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Optimized Passive Cell Balancing for Fast Charging in Electric Vehicle

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ABSTRACT

Electric vehicles (EVs) are clean substitutes for conventional vehicles. Battery management system (BMS) is the intelligence behind the EV battery packs. One of the key functions of BMS is cell balancing, which balances the battery cells voltages equally during charging. Most of today's EVs are adopting a passive cell balancing scheme, which uses fixed dissipative resistors to remove the extra charge from the overcharged cell to balance the charge in all the cells equally. One of the main concerns about the passive balancer is the balancing time. The long balancing time is manageable if the vehicle is charged through conventional charging (5–6 h) system and cell imbalance is minimum. Under fast DC charging scenarios as well as maximum imbalance condition, passive balancing with a fixed resistor is not an optimum solution. Either for fresh cell or aged cell, the passive cell balancing with variable balancing resistor is used based on the balancing current requirement under slow or fast charging scenarios are implemented. The passive system with variable resistor outcome is compared using Matlab-Simscape.

KEYWORDS

Battery management system; electric vehicle; fast charging; lithium-ion battery; passive cell balancing; state of charge

1. INTRODUCTION

Electric vehicles (EVs) reduce greenhouse gas emissions which contribute to improve public health, climate change and reducing the damage to the ecological system. Charging EVs using renewable energy such as wind or solar reduces these emissions further down. Present EVs include high power and high energy density lithium-ion batteries [1] and comparatively lithium-ion (Li-ion) batteries require advanced monitoring systems for safe operation. Battery management system (BMS), monitors and controls the EV batteries to protect it from damage [2,3].

Cell balancing is one of the significant features of BMS which helps to distribute the charge among the battery cells equally to attain maximum efficiency [4].

The root causes for the cell imbalance are shown in Figure 1. Undercharged or overcharged cell quickens cell ageing or causes permanent damage to the battery pack. To extend the battery life as well as to increase the energy usage, passive and active balancing systems have been established. In passive balancing, the excess energy from the overcharged cell is removed and dissipated as heat, using resistors. Instead, the active balancing transfer the energy from the overcharged cell to lower charged one [5]. However, it requires a complex control and more expensive hardware. The former one is a commonly preferred method for e-mobility application because of its low cost, easy to implement and simple to control [6].

Many algorithms are proposed in the literature to control the passive balancing process. In the article [7], the MOSFET internal resistance and power resistor are used as a balancing resistor to save space on BMS; however, it takes more time to balance due to the huge difference between the cell voltages. In [8], the author concluded that the Li-polymer battery using the shunt resistor balancing method shows the better performance at 0.1C discharge rate, since it does not alter the battery voltage characteristics significantly. The lesser balancing level affects the battery characteristics less significantly, but it takes more time to reduce the voltage. The fast passive balancing is implemented for four LiFePO4 cells to replace conventional 12 V lead–acid battery of a vehicle in [9]; however, the efficiency of the balancing system is low.

In the article [10], cell balancing is taken place for 8 cell; LiFePo4 battery pack at every charge cycle with different charge currents to reduce the balancing time, but the balancing system needs a precise voltage measurement and controllable charger due to the transition of charge current. The author proposed a balancing algorithm based on the state of charge (SOC) and cell capacity in [11], but

