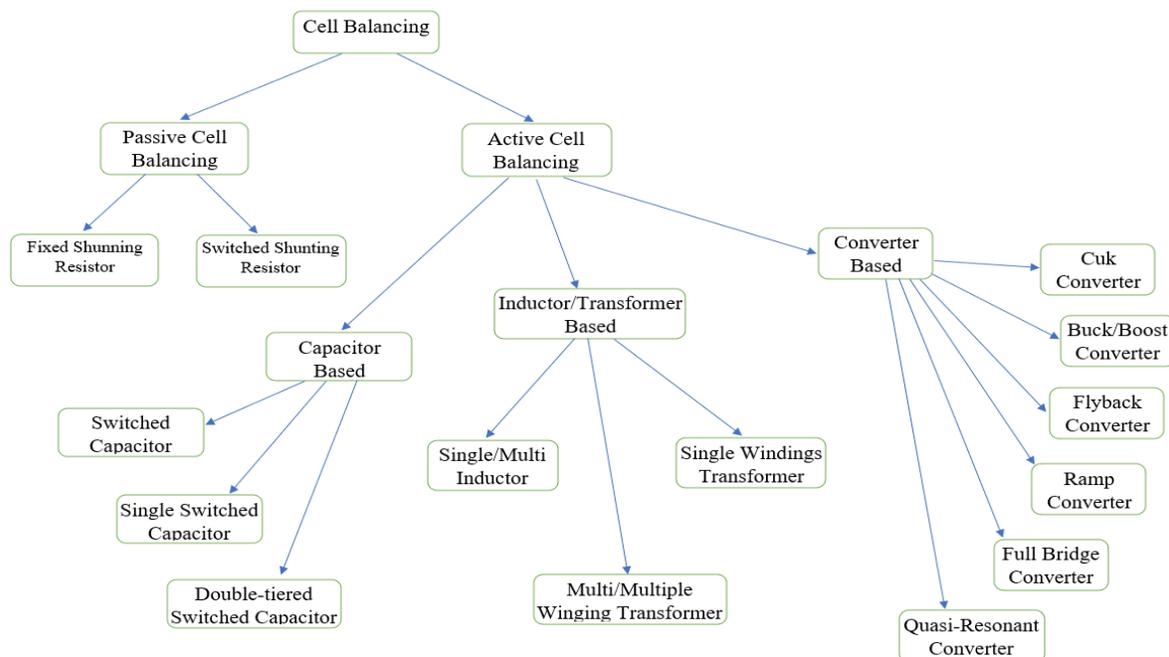


Fig. 1. Balancing topologies [21]

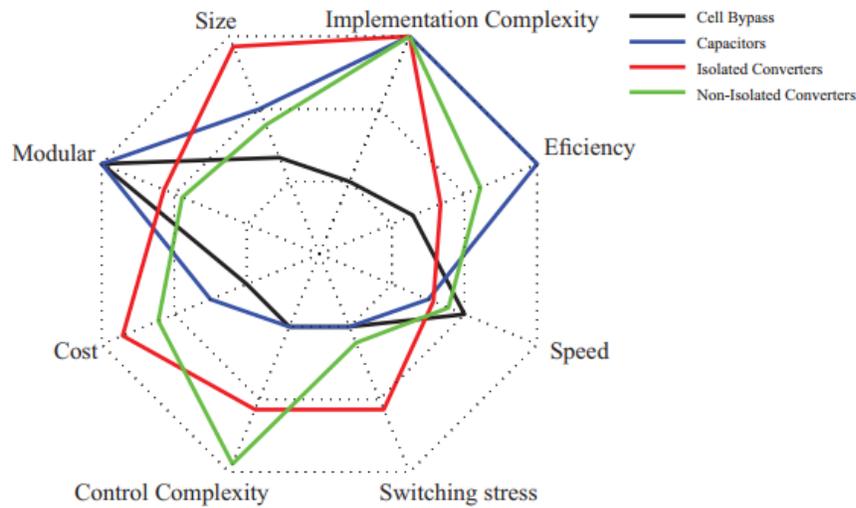


Fig. 2. Balancing methods comparison [22]

3.2. Flyback converter for cell balancing

F-C belongs to the family of converters with isolation; as such, it is beneficial when designing a DC-to-DC Converter to operate off the power line. The F-C is top-rated and used in many applications, including chargers and others. The flyback regulator converts the input voltage into an output voltage with a higher or lower value [23]. The primary operational concept for this F-C is that we can control the voltage on the secondary side by controlling or modulating the current through the primary side. So, the switch is in charge of modulating and controlling the current through the primary side [24, 25]. Fig. 3.a, shows the F-C's circuit diagram. The Duty Cycle is calculated from Eq. (1), and the capacitance value from Eq. (2).

$$\frac{N_2}{N_1} = \frac{V_0}{V_s} * \frac{1-D}{D} \quad (1)$$

$$C = \frac{D * V_0}{R * f * \Delta V_0} \quad (2)$$

This converter operates in two States [26]:

- State 1: When S the switch is closed (Fig. 3.b), the primary winding of the transformer becomes directly connected to an input voltage source. The current and the magnetic field through the primary side of the transformer increase, and its stored energy, the secondary winding, is induced to a negative voltage. The diode is thus reverse-biased and supplies energy to the load by the output capacitor.
- State 2: When S the switch opens (Fig. 3.c), the primary current and magnetic field drop, while the secondary winding voltage becomes positive. In this case, the diode is biased forward, and current can flow from the transformer. The load is powered by the energy from the transformer core, which also recharges the capacitor.

