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ORIGINAL RESEARCH

Investigation of active cell balancing performance for series connected lithium-ion cells in electric vehicle applications

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Abstract

Lithium-ion batteries have a very wide application range. They can power up small electronic devices such as smart watches to larger electric vehicles. Due to its varied range of applications, they come in different packaging and in such battery packs, even when individual cell voltage exceeds by a few milli-volts above 4.2 V, it may result in thermal runaway and explode the cell. During discharge cycle, cell imbalances hinder the use of battery to its full capacity. This in turn decreases the battery lifetime. The individual battery cells should be equalized on a regular basis to keep the imbalances to a minimum and to have a good battery life. The process of balancing the individual cell charges by measuring the cell state of charge (SoC) and its voltage in a battery pack is known as cell balancing. This paper details an active cell balancing technique that uses a buck converter for balancing a series connected battery pack of lithium-ion cells. A buck converter along with a pair of MOSFET switches for each cell, one turned on for charging the cell and the other one turned on while discharging the cell is used in this experiment. An algorithmic model suitable for reconfigurable battery systems that measures the individual cell voltages and is developed for balancing a pack of series connected Li-ion battery cells. The developed model is simulated using MATLAB for verifying its performance. A state of charge of 25% is maintained across the cells and when SoC value drops below this even a difference of 0.02% is sensed by the algorithm to initiate balancing function. This balancing is found to take 275 ms to balance three 3.7 V batteries and thus the model is found to respond faster. The results show that this method can self-adaptively attain satisfactory performance within a limited equalizing period.

1 | INTRODUCTION

As the whole world has started moving toward "Green Technologies" with the aim of reducing global warming, almost every country is insisting the development and use of electric powered vehicles. And when electric vehicles are talked about, the backbone of such a vehicle will be its battery. This states the importance of research and development in the field of battery design and management. Battery management system (BMS) ensures safety of the battery pack by continuous monitoring, controlling and regulating the energy storage and transfer in electric vehicles. A BMS will collect information from sensors in the battery, controlling the charger to ensure proper charge of the battery, managing cell balance, safety control to avoid overcharge or over discharge or other major anomalies, reporting battery state, thermal conditions of the battery, communication with the vehicle and data transfer to a computer. Considering the monitor and control of the battery charging and discharging, BMS charges a cell based on its state of the charge and discharges cell based on demand and charge available in the cell. Similarly, battery life degradation can be reduced by monitoring the cell voltages of individual battery cells and keeping them as constant. BMS has a dedicated cell balancing unit. The temperature is also monitored and controlled by the BMS. In any multi-cell battery chain, there are no two cells that are identical, meaning that there are always at least slight differences

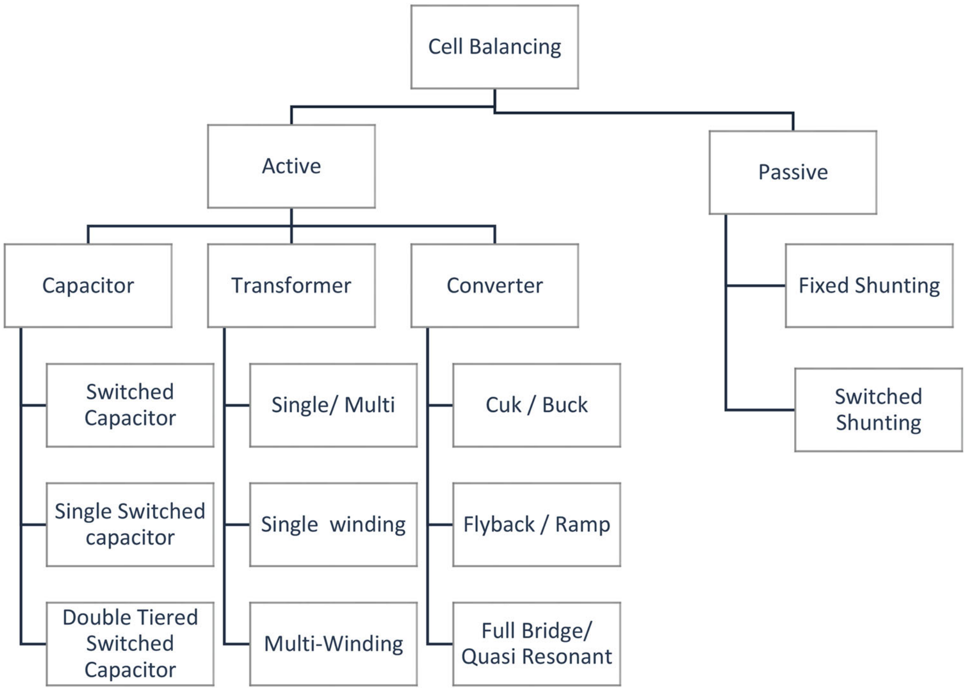


FIGURE 1 Classification of cell balancing.

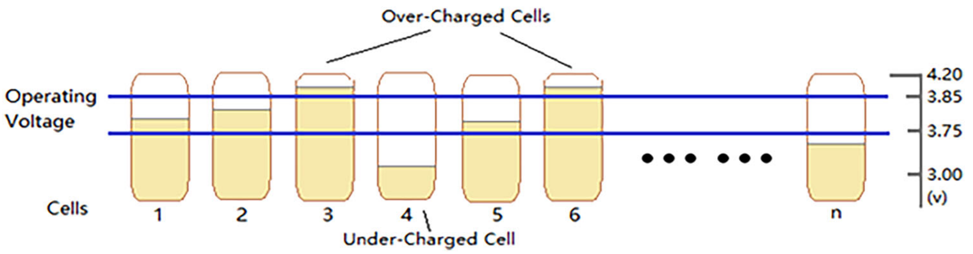


FIGURE 2 Charge imbalance.

in the properties such as self-discharge, capacity, state of charge, impedance and temperature characteristics. Also, when a multi-rank pack protection integrated circuit (IC) is used, its unequal draining may cause imbalance in the cells which may lead to degradation of battery life. With this said, reconfigurable battery systems capable of configuring itself as per the need for optimal performance is the topic most researched at present and this paper discusses an active cell balancing topology based on algorithmic model that is capable of reconfiguring itself as per the state of charge (SoC) of individual cells in the battery pack.