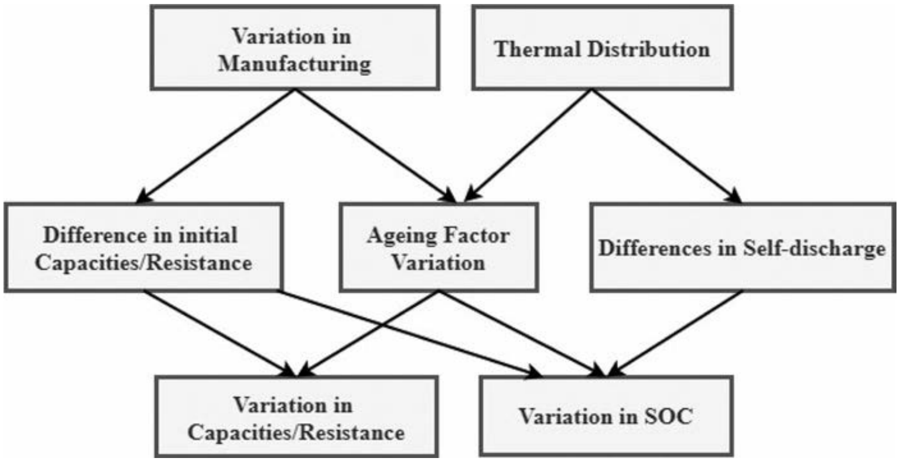

Figure 1: Causes for the cell imbalance [2]

the accurate measurement of the SOC and capacity is a difficult task, needs an advanced BMS.

The passive balancing system used in conventional BMS uses a fixed resistor to dissipate the extra energy from the overcharged cell to balance the cells equally. For a cell voltage of 4.2 V, these systems are handling small balancing currents in the range of 100 mA with balancing resistors in the range of 30–40 Ω. But it takes more time to balance the cells. The fastest cell balancing technique is implemented to reduce the balancing time by increasing the balancing current under fast charging and maximum voltage deviation among cells. In order to achieve this scenario, the resistors in parallel are selected using selection logic, instead of fixed resistors.

Based on the balancing time requirement, the balancing current values are selected. From that, the balancing resistor values and power loss are estimated at different balancing threshold voltage (ΔV). The balancing current of the cell is calculated as follows:

we know that charge

$$Q = I \times t \tag{1}$$

Balancing current (I_B)

$$= \frac{\text{Imbalance voltage (V)} \times \text{Capacity (Ah)}}{\text{Balancing time } (t_B)} \tag{2}$$

$$R_B = \frac{V_C}{I_B} \tag{3}$$

where V_C is a charging voltage and R_B is the balancing resistor

$$\text{Power loss, } P = I_B^2 R_B \tag{4}$$

The major contribution of this work is to improve the passive balancing circuit with the inclusion of switched variable balancing resistor topology, to address the slow balancing issue of the state-of-the-art algorithms. The implemented algorithm keeps the system complexity and costs in low level.

The research work of this paper is composed of four sections. Section 2 explains about the operating principle of conventional passive balancing and proposed passive balancing system based on the control flow algorithm. Balancing simulation outcomes are analyzed in Section 3 followed by the conclusion in Section 4.

2. PASSIVE BALANCING SYSTEM IMPLEMENTATION IN MATLAB-SIMSCAPE

2.1 Battery Model

The simulation modeling is done using the Matlab-Simscape mathematical tool and the battery pack is designed for 12 V, 3.5 Ah system using 3S1P, Nickel Manganese Cobalt (NMC) cells. The maximum and minimum threshold voltage of the cell considered for this design are 4.2 and 2.5 V. The recommended charging method for these cells is a constant current (CC) at 0.5 C until the voltage reaches 4.1 V, then constant voltage (CV) charging at 4.1 V until the current falls near to zero. The fast charging is realized at 1.0C, due to the fact that safely accepted charging C-rate of the EV batteries are 1.0–1.5 C in most of the cases [12].

The electrochemical reaction in a Li-ion battery can be described by an equivalent circuit model (ECM). Among ECMs, the Thevenin's ECM frequently applies to the operation of Li-ion batteries. It consists of a parallel RC and an internal resistor. Based on the study from [13,14],

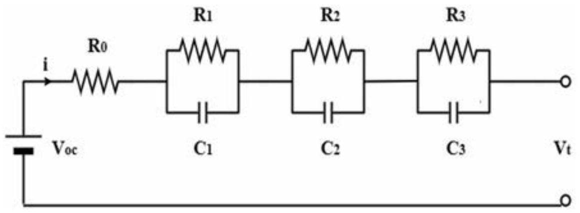

Figure 2: 3RC equivalent circuit model

the 3RC ECM is selected as a battery model for the simulation work which is represented in Figure 2

$$V_{\mathrm{t}} = V_{\mathrm{oc}} - R_0 i - V_{R_1C_1} - V_{R_2C_2} - V_{R_3C_3} \tag{5}$$

where V_t describes the battery voltage, V_{oc} describes the open circuit voltage (OCV) and $V_{R_1C_1}$, $V_{R_2C_2}$and $V_{R_3C_3}$ describe the voltage across the 3RC network. The battery model impedance characteristics are studied by conducting the AC impedance test. The RC model parameters are extracted by fitting the experimental test data based on the ECMs using non-linear regressive algorithm.