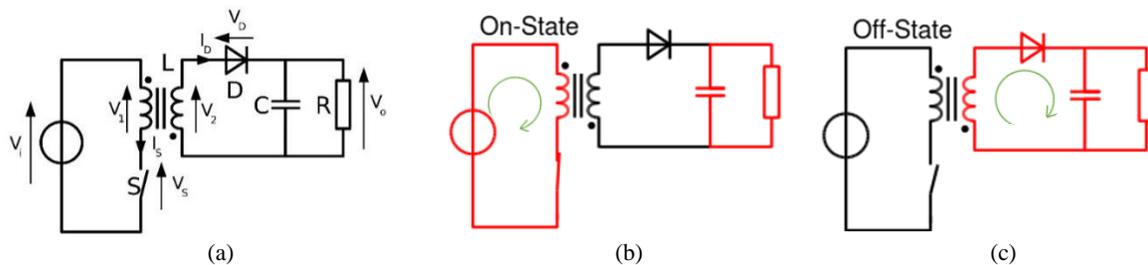


Fig. 3. a) Flyback converter operation, b) Growing magnetic field, c) shrinking magnetic field [26]

The converter category within the active balancing methods can be further divided into two sub-groups: isolated converters and non-isolated converters. When implementing different balancing methods, these techniques rely on utilizing the battery pack or individual cell as a power source for the converter, which then transfers energy to another cell or pack. The first sub-group, isolated converters, employs isolated DC-DC converters with a variety of topologies, including multi-winding transformers, multiple transformers, and single-switched transformers.

4. Methodology

According to the literature review, active balancing is more efficient and radiates less heat due to the use of active elements. The primary focus of this study is to develop an active battery balancing system that operates mainly during the discharge cycle.

Estimating the battery's State of Charge (SoC) is crucial for this system's functionality. Several methods exist for SoC estimation, such as voltage-based estimation, the use of a coulomb meter [27], deep learning [28], or the implementation of a Kalman filter [29]. This study explores a combination of these techniques to achieve the most accurate SoC estimation.

The proposed active balancing system works based on the deviation of SoC between cells. It specifically involves the active regulation of each cell to maintain its balance during the discharge process. As charge levels start to diverge, the active balancing circuitry slightly discharges each cell as needed, preventing significant divergence of SoC levels.

This process continues throughout the entire discharge cycle, with each cell continuously monitored. This active management ensures that each cell operates within a narrow range of its optimal voltage level, thereby promoting overall battery efficiency, safety, and lifespan.

The subsequent sections will delve deeper into the design and implementation of the proposed active balancing system, discussing the specific algorithms used for SoC estimation, the design of the active balancing circuitry, and the control strategy used to regulate each cell's discharge.

Fig. 4 presents a representation of the discharging current reference, which directly corresponds to the battery's SoC, illustrating how the discharging current changes about the SoC.

For the balancing process, we utilize pack current mode control. This method involves controlling the overall current of the battery pack instead of controlling individual cells. This strategy allows for faster response times as it bypasses the need to manage the discharge rates of each cell independently. Instead, it handles the entire pack as a unit, resulting in quicker adjustments and a faster balancing process.

In pack current mode control, the overall pack current is adjusted when the SoC of any cell diverges from the reference SoC. This affects the SoC of all cells, guiding them toward the desired state of balance. This control mechanism allows for quick correction of SoC imbalances, contributing to a faster balancing speed and better overall battery pack performance.

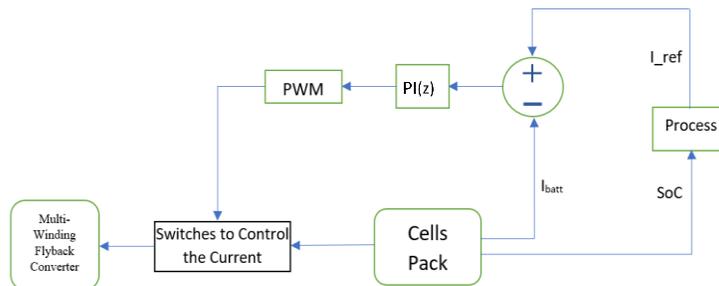


Fig. 4. Balancing Controller

5. Simulation Results and Discussion

The MATLAB Simulink software was used to construct and simulate the system to verify the suggested F-C circuit, shown in Fig. 5. The multi-winding saturable transformer with a turn ratio of 1: 3 is selected to simulate the circuit. One primary and three secondary conductors make up the transformer. The number of secondary winding can be changed depending on the required numbers, and each secondary winding is connected to one cell via a switch (MOSFET). The switch is controlled by a (PWM) signal with a frequency of 25kHz and a duty cycle dependent on current control. The F-Cs are simpler to implement and require fewer components. The process has two stages. The initial phase involves storing energy in the transformer when the switch is turned on. In the subsequent step, the secondary devices will receive the stored energy when the switch is off.