Cell Balancing is used for equalizing the voltage and state of charge (SoC) of battery cells in a pack and passive and active cell balancing are its types. Passive cell balancing uses some dissipative element to remove the excess charges from the high charged cells. Active cell balancing uses some power electronic switches along with inductors and capacitors to transfer charges between cells in order to make them equalized. There are lots of cell balancing techniques available and they are listed in Figure 1.

Xu in [1] proposed a simple yet efficient battery balancing strategy based on SoC of the battery pack. Here discharging is delayed when the SoC is low and it is advanced when SoC is high with the objective of attaining a balanced battery system. As a new method of finding the faulty cell in a battery pack, [2] uses the power electronic devices in cell balancing circuit to find faulty cells. In order to achieve quick balancing of battery pack a control algorithm is used to select a single gating device to gate energy between high and low voltage cells in [3]. A detailed study of the battery management system and its requirements in the case of a Li-ion battery is given in [4]. A review of the passive and active cell balancing techniques is explained and it is revealed that a hybrid technique will help achieve better balancing [5]. A prediction algorithm based on outlier distance is used to predict the unbalanced cell which is then balanced by a bleeding circuit in [6]. A comparison of the existing active and passive cell balancing techniques is carried out and active balancing is found to give better performance in the case of Li battery in [7]. A review of active and passive balancing is done in [8] and it is found that passive balancing techniques are cost effective and simple as compared to active balancing techniques which are efficient with higher cost and complex design.

A simple yet effective way of computing the cell imbalance is done in [9] where the difference in open circuit voltage is

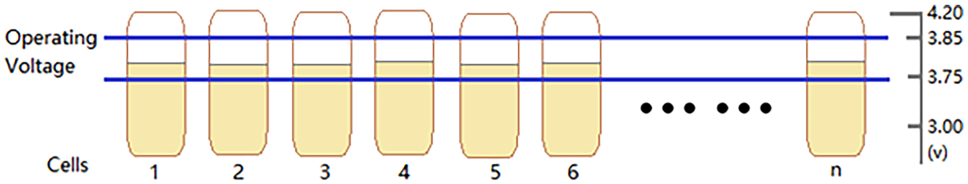


FIGURE 3 Charge equalized after cell balancing.

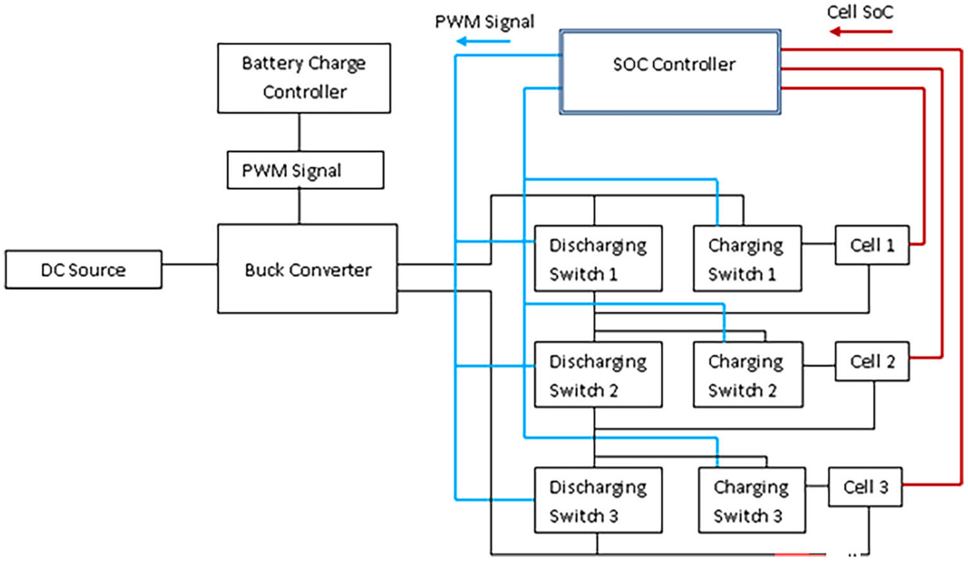


FIGURE 4 Proposed buck converter and state of charge controller-based cell balancing system block diagram.

converted to represent the SoC of the cell. In [10], a framework is developed to model the state and parameter differences between cells in a battery pack induced due to manufacturing and environmental conditions. And this model in turn is used to achieve cell balancing. The merits and demerits of various cell balancing techniques say active and passive techniques are verified experimentally in [11]. A model predictive control algorithm is used to predict the life time of a battery for different active cell balancing techniques and results reveal that a 10% increase in battery life can be achieved by using proper balancing method [12]. A review and simulation of passive cell balancing techniques is done in [13]. Inductor based switching and current mode controller for switching control is explained in [14].

A cell balancing technique for the case of medical devices is studied and an effective DC–DC converter-based design is explained in [15]. Different battery management systems are reviewed and their corresponding performance parameters are studied in [16]. A review of the different SoC estimations for Li-ion battery is done in [17]. In [18], the shortest path between cells is found to improve its efficiency using a Switched Capacitor Structure in closed loop. This method of cell balancing is found to be economical. Two different balancing strategies each for the charging and discharging of the batteries is proposed in reference [19] and the results show that the such a balancing helps in reducing the inconsistencies and improves the battery capacity. A cell balancing method that uses a resonant LC circuit, converter, pulse width modulation (PWM) switching circuit are used with parallel battery packs for balancing their charging and discharging in [20]. A method of cell balancing that pacifies the impact of temperature on the cell is checked in [21]. In [22] active cell monitoring is done using a transformer switching. A machine learning based battery management system with a DC converter is found to produce good efficiency in balancing batteries in parallel with an error of 1.15% [23].