SOC is an important state that needs to be predicted to optimize the battery performance and extend the battery lifetime [15–17]. The battery model SOC is estimated using measured voltages, currents and temperature of the battery. The model RC values are dependent on the SOC and battery temperature. The parameter in the look-up tables is identified using test data [18]. The non-linear Kalman filter-based methods are effective for accurate SOC measurement [19, 20].

2.2 Proposed Passive Balancing Circuit

The proposed method utilizes a variable resistor to balance the voltage of each cell in a battery pack. The operation mode has been divided into standard (slow charging) and fast charging modes for both fresh and aged cells. Fast charging is realized only up to 80% of SOC, due to safety limitations [12]. The charging method for three different Li-ion cell chemistries are compared in [20], and concluded that the CC–CV is a suitable method for fast charging of high-power cells.

In the conventional passive balancing scheme represented in Figure 3, a fixed value of balancing resistors is used to dissipate the excess energy from the overcharged cell. The proposed passive balancing system chooses a variable resistor from the parallel combination of resistors based on the balancing current, as represented in Figure 4.

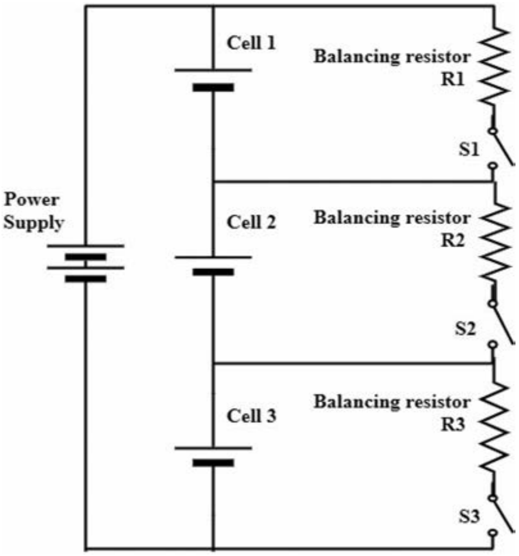

Figure 3: Conventional passive balancing circuit

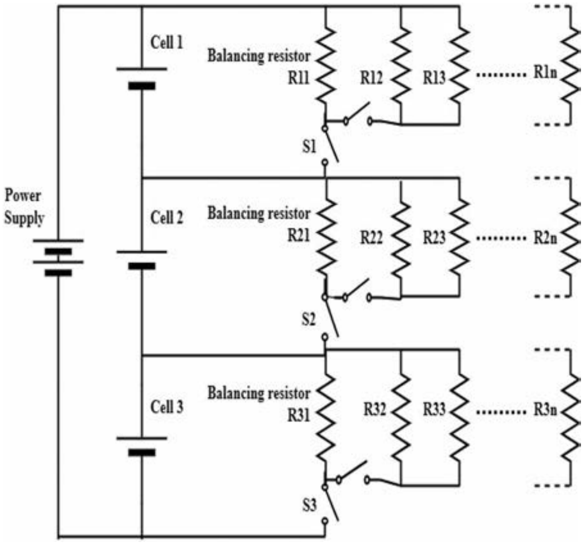

Figure 4: Proposed passive balancing circuit

Balancing resistor values are minimized by connecting the resistors in parallel along with the existing balancing resistor to increase the balancing current in order to reduce the balancing time. The optimizations of the balancing parameters are essential to improve the inconsistency of the Li-ion battery pack [21].