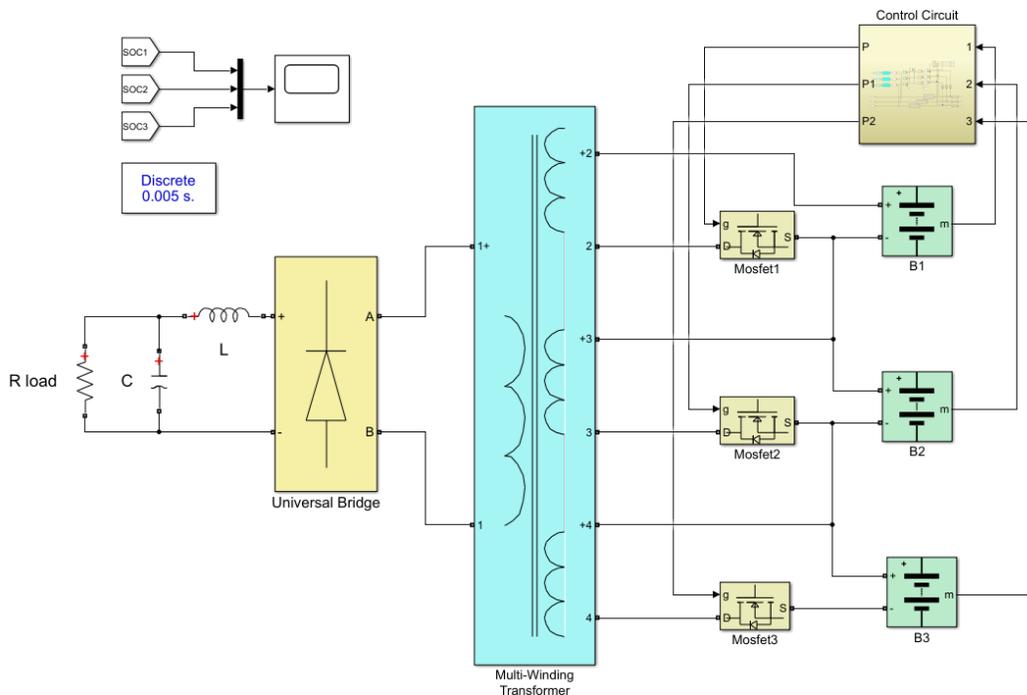


Fig. 5. System Circuit

6. The Main Controller Architecture

The balancing strategy first aims to accurately obtain the battery cells' State of Charge (SoC) values. Next, the maximum value is extracted, and the other values are divided by this maximum value. This process is commonly referred to as "normalizing" or "scaling" the values. The resulting normalized values fall between 0 and 1. To normalize the maximum SoC to the cell pack, equations (3) and (4) are defined. SoC_i represents the ratio of the SoC to each cell, and SoC_{max} represents the maximum SoC in the pack. The U_i parameter refers to the ratio of the residual capacity to the maximum capacity.

Where U_i represents the relative amount to the maximum capacity. To ensure a boost in current from the cell with the highest SoC, it is necessary to amplify the differences between the cells. This can be accomplished by utilizing a power function. Since U_i is limited to the range of [0-1], this implies converting the signal from linear to nonlinear.

Compared to conventional equalization, increasing the power number in the system results in more aggressive power consumption from the highest battery cell and reduces the balancing time. This leads to an improvement in equalization speed and efficiency among the cells. The proposed balancing circuit features a flexible current flow path, where cells with low SoC receive a lower current flow rate during charging, while cells with higher SoC undergo discharge operations at a higher flow rate. To achieve a load share percentage between all batteries, the measurements are divided by the sum of the values. This approach is beneficial when comparing variables with different scales or when the learning algorithm requires input features to be on the same scale.

In general, the discharge rate or coefficient of a battery measures its ability to supply current relative to its capacity. This rate is typically expressed as a multiple of the battery's capacity, commonly denoted as "C". According to the equation, the discharge current of a specific cell or battery is equal to the discharge rate of that cell multiplied by a reference current. This implies that the discharge current can be regulated by adjusting either the reference current or the discharge rate.

For instance, if the discharge rate is too high given a certain reference current, the discharge current will exceed safe limits, potentially leading to overheating or battery failure. By modifying the discharge rate or the reference current, the discharge current can be brought within a safe operating range. In this context, I_{Disch_i} represents the discharge current of the i-th cell, while I_{ref} corresponds to the total reference current required from the battery pack. The new setpoint of the Proportional-Integral (PI) controller, which regulates the supplied current from the i-th cell, will be I_{Disch_i} . The error between the desired reference and the actual battery current is fed into the PI controller, which in turn controls the Flyback controller's duty cycle

Fig. 6 illustrates the overall architecture of the main controller design.

$$SoC_{max} = \text{Max}(SoC_1, SoC_2, \dots, SoC_N) \quad (3)$$

$$U_i = \frac{SoC_i}{SoC_{max}} \text{ where } i = 1 \text{ to } N \quad (4)$$

$$Y_{NL_i} = U_i^n \quad (5)$$

$$\text{Load Share Percentage (LSP}_i\%) = \frac{Y_{NL_i} \times 100\%}{\sum_{i=1}^n Y_{NL_i}} = \frac{U_i^n \times 100\%}{\sum_{i=1}^n U_i^n} = \frac{(\frac{SoC_i}{SoC_{max}})^n \times 100\%}{\sum_{i=1}^n (\frac{SoC_i}{SoC_{max}})^n} \quad (6)$$

$$I_{Disch_i} = LSP_i\% \times I_{ref} = \frac{Y_{NL_i} \times 100\%}{\sum_{i=1}^n Y_{NL_i}} \times I_{ref} = \frac{(\frac{SoC_i}{SoC_{max}})^n \times 100\%}{\sum_{i=1}^n (\frac{SoC_i}{SoC_{max}})^n} \times I_{ref} \quad (7)$$

In

Fig. 6, we have a Simulink model that processes three main inputs denoted as 1, 2, and 3. These inputs are multiplexed signals, each containing various parameters of the cells in the battery pack.

- After these signals are demultiplexed, we obtain the following sets of data: The States of Charge (SoC) of the three cells ($SoC_1, SoC_2,$ and SoC_3), The current for each of the three cells ($I_{B1}, I_{B2},$ and I_{B3}) and The voltage for each of the three cells ($V_{B1}, V_{B2},$ and V_{B3}). This data represents the primary parameters of each cell in the battery pack.
- Each battery cell's SoC is closely monitored. It is a critical aspect of battery management, as it helps prevent the risk of over-discharging. The system automatically disconnects any battery whose SoC falls at or below the minimum allowed Depth of Discharge (DoD) as specified by the manufacturer. This minimum DoD is a safeguard against over-discharge, preserving the lifespan and health of the batteries. By incorporating this feature into our active balancing system, we ensure that the discharge process is safely regulated and battery cells are not pushed beyond their safe operational limits.
- Here, the maximum SoC is examined.
- At this state, Eq. (4) is calculated to normalize the maximum SoC to the cell pack. It also considers the DoD enable signal done in step 2.
- This step calculates Eq. (5) based on the selected power to increase or decrease the aggression. To more aggressively consume power from the highest battery cell.
- Here, in this step, we calculate I_{Disch_i} using Eq. (7). In this equation, I_{Disch_i} represents the discharge current for the 'i-th' cell in the battery pack, which is derived based on a specific reference current. The reference current serves as a benchmark against which the discharge

current of each cell is regulated. The purpose of this step is to use the calculated discharge current, I_{Disch_i} , to guide the power management of the 'i-th' cell during discharge. By aligning the discharge current with the reference current.