A comprehensive review of the active and passive cell balancing is explained in paper [24]. Lei et al. in [25] proposes a non-dissipative equalization method to balance the cell charging and discharging. An In-cell thermal monitoring to study the temperature profile is proposed in [26]. In [27], an adaptive balancing control method is proposed in the review and its charging and discharging modes are studied. A hybrid converter circuits that uses a fly back converter for charging and buck converter for discharging is proposed for cell balancing in [28]. As Passive cell balancing methods are the low-cost methods, it is implemented by making use of machine learning based algorithm to select the appropriate balancing resistor value based on various factors and the resulting system is evaluated using a number of back propagation techniques [29]. As far as cell balancing by bidirectional flyback converters are considered [30], the primary drawbacks are the switching losses associated with the large number of switches used and the reduced efficiency. But for low cost and low power application flyback converter's

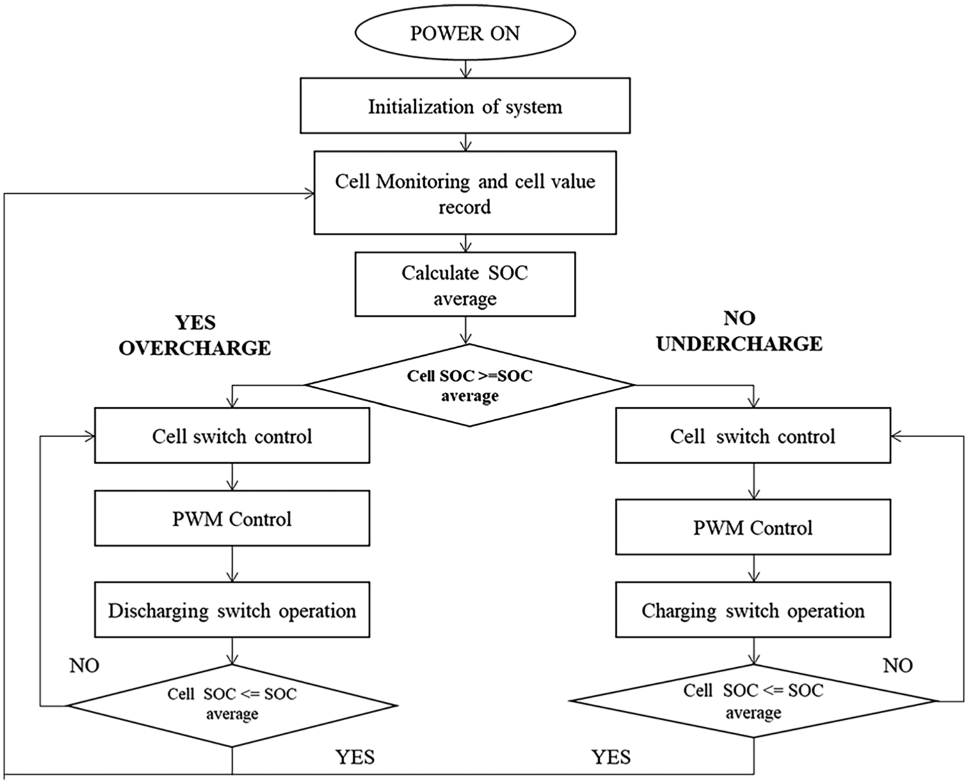


FIGURE 5 Flowchart of the process.

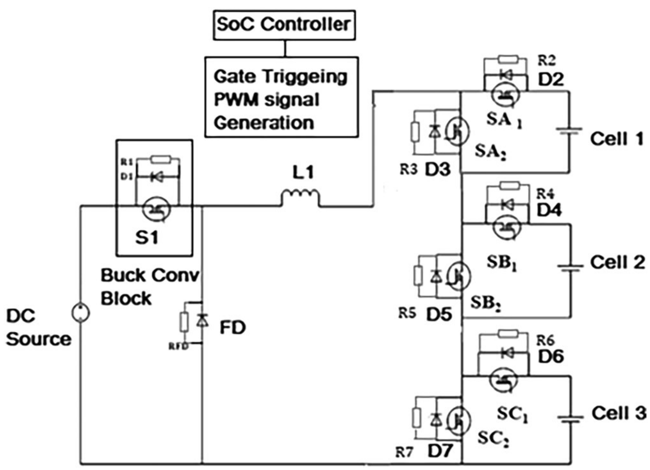


FIGURE 6 Proposed circuit model.

efficiency can be improved when used with a lossless snubber and transformer [31].

The requirement of large capacitors for cell balancing while using a combination of buk-boost converter and cuk converter is explained in paper [32]. Such larger capacitors also lead to larger charging and discharging currents that requires high-current tolerant switches for switching which are costlier. A high voltage stress which leads to high electrical weights on switches and diodes is the main drawback of using a bidirectional Cuk converter in balancing operation [33]. Mohamed et al., in [34], explains a switched capacitor method for battery equalization. It is found that the charge equalization takes low equalization time and requires huge number of switches. Whereas in [35], Markus Einhorn, explains the use of a multi-winding transformer for active cell balancing in Electric Vehicles and found that the multi-winding requires complex control and use a greater number of cells. A fuzzy based control for cell balancing is explained in [36]. In [37], Chol-Ho Kim et al., says that it requires more equalization time an accurate voltage sensing for a fly-back converter to work. In [38], Maharjan proposed a full bridge cascade pulse width modulation (PWM) Converter and found that it requires a high-cost intelligent control. In [39], Hong et al., proposed a buck boost converter-based charge equalization. The deterrents to the design and use of different converter-based cell balancing models is described in the following subsection.

1.1 | Charge imbalance—Causes and balancing methods

The major causes for cell imbalances in lithium-ion batteries are twofold, they are: (i) charge imbalances caused by manufacturing inequalities and (ii) cell Charge imbalances caused by repeated charging cycles. Such imbalances are intolerant towards over charge which leads to explosion of battery and over discharge which may result in reducing battery's lifetime Thus cell balancing has to be done in two different phases say (i) charging phase and (ii) discharging phase of the battery. While charging,