The balancing control algorithm is implemented to arrive at this condition. The algorithm is executed when the cells are under-charging which selects the balancing resistance with respect to the charging current and maximum cell voltage imbalance. Under standard charging, no extra resistors are added with the existing balancing resistor. The balancing algorithm is shown in Figure 5,

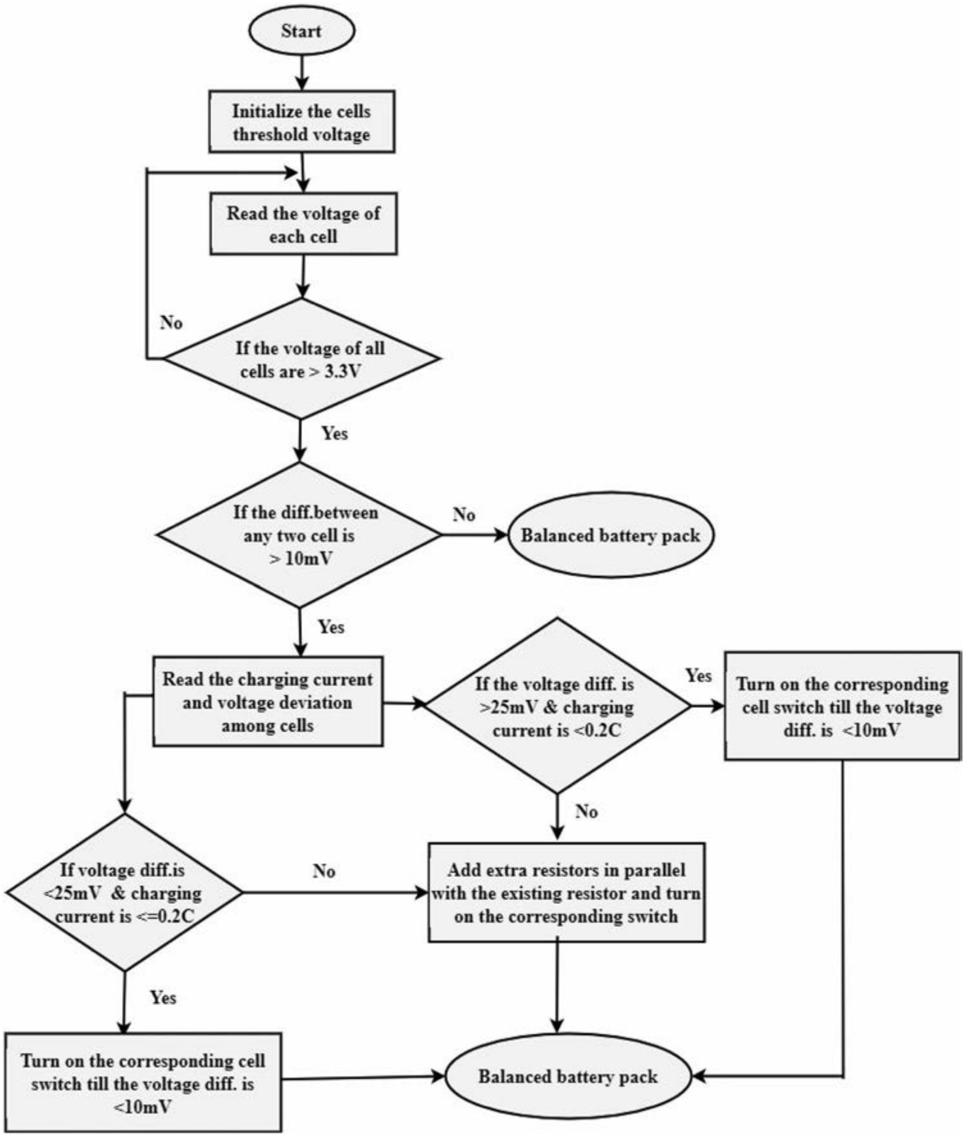

Figure 5: Passive balancing algorithm flowchart

the cell balancing is activated when all the cell voltages above 3.3 V and the voltage deviation is more than 10 mV. Lesser differential voltage (ΔV) among the cells in the battery pack attains greater balancing performance [22]. The Li-ion cells used for the EVs have the voltage deviations among fresh cells are smaller while comparing with aged cells. In order to explore the balancing current and balancing time requirement under maximum voltage deviation between cells as well as fast charging state, the initial cell voltages are considered as $V_1 = 3.52$ V, $V_2 = 3.545$ V and $V_3 = 3.795$ V.