- A dual-stage low-pass filter is implemented as high-frequency switching is used to minimize the ripple factor in the computed current values. High-frequency switching, while beneficial for improving the efficiency and response times of the system, can also introduce unwanted high-frequency noise or 'ripple' into the calculated current values. This ripple can cause inaccuracies in the control algorithms, potentially leading to less-than-optimal performance or even system instability. To address this issue, we use a dual-stage low-pass filter. Low-pass filters work by attenuating the high-frequency components of a signal, allowing only the lower-frequency components to pass. By employing two stages of such filtering, we can significantly reduce the ripple in current measurements, leading to more accurate and stable control of the system.
- At this step, the error between the measured I_{Disch_i} and the real current is calculated to be delivered to the PI controller. This error calculation serves as a critical input for the Proportional-Integral (PI) controller. The PI controller uses this error to adjust its output and regulate the system behavior in an attempt to minimize the error over time.
- The output duty cycle from the PI controller is limited based on the designed flyback converter. This controller is tuned using the trial-and-error method. The tuning process continues until the desired system performance is achieved.
- This step uses the PWM generator at a 25kHz frequency to control the MOSFET gate.

The Li-ion pack is discharged by the electronic load With current control by a switch for each battery cell, and the initial SoCs of the three battery submodules are 80%, 70%, and 60%, respectively. The controller will continue to discharge until it achieves the desired depth of discharge, reaches 10%, and stops discharging. The voltage and current between cells progressively decrease throughout the discharge equalization process, and the discharge level of each battery cell becomes increasingly similar and stable at about 175 seconds. The SoCs of the three batteries are shown in Fig. 7. When the discharging time is 323.722 seconds, the SOC of the three cells after discharging is 10%. Table 1 displays the variation of a battery's State of Charge (SoC) over time, with different initial SoCs: 80%, 70%, and 60%. As time elapses, the SoC of each scenario diminishes. The following are some general observations derived from the table: "All batteries start at their respective designated SoC levels: the first battery begins at 80%, the second at 70%, and the third at 60%. The rate of decrease is quickest for the 80% SoC battery, followed by the 70% SoC battery, and finally, the 60% SoC battery. This suggests that batteries with a higher initial charge deplete more rapidly. From the 200s, all three batteries diminish at approximately the same rate. This indicates that the depletion rate becomes relatively constant beneath a certain charge level. At time 325s, the controller achieves 10% of the desired depth of discharge. At this point, the discharge process is halted".

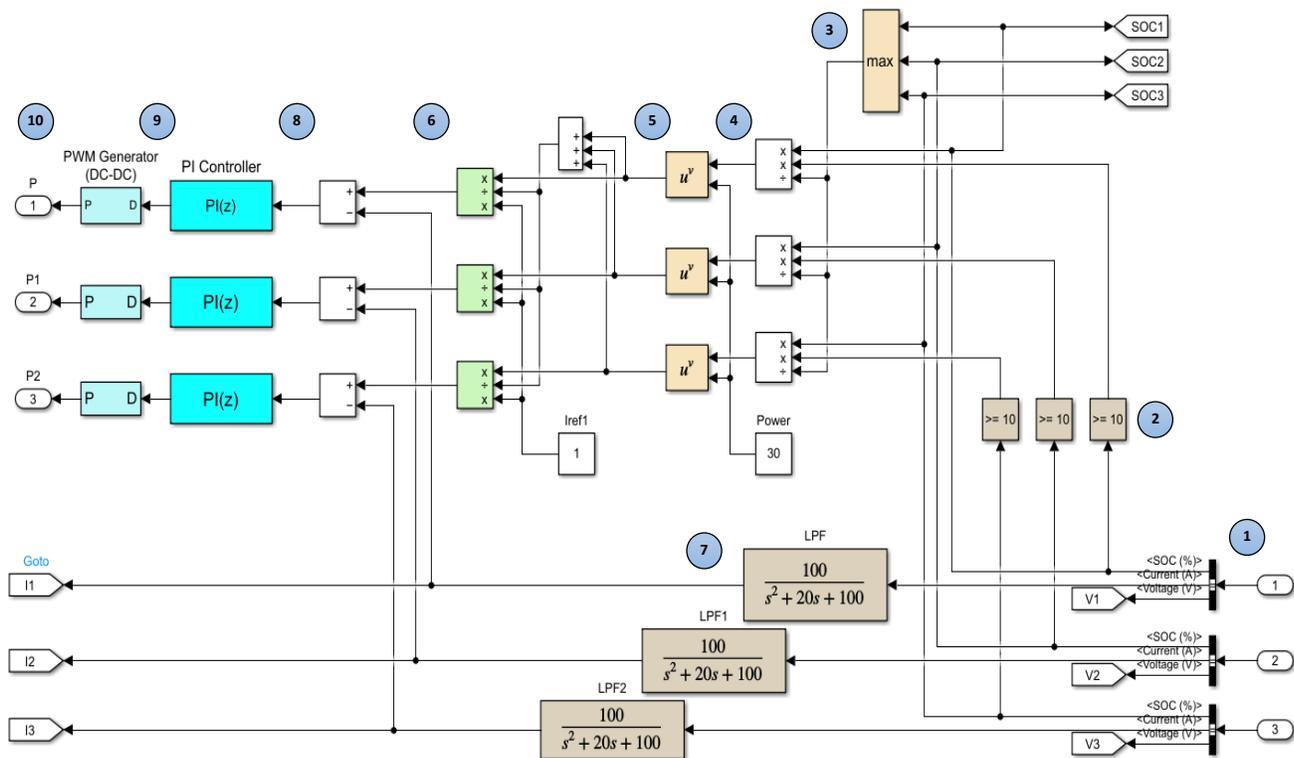


Fig. 6. The main controller architecture design

7. Case Study

To test and evaluate the proposed system three batteries are used with the same capacity but with a different SoC, the first battery SoC was $SoC_1 = 80\%$, while the second and third battery SoC was $SoC_2 = 70\%$, and $SoC_3 = 60\%$. The maximum SoC, according to (3), is equal to $SoC_{max} = \text{Max}(SoC_1, SoC_2, \dots, SoC_N) = \text{Max}(80\%, 70\%, 60\%) = 80\%$. To utilize the results as in (4):

- $U_1 = \frac{80\%}{80\%} = 1.000$, $U_2 = \frac{70\%}{80\%} = 0.875$, and $U_3 = \frac{60\%}{80\%} = 0.750$.