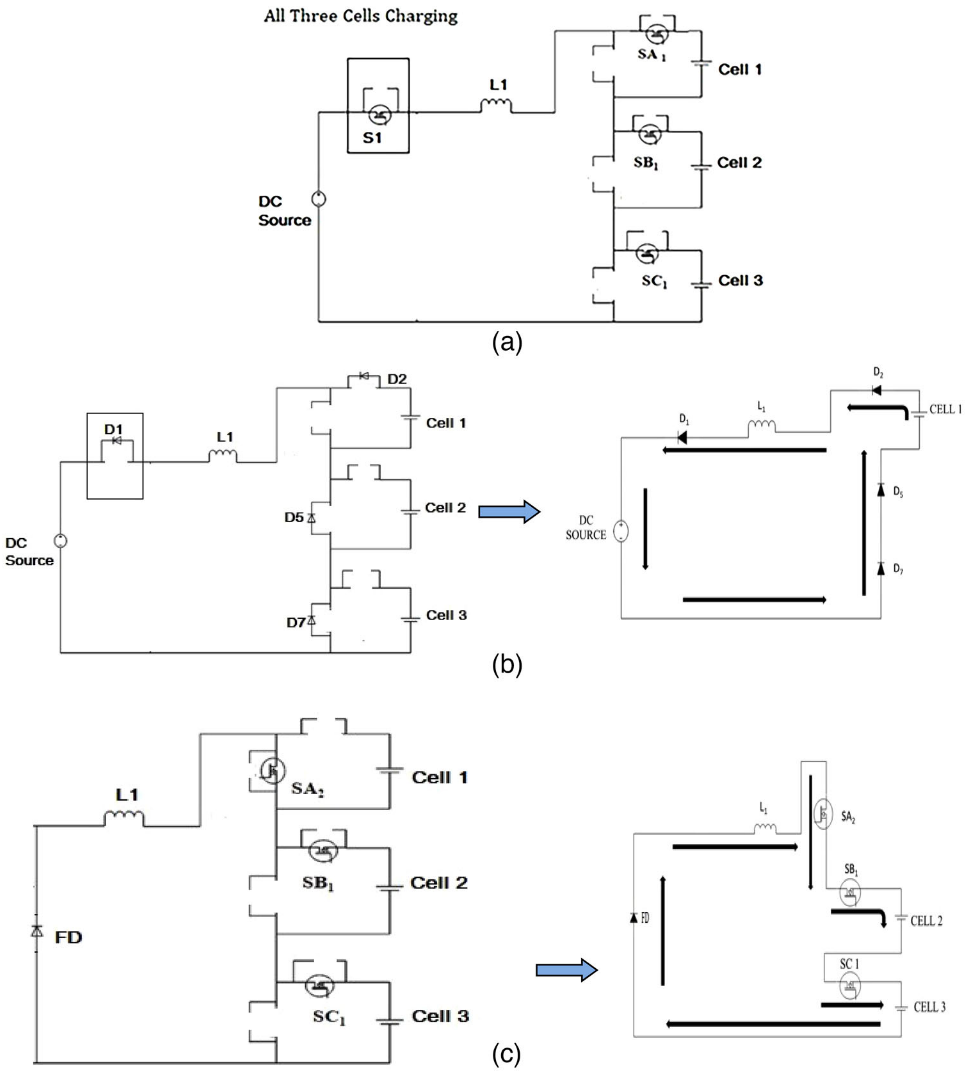


FIGURE 7 (a) Operation of the proposed circuit when all the three cells are charging from direct current source (b) Operation of the proposed circuit in Step I depicting the current flow path and conducting elements, (c) Operation of the proposed circuit in Step II depicting the current flow path and conducting elements.

the battery compares the individual cell voltages with the voltage regulation point to stop further charging.

Hence weak cells are slightly over charged but stronger cells are slightly under charged as depicted in Figure 2. This makes the degradation faster in weaker cells and thus the battery pack also experiences it. During discharge cycle, the weaker cell is discharged quickly whereas the stronger ones are still having some charge in them. Hence, again weaker cells face degradation due to over discharge. These issues can be rectified by using a proper cell balancing method which helps improve battery life and its safety.

The SoC is estimated by measuring the current, voltage and temperature of the individual cells and from which the imbalances are detected by the cell equalization. Cell balancing is achieved by transferring the required charge to the undercharged cell either from the most charged cell or from any adjacent cell with the aim of equalizing the voltage or charge below the threshold operating point. Figure 3 shows the cell balancing and equalization for N-cells of a battery pack. The major merit of cell balancing and equalization is to enhance the efficiency and lifetime of battery and to protect the same. Cell monitoring and charge equalization along with other similar control are the parts of the battery management system.

2 | SYSTEM DESIGN

2.1 | Block diagram of the proposed system

The proposed system can be broadly classified as (i) the buck converter block (ii) SoC controller block and (iii) solid state switch array block. The DC source is connected to the battery cells through a Buck converter. A Battery charge controller will take the current feedback from the buck converter and the feedback signal is filtered and then given to the Proportional Integral