The voltage deviation among cell 1 to cell 2 is 25 mV and cell 1 to cell 3 (aged cell) is 275 mV. During slow charging (5 h), 36 Ω resistor is added across all three cells and the balancing current is around 100 mA with a charging current of 0.2 C. Cell 2 is balanced within the charging period; due to high voltage imbalance, cell 3 voltage is not balanced. By adding extra resistors in parallel with balancing resistor as represented in Figure 6(a), the required balancing is achieved by increasing the balancing current within the charging time.

Under 0.5 C charging, the charging period is 2 h, but the cell balancing circuit needs and takes almost 3 h to complete the balancing process. To achieve the balancing within the charging time, the balancing current should be increased by adding extra resistors in parallel with the existing balancing resistor. In cell 2, three 36 Ω resistors are added to reduce the resistance value in order to

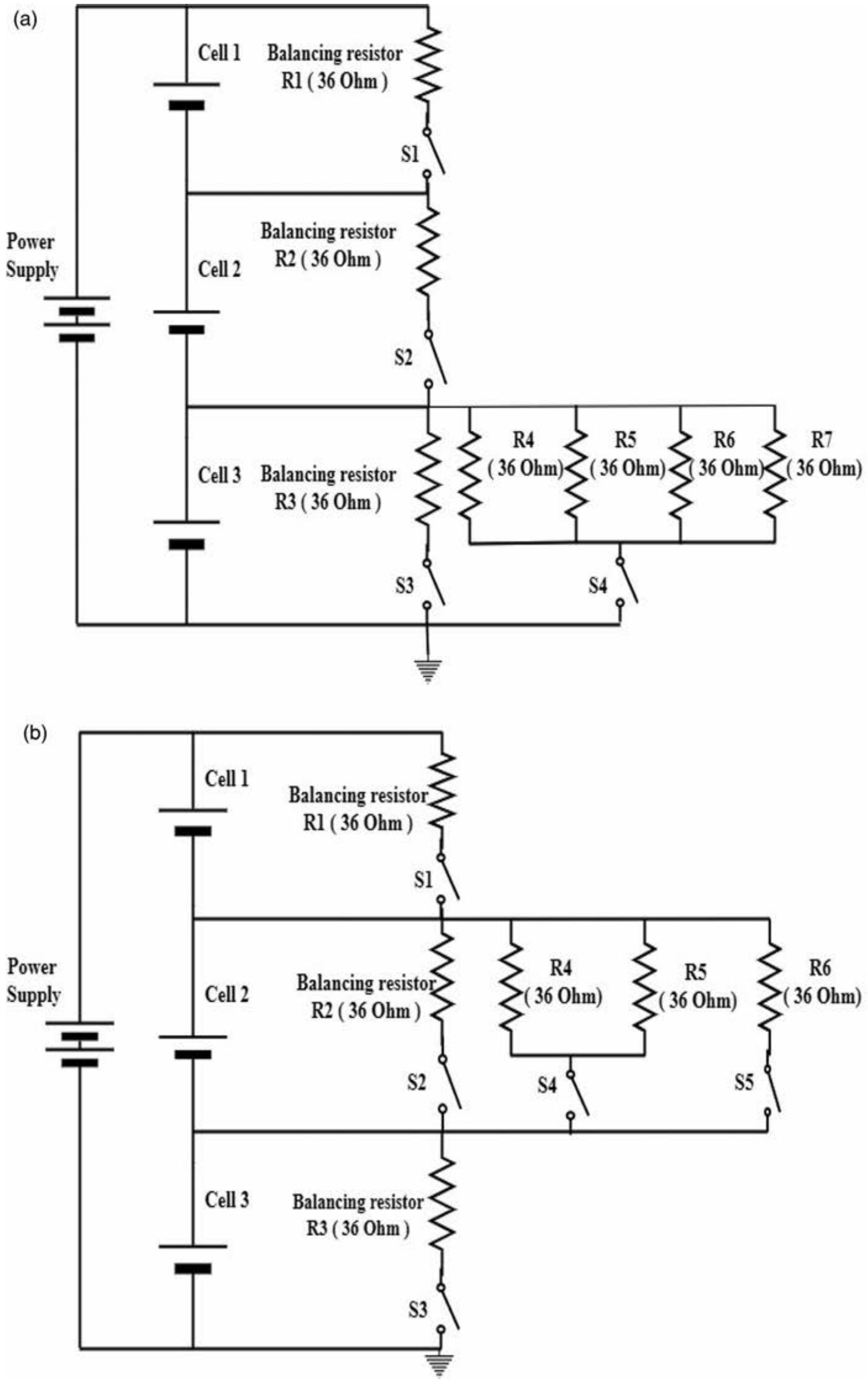