- $Y_{NL_i} = U_i^n \rightarrow Y_{NL_1} = U_1^{30} = (1.000)^{30} = 1.0000, Y_{NL_2} = U_2^{30} = (0.875)^{30} = 0.0182, \text{ and } Y_{NL_3} = U_3^{30} = (0.750)^{30} = 0.0012$
- $LSP_i\% = \frac{Y_{NL_i} \times 100\%}{\sum_{i=1}^n Y_{NL_i}} \rightarrow LSP_1\% = \frac{1.000 \times 100\%}{(1.000+0.0182+0.0012)} = \frac{100\%}{1.0194} \approx 98.0\%, \quad LSP_2\% = \frac{0.0182 \times 100\%}{(1.000+0.0182+0.0012)} = \frac{1.8\%}{1.0194} \approx 1.80\%, \quad \text{and}$
 $LSP_3\% = \frac{0.0012 \times 100\%}{(1.000+0.0182+0.0012)} = \frac{0.12\%}{1.0194} \approx 0.20\%.$
- According to (7), if $I_{ref} = 10A, I_{Disch_1} = 98.0\% \times 10A = 9.8A, I_{Disch_2} = 1.80\% \times 10A = 0.18A, \text{ and } I_{Disch_3} = 0.20\% \times 10A = 0.02A.$
 When the balance is reached and for example $SoC_1 = 60\%, SoC_2 = 70\%, \text{ and } SoC_3 = 60\%.$
- $U_1 = \frac{60\%}{60\%} = 1.000, U_2 = \frac{60\%}{60\%} = 1.000, \text{ and } U_3 = \frac{60\%}{60\%} = 1.000.$
- $Y_{NL_i} = U_i^n \rightarrow Y_{NL_1} = U_1^{30} = (1.000)^{30} = 1.0000, Y_{NL_2} = U_2^{30} = (1.000)^{30} = 1.0000, \text{ and } Y_{NL_3} = U_3^{30} = (1.000)^{30} = 0.0012$
- $LSP_i\% = \frac{Y_{NL_i} \times 100\%}{\sum_{i=1}^n Y_{NL_i}} \rightarrow LSP_1\% = \frac{1.000 \times 100\%}{(1.000+1.000+1.000)} = \frac{100\%}{3.000} \approx 33.33\%, LSP_2\% = \frac{1.000 \times 100\%}{(1.000+1.000+1.000)} = \frac{100\%}{3.000} \approx 33.33\%, \text{ and } LSP_3\% = \frac{1.000 \times 100\%}{(1.000+1.000+1.000)} = \frac{100\%}{3.000} \approx 33.33\%$
- According to (7), if $I_{ref} = 10A, I_{Disch_1} = 33.33\% \times 10A = 3.33A, I_{Disch_2} = 33.33\% \times 10A = 3.33A, \text{ and } I_{Disch_3} = 33.33\% \times 10A = 3.33A.$

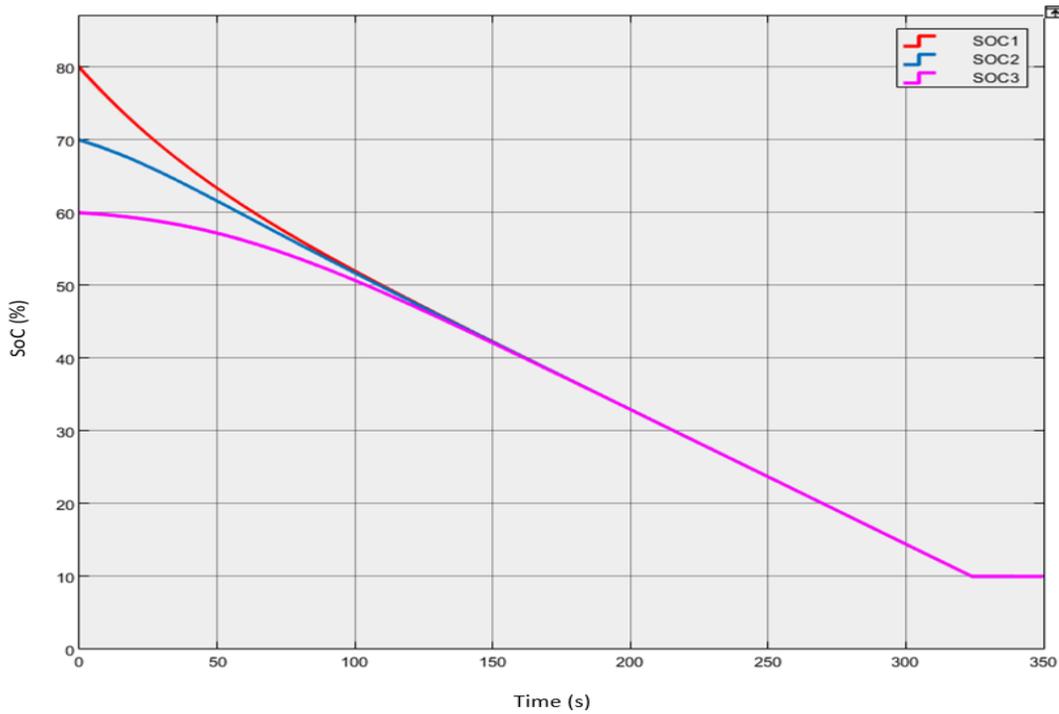


Fig. 7. SoCs of Three Batteries During Discharging

Table 1. Three Batteries @SoC (80%) b) @SoC (70%) c) @SoC (60%)