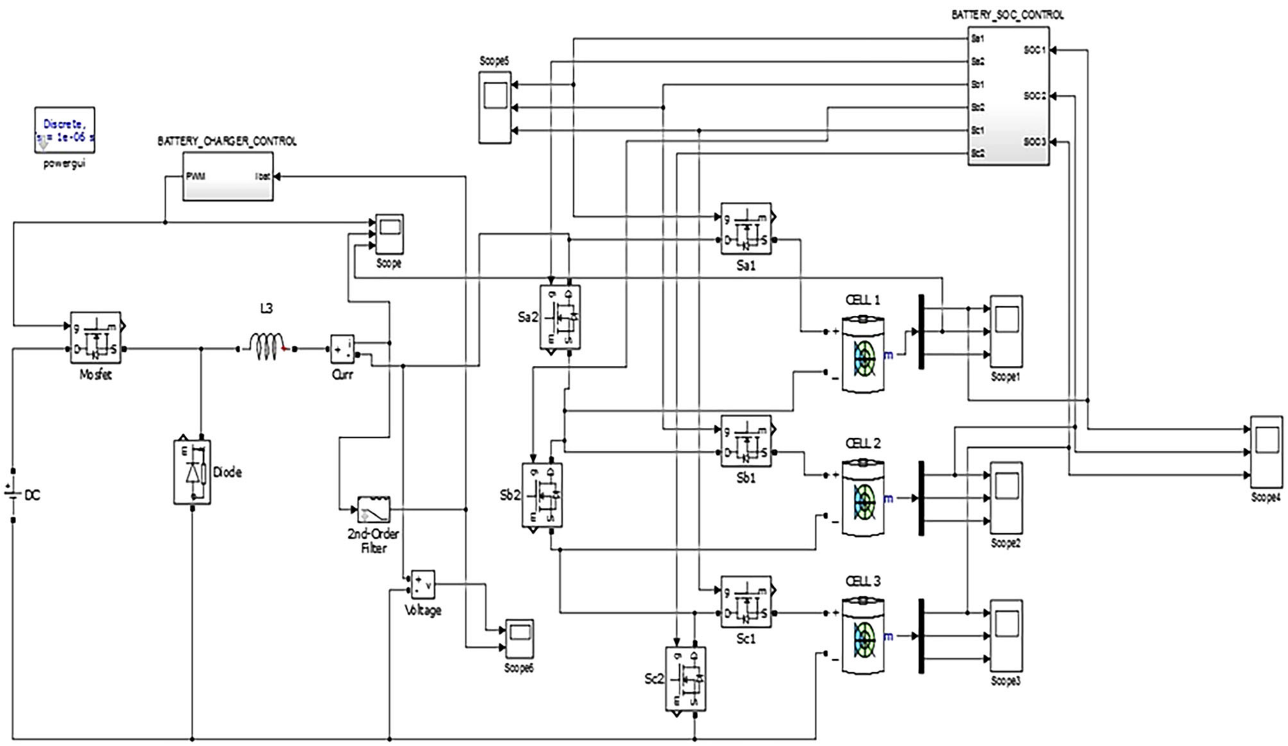


FIGURE 8 Simulink simulation of proposed system .

TABLE 1 Condition I: All three cells have low State of Charge (SoC).

Cell	Condition	V_{DC}	Cell 1 current	Cell 2 current	Cell 3 current
1	LOW	17 V	−1.4 A	−1.4 A	−1.4 A
2	LOW				
3	LOW				

TABLE 2 Condition II: Cell 1 State of charge (SoC) is kept HIGH, and the cells 2, 3 State of charge (SoC) are kept LOW.

Cell	Condition	V_{DC}	Cell 1 current	Cell 2 current	Cell 3 current
1	HIGH	11 V	2.6 A		
2	LOW			−1.2 A	
3	LOW				−1.2 A

TABLE 3 Condition III: State of charge (SoC) of cells 1 and 3 are kept HIGH, and that of Cell 2 State of charge (SoC) is kept LOW.

Cell	Condition	V_{DC}	Cell 1 current	Cell 2 current	Cell 3 current
1	HIGH	5.1 V	2.6 A		
2	LOW			−1.6 A	
3	HIGH				2.6 A

(PI) controller that produces the pulse width modulated signal which is a function of the current feedback from the buck controller. This PWM signal will controls buck converter switches to gate the input DC source to individual cells through charging and discharging switches.

The SoC controller block is the additional block introduced in the proposed system is an algorithmic controller that selects the unbalanced cell from the pack based on the individual voltage levels and controls the cell switching to gate the signal from buck converter. If the individual cell SoC is greater than the SoC average then the discharging switch will be provided with high pulse to conduct the switch. The inverted output of the discharging switch will be given to the charging switch. The solid-state switch array is responsible for charging and discharging of individual cells and this is controlled by a pair of bi-directional switches along with the buck converter as in Figure 4.

The proposed scheme picks up the undercharged cell and transfers charge from the other overcharged cells in the battery pack. This is made possible by the SoC controller along with the bi-directional switches. The input to the SoC controller is the SoC of the individual cells. The SoC controller uses an equalization algorithm that compares the individual cell SoCs and compares them with the average SoC of all the cells to produces two output signals that are complements of each other. Output 1 controls the charging network and output 2 controls the discharging network. As the two set of outputs are complements of each other the overcharged cells will be triggered to discharge its excess charge whereas the under charged cells will be gated for charging. Thus, charge flows from overcharged cell to undercharged cell via the bi-directional switches.

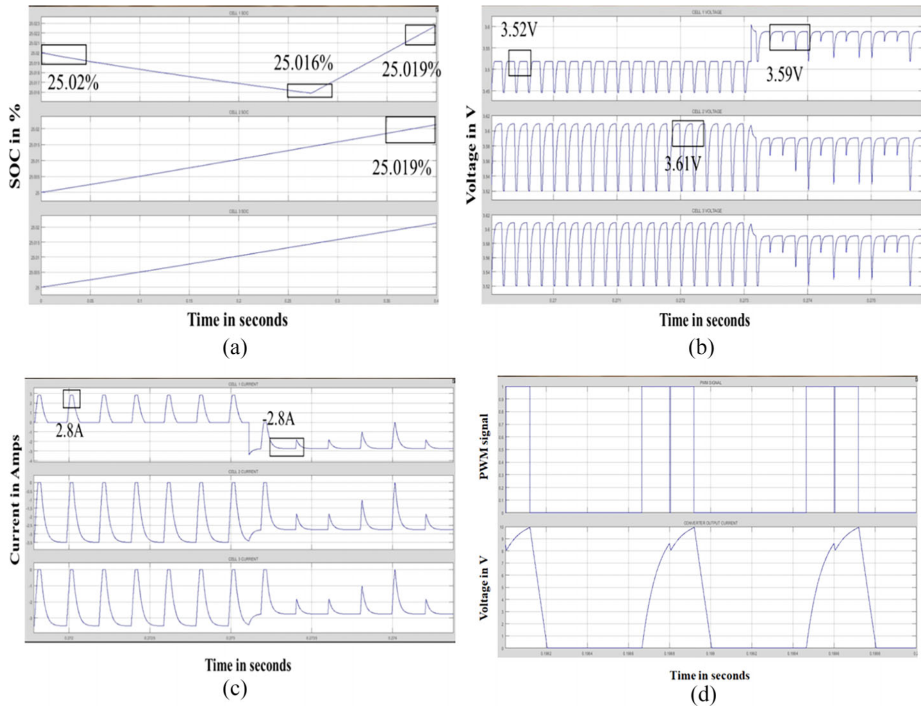


FIGURE 9 (a) State of charge (SoC) of three cells, (b) voltage comparison of three cells, (c) current comparison of three cells, (d) pulse width modulation (PWM) signal and converter voltage.

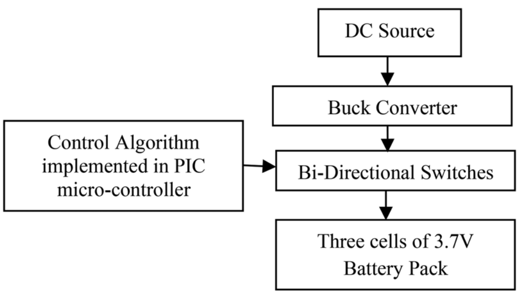


FIGURE 10 Blocks in the hardware prototype.