Figure 6: (a) Balancing circuit for cell 3. (b) Balancing circuit for cell 2

improve the balancing current which is represented in Figure 6(b). The total resistance becomes 9 Ω and the balancing current is increased from 100 to 400 mA and the similar way for cell 3 as well. Based on the charging current and balancing voltage threshold, the resistors are added to improve the balancing time and similarly, the resistors are added for 1.0 C charging current.

3. PASSIVE CELL BALANCING SIMULATION OUTCOME

The passive simulation was conquered on Matlab-Simscape 2019a. The cell balancing system consists of two important blocks, voltage measurement and switching circuit block. Simulation was performed with a different set of discharge current 0.2 C, 0.5 C and 1 C to study

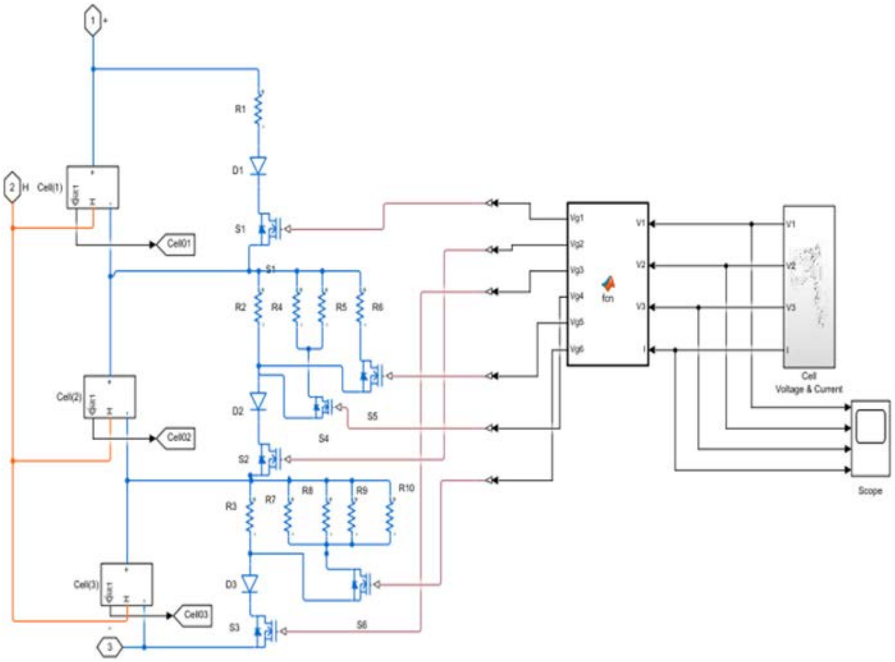

Figure 7: Passive cell balancing subsystem in Matlab-Simscape

the balancing characteristics. Figure 7 shows the proposed cell balancing subsystem implemented in Matlab-Simscape environment.