Time(s)	SoC (80%)	SoC (70%)	SoC (60%)
0	80	70	60
25	73.07262	68.54427	59.67754
50	65.58754	63.66763	59.07728
75	59.30461	58.47042	56.12863
100	53.82462	53.31756	52.38860
125	48.67479	48.53568	47.98779
150	43.72304	43.67215	43.37123
175	38.91496	38.86910	38.68763
200	33.98438	33.98466	33.98438
225	29.17326	29.17322	29.17326
250	24.41759	24.41759	24.41759
275	19.61302	19.61371	19.61382
300	14.82464	14.82460	14.82460
325	10.00557	10.00080	10.00291
350	10.00356	10.00179	10.00238

As presented in Fig. 8 a, it can be seen in the waveform of the cell currents due to the cells not being balanced yet. At the beginning of the period, the cell current waveforms are not equal. Then, after a short period, in a steady state, all currents have the same value, indicating that the cells have been equalized and are at the same amount of charge for each cell. as shown in Fig. 8.b.

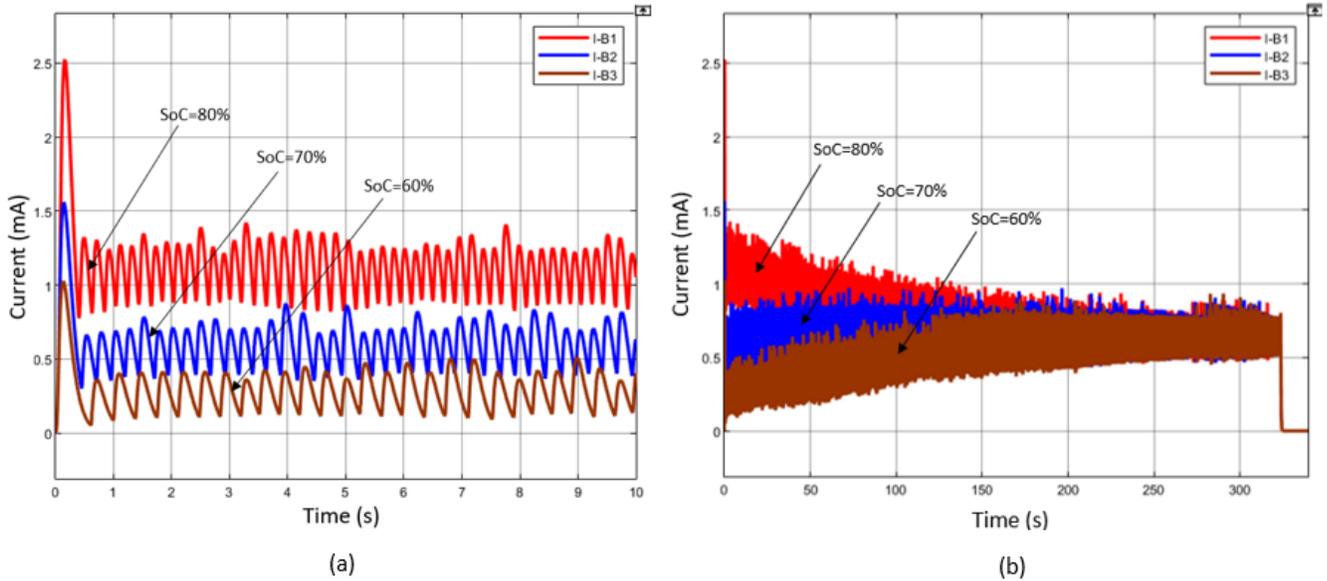


Fig. 8. The waveform of cell Currents; a) Beginning of the balancing process, b) equalization period

Fig. 9 shows the gate voltages to MOSFETs are adjusted based on the duty cycle of the power converter. It determines the time that the MOSFET is switched ON or OFF. Additionally, the SoC of the battery or cell is used to adjust the gate-source voltage to regulate the discharging current.