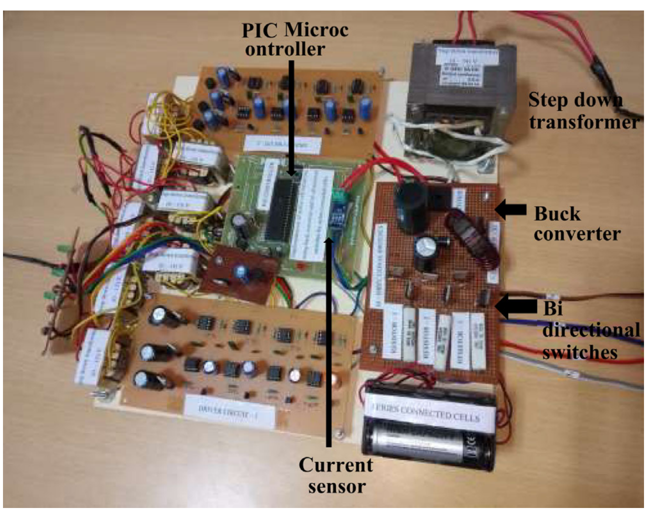


FIGURE 11 Hardware prototype.

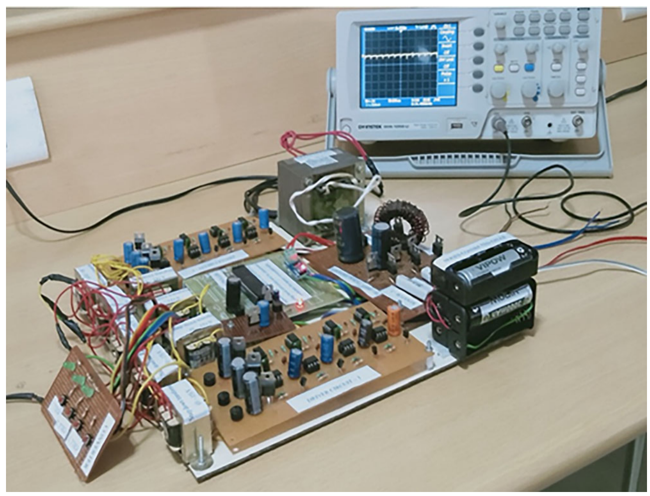


FIGURE 12 Prototype under working condition.

2.2 | SoC equalization algorithm

Determining the SoC of a battery accurately is the factor that decides the effectiveness of any cell balancing model [40] and thus this paper utilizes linear model for SoC prediction [41]. This prediction method works based on the reference SoCs and present battery states. The present SoC value is predicted from input current I_i, output current I_o, output voltage V_o of each cell at present and reference SoC values from available data using Equations (1) and (2). The cells that are overcharged and under-charged are found by comparing the predicted SoC values with

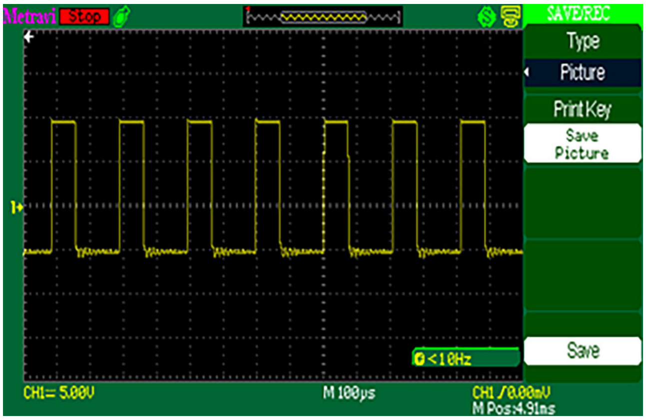


FIGURE 13 Buck converter switch gate pulse.

the allowed deviation S_d. Here, β, is found from the previous reference values by least square method, $S(i)$, is the present State of Charge, $\Delta S(i)$, is the difference in SoC, $V(i)$ represents the voltage and $I(i)$ represents the current at the present state.

$$\Delta S_o(i) = \beta_0 + \beta_1 V_o(i) + \beta_2 I_o(i) + \beta_3 S_o(i-1) \quad (1)$$

$$S_o(i) = S_o(i-1) + \Delta S_o(i) \quad (2)$$

An array of parameter values is generated for every individual sample. The input current is given by Matrix I_i whereas the different output parameters are represented by matrices S_o, V_o, I_o and the deviation of SoC from allowed value S_d is found. Thus, the SoCs computed by this linear model are compared to achieve cell balancing between the battery cells. Figure 5 shows the flowchart for the charge equalization algorithm used for generating the complementary PWM signal for gating the charging and discharging bi-directional switches in the array.

In this model, a Peripheral Interface Controller, PIC microcontroller is chosen to hold the SoC based Control algorithm that generates the PWM signal to gate the solid-state devices that control the charging and discharging of the various Cells in the battery pack. The algorithmic controller compares the individual cell SoC with the SoC average. If an individual cell SoC is greater than average then the discharging switch of that particular cell should be triggered ON and its charging switch should be turned OFF. Similarly, if SoC is not higher then, those cells should be turned ON for charging by triggering the charging switches and closing the discharging switches. Thus, the SoC controller generates the appropriate PWM signals to gate the charging and discharging network of bi-directional switches and connects the cells with the source in a balanced fashion.

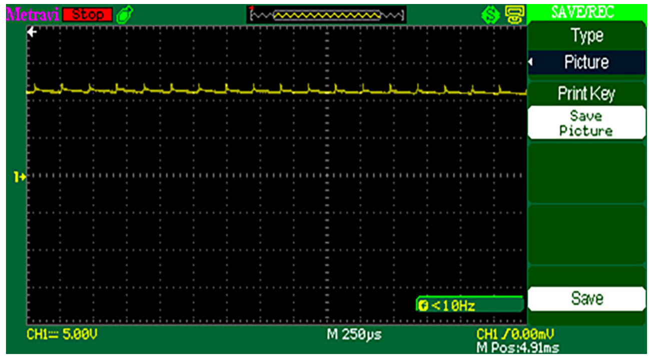
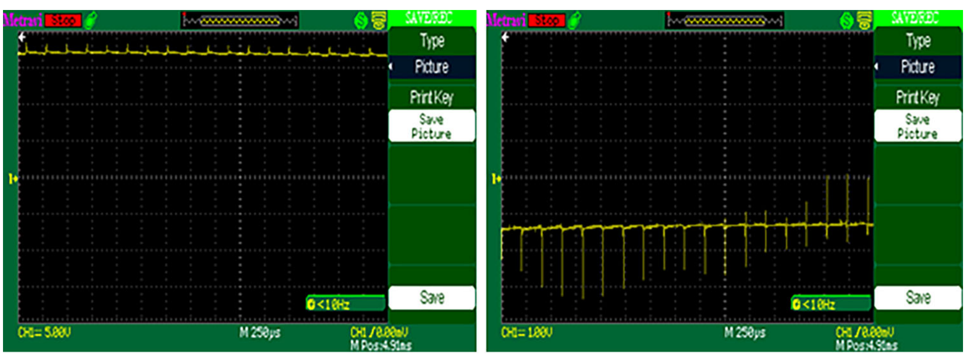