From Figure 8(a), the cell 2 voltage is 25 mV more than the cell 1 voltage. It took around 10,500 s to reach the balancing voltage threshold value (< 10 mV). The voltage variation among cell 1 and cell 3 is 275 mV which is represented in Figure 8(b). Since, the voltage difference is more, extra resistors are added to increase the balancing current. With the inclusion of four 36 Ω resistors, the cell 3 voltage is balanced in 15,000 s which is within the charging period of 18,000 s.

The balancing time is reduced from 5 to 2 h under 0.5 C charging current. To cope up within this time, three 36 Ω resistors are added with cell 2 resistors, the voltage of cell 2 is balanced and time taken to balance the cell is 3900 s which is described in Figure 9(a). For cell 3, 13 resistors are added to balance the cell within the charging time which is shown in Figure 9(b).

For 1.0 C charging and for the balance of cell 2, four resistors are added with the existing cell 2 resistor. The balancing time is 3360 s for a charging period of 3600 s, as shown in Figure 10(a). For cell 3, the balancing time is 3240 s with the inclusion of 40 resistors in parallel which is shown in Figure 10(b).

While comparing with the legacy balancing methods [7,23], the proposed balancing concept can curtail the balancing time efficiently. Moreover, after the balancing process, the maximum voltage discrepancy among the balanced cells is < 10 mV. Table 1 represents the balancing time, current and power loss of the cell at different charging rate with respect to variable balancing resistors to balance the cells within the recommended charging duration. The power loss across the balancing resistor is

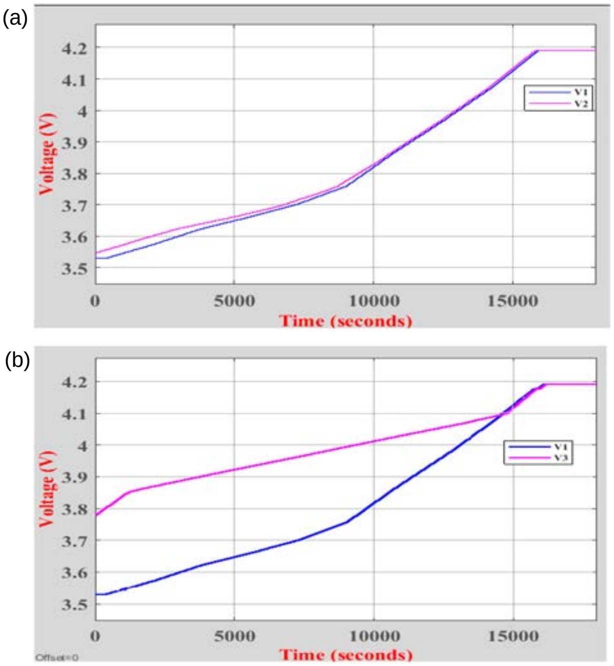

Figure 8: (a) Cell 2 voltage under 0.2C charging. (b) Cell 3 voltage under 0.2C charging

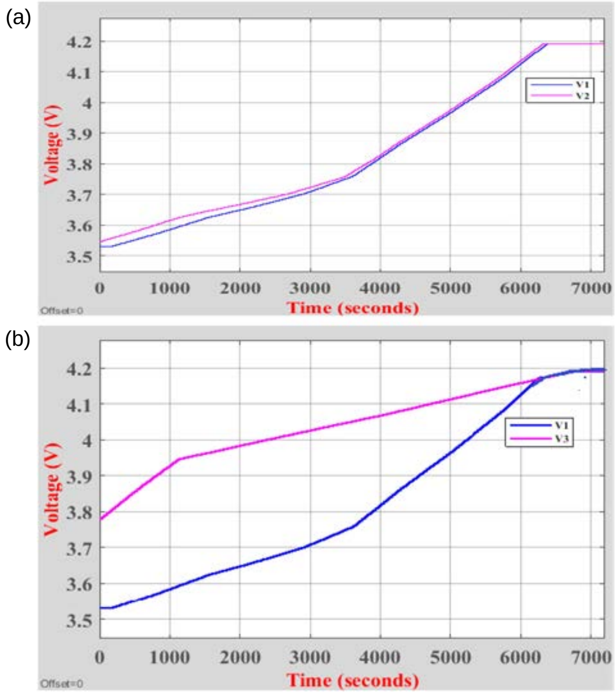

Figure 9: (a) Cell 2 voltage under 0.5C charging. (b) Cell 3 voltage under 0.5C charging