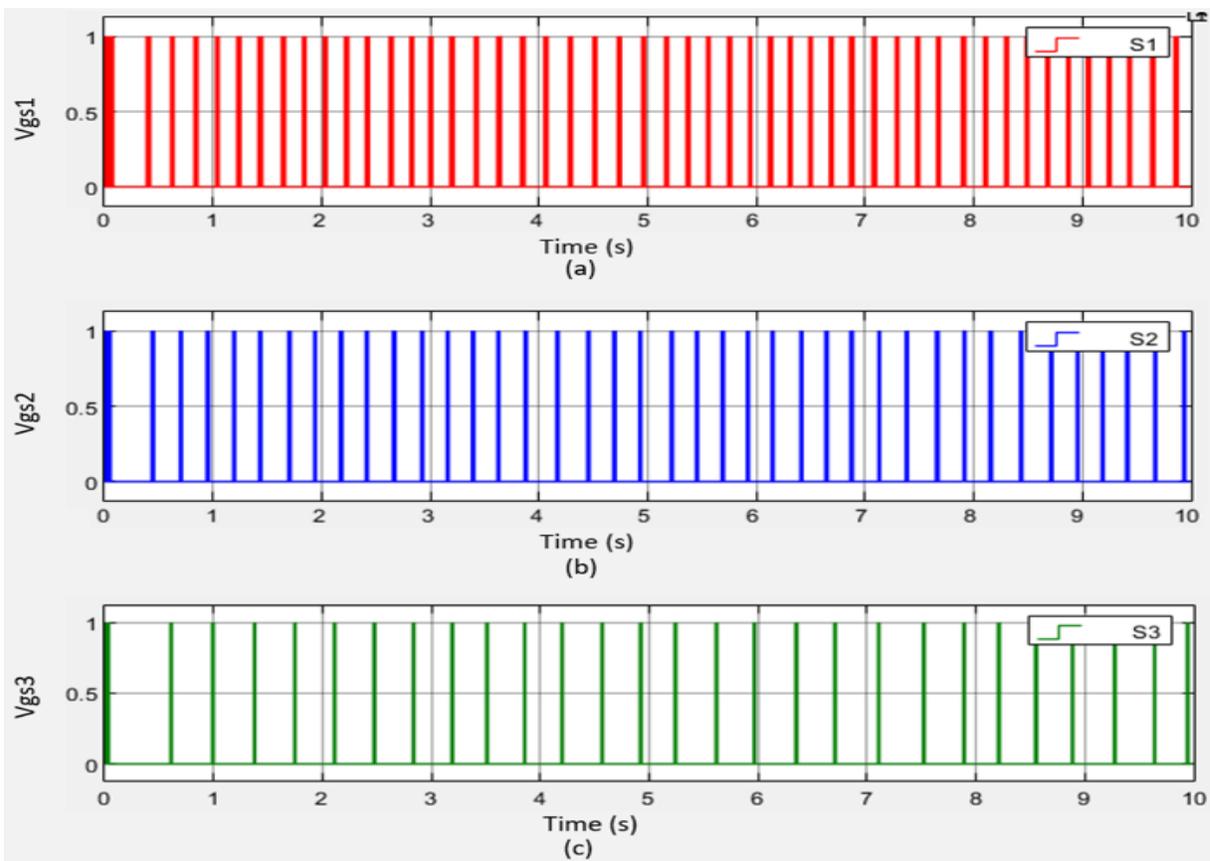


Fig. 9. MOSFET Gate Source Voltage a) @SoC (80%) b) @SoC (70%) c) @SoC (60%)

The gate-source voltage controls the current flow through the MOSFET, acting as a power converter circuit switch. By adjusting the gate voltage, the amount of current flowing through the MOSFET can be regulated, which controls the discharging of the battery or cell.

The duty cycle of the power converter determines the on and off time of the MOSFET and is usually adjusted to maintain a specific voltage or current output. By adjusting the gate voltage based on the SoC of the battery or cell, the power converter can regulate the discharging current

to prevent over-discharging, which can damage the battery or cell. Overall, this control strategy helps to ensure that the battery or cell is discharged safely and efficiently, which can improve the overall performance and lifespan of the battery.

8. Conclusion

This study explores a balancing technique that employs a multi-winding flyback converter structure. The proposed system aims to balance battery cells connected in series within a battery pack. It's observed that batteries with a higher initial (SoC) deplete faster. However, discharge rates tend to equalize once a certain level is reached. Importantly, the controller successfully halts the discharge at 10%. Implementing such controlled discharge is crucial for preserving battery life. Flyback balancing is not only easy to control, but it also provides a quick equalization time. To assess the balancing efficiency during the battery discharge process, this paper thoroughly explains the operating principle and analytical procedure to prevent deep discharge. Simulation results demonstrate that the new balancing approach offers superior balancing speed and efficiency and is less costly than other methods. According to experimental results, the proposed method significantly enhances the consistency of a series battery pack, proving its robust balancing effects. It also reduces the current difference in target cells using cell-specific control. Future work will extend this study to include the charging of the cell pack. As a proactive recommendation, the author suggests constructing this system using dSPACE DS1104, enabling more precise control and data collection for further optimization.

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Reference

- [1] Z. Zhang, L. Zhang, L. Hu, and C. Huang, "Active cell balancing of lithium-ion battery pack based on average state of charge," *International Journal of Energy Research*, vol. 44, no. 4, pp. 2535-2548, 2020, doi: <https://doi.org/10.1002/er.4876>.
- [2] Y. Cao, K. Li, and M. Lu, "Balancing Method Based on Flyback Converter for Series-Connected Cells," *IEEE Access*, vol. 9, pp. 52393-52403, 2021, doi: <https://doi.org/10.1109/ACCESS.2021.3070047>.
- [3] T. A. Abdul-jabbar, A. Kersten, A. Mashayekh, A. A. Obed, A. J. Abid, and M. Kuder, "Efficient Battery Cell Balancing Methods for Low-Voltage Applications: A Review," in *2022 IEEE International Conference in Power Engineering Application (ICPEA)*, 2022: IEEE, pp. 1-7, doi: <https://doi.org/10.1109/ICPEA53519.2022.9744677>.
- [4] F. Ran, H. Xu, Y. Ji, J. Qin, and W. Li, "An active balancing circuit for lithium battery management system with optoelectronic switches," in *TENCON 2015-2015 IEEE Region 10 Conference*, 2015: IEEE, pp. 1-5, doi: <https://doi.org/10.1109/TENCON.2015.7373096>.
- [5] L. McCurlie, M. Preindl, P. Malysz, and A. Emadi, "Simplified control for redistributive balancing systems using bidirectional flyback converters," in *2015 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2015: IEEE, pp. 1-6, doi: <https://doi.org/10.1109/ITEC.2015.7165817>.
- [6] A. F. Moghaddam and A. Van den Bossche, "Flyback converter balancing technique for lithium based batteries," in *2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAS)*, 2019: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/MOCAS.2019.8741893>.
- [7] C.-C. Hua and Y.-H. Fang, "Design of a charge equalizer based on multi-winding transformer," in *2014 International Conference on Information Science, Electronics and Electrical Engineering*, 2014, vol. 1: IEEE, pp. 446-449, doi: <https://doi.org/10.1109/InfoSEEE.2014.6948150>.
- [8] J.-W. Kim, J.-W. Shin, and J.-I. Ha, "Cell balancing control using adjusted filters in flyback converter with single switch," in *2013 IEEE Energy Conversion Congress and Exposition*, 2013: IEEE, pp. 287-291, doi: <https://doi.org/10.1109/ECCE.2013.6646713>.
- [9] J.-W. Kim and J.-I. Ha, "Cell balancing control of single switch flyback converter using generalized filters," in *2014 IEEE Applied Power Electronics Conference and Exposition-APEC 2014*, 2014: IEEE, pp. 3273-3277, doi: <https://doi.org/10.1109/APEC.2014.6803775>.
- [10] Y. Shang, B. Xia, C. Zhang, N. Cui, J. Yang, and C. C. Mi, "An automatic equalizer based on forward-flyback converter for series-connected battery strings," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5380-5391, 2017, doi: <https://doi.org/10.1109/TIE.2017.2674617>.
- [11] X. Wei, X. Zhao, and H. Dai, "The application of flyback DC/DC converter in Li-ion batteries active balancing," in *2009 IEEE Vehicle Power and Propulsion Conference*, 2009: IEEE, pp. 1654-1656.
- [12] Z. Zhang, H. Gui, D.-J. Gu, Y. Yang, and X. Ren, "A hierarchical active balancing architecture for lithium-ion batteries," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2757-2768, 2016, doi: <https://doi.org/10.1109/TPEL.2016.2575844>.
- [13] B. L. Alvarez, S. V. García, and C. F. Ramis, "Developing an active balancing model and its battery management system platform for lithium ion batteries," in *2013 IEEE International Symposium on Industrial Electronics*, 2013: IEEE, pp. 1-5, doi: <https://doi.org/10.1109/ISIE.2013.6563771>.
- [14] D. Arnaudov, K. Kishkin, and V. Dimitrov, "An algorithm and circuits for active balancing systems," in *2020 21st International Symposium on Electrical Apparatus & Technologies (SIELA)*, 2020: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/SIELA49118.2020.9167066>.
- [15] A. M. Imtiaz and F. H. Khan, "'Time shared flyback converter' based regenerative cell balancing technique for series connected Li-ion battery strings," *IEEE Transactions on power Electronics*, vol. 28, no. 12, pp. 5960-5975, 2013, doi: <https://doi.org/10.1109/TPEL.2013.2257861>.
- [16] Y.-F. Lin, Y.-C. Hsieh, J.-m. Wang, J.-Y. Lin, H.-J. Chiu, and K.-C. Lin, "Modular battery balancing circuit based on bidirectional flyback converter," in *2016 Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, 2016: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/ACEPT.2016.7811543>.
- [17] J.-W. Shin, G.-S. Seo, C.-Y. Chun, and B.-H. Cho, "Selective flyback balancing circuit with improved balancing speed for series connected