FIGURE 15 Output voltage of the buck converter.

2.3 | Circuit diagram of the proposed model

The circuit diagram of the proposed model is shown in Figure 6. The model uses a buck converter block represented by S1 and D1 along with inductor L1 and free-wheeling diode FD, constitute the conventional cell balancing circuit. The proposed cell balancing switch array consists of six switching blocks each made from a power switch S and diode D pair. SA1, SA2 along with D2, D3 form the charging and discharging block switches for cell1 respectively. Similarly, SB1, SB2 with D4, D5 and SC1, SC2 with D6, D7 form the block switches for cell 2 and cell 3 respectively. The SoC controller communicates regularly with the cells, switches and the buck converter and sends switch control signals accordingly. This control signal confirms the electrical path between the buck converter and the cells. (Figure 7, 8, Table 1, 2 and 3)

The Current flow path when all the cells are charging from source is (DC source – S1 –L1 – SA1 – Cell 1 – SB1 – Cell 2



(a) (b)

FIGURE 14 (a) Output voltage of the buck converter, (b) current across the shunt resistors.

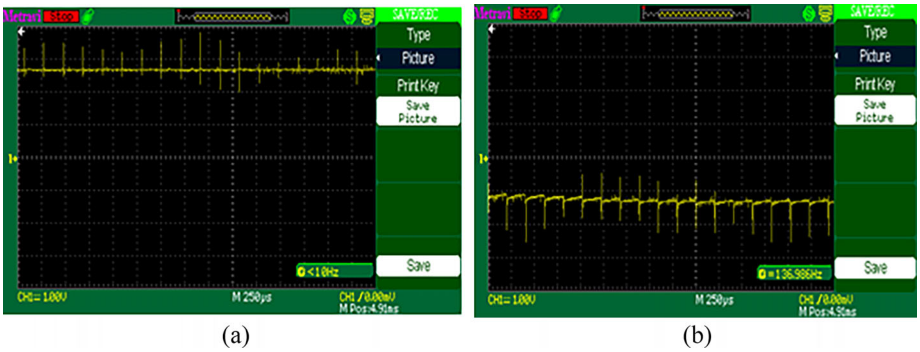


FIGURE 16 (a) Current across the shunt resistor 1, (b) current across the shunt resistors 2 and 3.

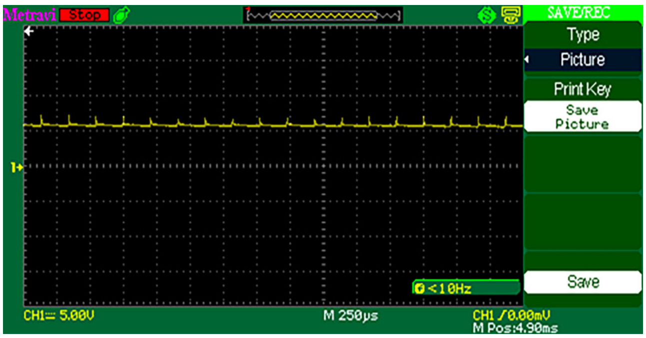


FIGURE 17 Output voltage of the buck converter.

– SC1 – Cell 3 – DC source) as shown in Figure-7a. In this mode, all the three cells are charging from the source. Now, an imbalance is introduced by making SoC of Cell 1 high and keeping SoC of Cell 2 and Cell 3 low. Under this experimental condition, excess charge in Cell 1 is discharged to Cell 2 and Cell 3 in two steps. And this is explained in the Step I (Figure-7b) and Step II (Figure-7c) and the current flow in each case is explained below.

2.4 | STEP I

Assume cell 1 is higher energy charged compared to other cells, to equalize this, the below mentioned process will takes place. The buck converter switch S1 is in off condition. The inductor energy stored during the switch S1 on condition is lower than the Cell 1 energy. Cell 1 energy charges the inductor via D2. The current flow path is (Cell 1 – D2 – L1 – D1 – DC source – D7 –D5 – Cell 1). Here, the cell 1 alone is connected to the path thus discharging of Cell 1 takes place. Once the inductor L1 is energized more than the Cell 1 charge the step II process will take place.

2.5 | STEP II

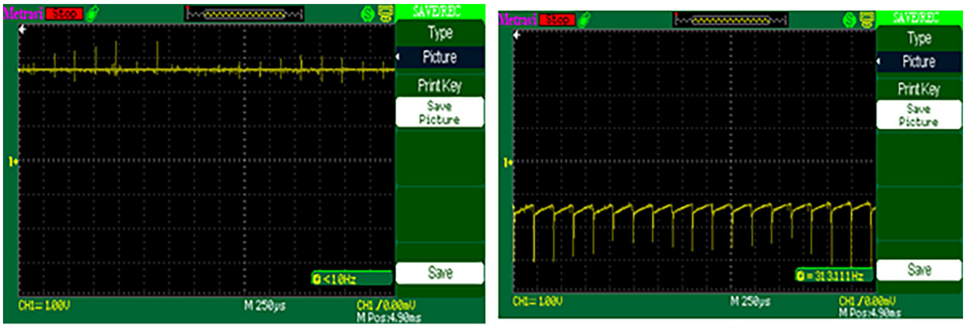
In step II operation, the buck converter switch S1 is in off condition and the inductor energy is higher than the energy of the cell then the inductor L1 will be discharged to the cells 2 and 3 through the conduction of the discharging switch SA2 and the charging switches SB1 and SC1. Cell 1 is cut-off from charging and only cells 2 and 3 are charging from the stored inductor energy through SA2 switch. The current flow path is (L1 – SA2 - SB1 – Cell 2 - SC1 - Cell3 - FD – L1). Respectively, all other cells are maintaining the balanced cell charging through the control process by switching ON and OFF the switches.