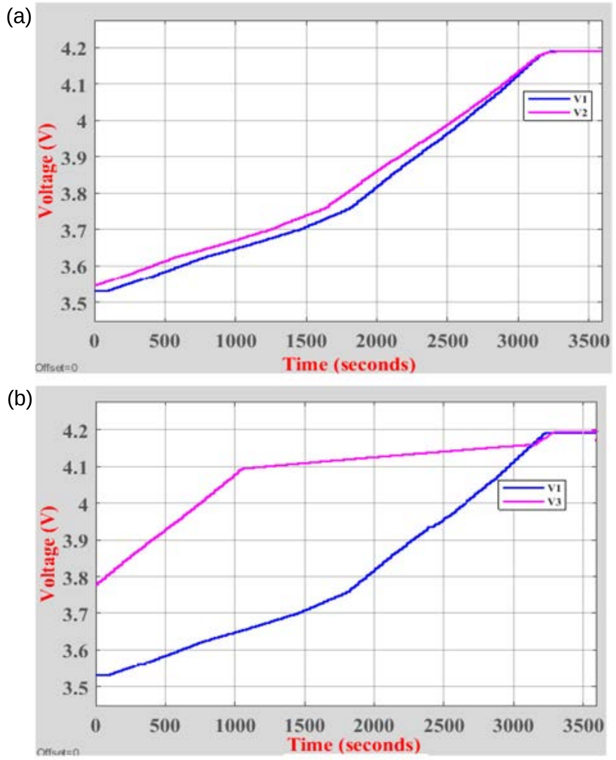

Figure 10: (a) Cell 2 voltage under 1.0C charging. (b) Cell 3 voltage under 1.0C charging

maximum under higher balancing current leads to temperature rise in the pack, so placing shunt resistors in a distributed way in the circuit board to keep the cell temperature within the safety limit.

Table 1: Power loss *V*s balancing resistance

Cell	C-rate	$R_B(\Omega)$	I_B(mA)	T_B(min)	Power lossin R_B (W)
Cell 2	0.2C (0.7A)	36	100	175	0.35
	0.5C (1.75A)	12	300	65	1.04
	1.0C (3.5A)	9	400	56	1.40
Cell 3	0.2C (0.7A)	7.2	500	250	2.0
	0.5C (1.75A)	2.8	1286	117	5.2
	1.0C (3.5A)	0.9	4000	54	12.5

Table 2: Balancing time at different ΔV

Balancing threshold voltage (mV)	Balancing time (min)
10	58
20	38
30	27
40	21

Table 2 gives a balancing time with respect to differential voltage among cells. The balancing threshold voltage setting (ΔV) between the cells is based on the user requirement. Higher ΔV takes less time to balance, but the balancing performance was not satisfactory.

4. CONCLUSION

The main focus of this research is to simulate the passive balancing characteristics of serially connected Li-ion (NMC) cells under fast DC charging scenario. The passive balancing simulation with a parallel combination of shunt resistor circuit has been done. Higher balancing current reduce the balancing time significantly and it is suitable for fast charging. Lower voltage deviation among the cells in the battery pack attains good balancing performance, but it takes more time to balance. A higher balancing current during balancing would need a greater number of parallel balancing resistors which needs larger PCB area for dissipating the heat, and hence, effective placement of balancing the shunt resistor is required to handle the thermal load. Faster balancing provides higher flexibility, but design to be done very carefully in order to handle the higher balancing power transistor. Though active balancing has its own advantageous, complex circuit design and the cost involved are high. Hence, this optimal proposal of enhancing the passive balancing mechanism is to provide increased life time of the battery pack and reduction in balancing time.

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