- lithium-ion batteries," in The 2010 International Power Electronics Conference-ECCE ASIA-, 2010: IEEE, pp. 1180-1184, doi: <https://doi.org/10.1109/IPEC.2010.5543502>.
- [18] W. C. Lee, D. Drury, and P. Mellor, "Comparison of passive cell balancing and active cell balancing for automotive batteries," in 2011 IEEE Vehicle Power and Propulsion Conference, 2011: IEEE, pp. 1-7, doi: <https://doi.org/10.1109/VPPC.2011.6043108>.
- [19] S.-L. Wu, H.-C. Chen, and C.-H. Chien, "A novel active cell balancing circuit and charging strategy in lithium battery pack," *Energies*, vol. 12, no. 23, p. 4473, 2019, doi: <https://doi.org/10.3390/en12234473>.
- [20] Y.-L. Lee, C.-H. Lin, and S.-J. Yang, "Power loss analysis and a control strategy of an active cell balancing system based on a bidirectional flyback converter," *Applied Sciences*, vol. 10, no. 12, p. 4380, 2020, doi: <https://doi.org/10.3390/app10124380>.
- [21] T. A. Abdul-Jabbar, A. A. Obed, and A. J. Abid, "Design of an Uninterrupted Power Supply with Li-Ion Battery Pack: A Proposal for a Cost-Efficient Design with High Protection Features," *Journal of Techniques*, vol. 3, no. 2, pp. 1-10, 2021.
- [22] M. D. Beirão, A. C. Maria do Rosário, J. A. Pombo, and S. J. Mariano, "Balancing management system for improving Li-ion batteries capacity usage and lifespan," in 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), 2016: IEEE, pp. 1-6, doi: <https://doi.org/10.1109/EEEIC.2016.7555532>.
- [23] D. D. Stefanov, T. P. Todorova, and V. C. Valchev, "A flyback converter based system for an active charge balancing of Li-Ion battery packs," in 2018 IEEE XXVII International Scientific Conference Electronics-ET, 2018: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/ET.2018.8549663>.
- [24] X. Guo, J. Geng, Z. Liu, X. Xu, and W. Cao, "A Flyback Converter-Based Hybrid Balancing Method for Series-Connected Battery Pack in Electric Vehicles," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 7, pp. 6626-6635, 2021, doi: <https://doi.org/10.1109/TVT.2021.3087320>.
- [25] H. Xiong, D. Song, F. Shi, Y. Wei, and L. Jinzhen, "Novel voltage equalisation circuit of the lithium battery pack based on bidirectional flyback converter," *IET Power Electronics*, vol. 13, no. 11, pp. 2194-2200, 2020.
- [26] J. Sachin and G. Anitha, "Constant and Green Mode Operation Technique in Flyback and Push-Pull DC-DC Converter," doi: <https://doi.org/10.22214/ijraset.2022.42861>.
- [27] S. Zhang, X. Guo, X. Dou, and X. Zhang, "A data-driven coulomb counting method for state of charge calibration and estimation of lithium-ion battery," *Sustainable Energy Technologies and Assessments*, vol. 40, p. 100752, 2020 <https://doi.org/10.1016/j.seta.2020.100752>.
- [28] Z. Cui, L. Wang, Q. Li, and K. Wang, "A comprehensive review on the state of charge estimation for lithium-ion battery based on neural network," *International Journal of Energy Research*, vol. 46, no. 5, pp. 5423-5440, 2022.
- [29] P. Shrivastava, T. K. Soon, M. Y. I. B. Idris, and S. Mekhilef, "Overview of model-based online state-of-charge estimation using Kalman filter family for lithium-ion batteries," *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109233, 2019.