3 | RESULTS AND DISCUSSION

The proposed model simulink diagram is shown in Figure-8. The parameters such as cells SoC Comparison, Cells Current Comparison, and Cells Voltage Comparison for the proposed cell balancing model are depicted in the below figures. In addition, the PWM signal and the converter voltage are also studied. Figure 9a depicts the comparison of SoC of three cells. Initially, SoC of cell 1 is assumed as 25.02% and that of cells 2 and 3 are kept at 25% SoC level. As the SoC of cell1 is higher than the other two cells, cell1 starts discharging and the other two cells tend to charge. It is inferred from the results that even a small SoC difference of 0.02% is sensed by the proposed model and it starts to balance the cells. It is seen that the cell1 discharges up to 0.016% SoC after which it starts charging which reveals its sensitivity. These three cells will have a maximum SoC difference of 0.016% only and not more than that. The variations in the voltage and current during the discharging and charging phases are given by Figures 9b and 9c respectively. During the discharging phase, cell1 voltage reduces and its current is rising in positive axis whereas when charging begins voltage raises and its current reverses to negative axis which is clearly depicted by Figure 9b,c. Figure 9d shows the PWM signal which is given to the buck converter by the charge controller and the voltage generated by the buck converter.

4 | HARDWARE SETUP

The hardware prototype is developed based on the requirements and the same is as shown in Figure-11. The Figure-12 shows the developed prototype model in working condition and 1the blocks that constitute the hardware model are shown in Figure-10.



(a) (b)

FIGURE 18 (a) Current across the shunt resistors 1 and 3, (b) current across the shunt resistor 2.

TABLE 4 Comparison of the three states.

Condition	SoC high	SoC low	V_{DC}	Cell 1	Cell 2	Cell 3
I	–	C1, C2, C3	17 V	Charging	Charging	Charging
II	C1	C2, C3	11 V	Discharging	Charging	Charging
III	C1, C3	C2	5.1 V	Discharging	Charging	Discharging

The prototype has three 3.7 V, 3 Ah lithium-ion cells that constitute the battery pack. The output voltage of the Buck converter will be 12 V.

5 | HARDWARE RESULTS

5.1 | Buck converter gating pulse

The gating signal to the MOSFET switch of the buck converter as generated by the PIC controller is shown in the Figure 13. The magnitude and time period of the gating signals are 5 V and 100 ms respectively.

The efficiency of the cell balancing model is found by conducting the experiment under three different operating conditions and studying the results and the same is explained below:

The Table-1 shows the parameters of all the three cells have LOW state of charge. Figures 14a and 14b reveals the buck converter voltage V_{DC}, along with the current across the shunt resistors during condition I respectively. The buck converter voltage V_{DC} will be high having 17 V with a time period of 250 μs and the current across each shunt resistor will be of magnitude −1.4 A and time period 250 μs. Here, 1 ohm resistor shunt is used across the three cells therefore the voltage across the shunt resistors will be directly proportional to the current through the resistors.

The Table-02 shows the parameters of Cell-01 state of charge is kept HIGH, and the Cell 2, Cell 3 state of charge are kept in LOW condition. The converter voltage V_{DC} under condition II is 11 V in magnitude and this is revealed in Figure 15. As there are only two cells charging from the DC source the voltage drops to 11 V by the very nature of buck converter. Because of higher SoC, the current through Cell1 will be raising whereas that of cells 2 and 3 will be drooping. From Figure 16a,b it is found that the current through cell 1 is 2.6 A and that through cells 2 and 3 is −1.2 A. As SoC is high in cell 1 it is discharging and hence its current raises and is positive whereas, the charging cells 2 and 3 shows a negative value of current.

The Table-3 shows the parameters of state of charge of Cell 1 & 3 are kept HIGH, and that of Cell-2 state of charge is kept LOW condition The converter voltage V_{DC} under condition III is 5.1 V in magnitude and this is revealed in Figure 17. As there is only one cell charging from the DC source the voltage drops to 5.1 V by the very nature of buck converter. Because of higher SoC, the current through the cells 1 and 3 were raising whereas that of cell 2 will be drooping. From Figure 18a,b it is found that the current through cells 1 and 3 is 2.6 A and that through cell2 is −1.6 A. As SoC is high in cells 1 and 3, they are discharging and hence their currents raise and are positive whereas, the charging cell 2 shows a negative value of current.

A comparison of all the three modes of operation is depicted in Table 4. And it is clearly seen that cells with a higher SoC discharge to keep the cells balanced. When all the cells have a lower SoC they all charge simultaneously from the source which is revealed from condition I.

6 | CONCLUSION

Cell balancing in Li-ion battery pack of three 3.7 V, 3 Ah, Li cells are established a by buck converter and a linear prediction-based SoC algorithmic controller. The equalizing current and MOSFET control frequency are tuned adaptively by the control algorithm. The efficiency of the proposed method is found from the precision with which it switches the battery from charging and discharging states. Also, Simulink simulation of the proposed active cell balancing method under various initial conditions is carried out. It is clear from the results that the model is efficient, robust than the conventional buck converter-based cell balancing method and the system can adaptively improve its efficiency to achieve optimal performance in a prescribed period of equalization.

A hardware prototype of the proposed design is implemented, and the results depict that the outputs are on par with the simulation results. The proposed model will be tested for robustness by using them in real time environment where accurate SoC estimations are difficult. Due to its simplest design with minimum number of switches and solid-state devices make such converters suitable for use in future Hybrid Electric Vehicles and other battery powered systems. Further, optimization can be achieved by optimizing energy loss associated with other electronic components. Equalizing strategies for multi-cell packs with more individual cells should also be a topic of consideration for future studies.

AUTHOR CONTRIBUTIONS

Umapathi Krishnamoorthy: Writing—review and editing. G. S. Satheesh Kumar: Writing—review and editing. Sourav Barua: Writing—review and editing. Hady H. Fayek: Writing—review and editing

CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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