Comparative Analysis On Control Techniques For Active Cell Balancing

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***Abstract*— Electric vehicles (EVs) rely on lithium-ion batteries consisting of many cells interconnected in series and parallel to achieve higher output voltage and charge capacities. However, an imbalance in cell voltage causes a negative impact on life of the battery and effectiveness in energy storage systems. This discrepancy in batteries was addressed by different cell voltage equalization techniques. In this article, a current controlled switching algorithm is proposed for cell voltage equalization using an inductor based buck boost converter topology. The proposed algorithm's effectiveness is compared with PI and Fractional-order PID (FOPID) controller-based switch control algorithm, with a focus on cell voltage and State of Charge (SOC) balancing. The results demonstrate a considerable improvement in performance when compared with PI and FOPID controller-based switch control algorithms.**

Keywords*— *lithium-ion battery, buck-boost converter, FOPID controller, PI controller, Current controlled switching algorithm, Active cell balancing.

I. Introduction

The Li-ion battery pack utilized in EVs comprises of many cells interconnected in series and parallel, to produce necessary cell voltages and energy capacity [1]. Equalizing the discrepancy in voltage between the cells is crucial and difficult task, which plays a significant role in battery pack/module's performance and effective utilization [2]. During the regular usage of batteries, there will be slight variations across the cell charge capacity, impedance, charge, and self-discharge rates [3]. Over time, these discrepancies get worsen with charge/discharge cycles, which further reduces the amount of storage capacity, state of health, and potential safety risks for battery pack [4]. Therefore, it is essential to implement an efficient cell equalization topology, for battery packs ensuring each cell operates at a consistent level [5].

Numerous, battery equalization methods have been presented in the literature [6], broadly categorized as passive and active equalizers. In these, passive equalizers offer a simple integration of a single resistor and switch across each cell. However, this approach has limitations due to high energy dissipation and extended equalization periods. Moreover, it generates significant heat, leading to various thermal challenges. To overcome these shortcomings, active equalizers were proposed, which employ multiple energy storage devices such as capacitors and inductors to regulate power flow during active balancing, resulting in efficient cell balancing [7]. Passive equalizer is more effective for low and moderately-aged cells that maintain low balancing thresholds. However, active equalizers are crucial in enhancing the lifespan of aging cells in the field of e-mobility [8]. Active cell balancing plays a crucial role in Battery Management Systems (BMS) across diverse applications, ensuring the best possible battery performance, lifespan, and safety. It is indispensable in electric vehicles, renewable energy solutions, grid storage, telecommunications, aerospace, and other sectors, effectively preventing cell overcharging and over-discharging.

The active equalization topology is further divided into four categories depending on various power electronic devices utilized, including topology based on capacitors, inductors, capacitors and inductors, and transformers [9]. In capacitor-based topology, the control strategy is straightforward, however, there is little variation in SOC between the cells, the equalization speed is quite sluggish, and the capacitor is exposed to voltage stress [10]. The buck-boost equalization circuit characterizes the traditional inductor-based design, ensures precise cell balancing, and speeds up the equalization. Cuk equalization circuit is another design based on capacitance and inductance, the speed is fast but increases the construction complexity. The transformer equalization circuit operates on the principle of a multi-winding transformer, which is intricate and expensive. Aforesaid, properties of four equalization circuits are of straightforward layout, which is displayed in Table I. The buck-boost circuit is an excellent choice when compared to the topologies discussed above [11].

Apart from cell equalization circuit topologies, the suitable control techniques, for battery management are categorized into two types: based on voltage control and State of Charge (SOC) based control. Voltage-based control is widely employed in industry due to its simplicity, which involves charge and discharge of cells based on direct voltage measurement. However, inherent differences in chemical kinetics among cells lead to cell imbalance. Voltage difference is used here as an indication rather than the main factor [12]. The real characteristics of batteries cannot be adequately reflected by voltage. Direct voltage balancing may result in further amplifying the unevenness within the battery string. SOC based regulation is more logical because it considers the main reason for the voltage difference. The voltages of the cells will finally balance when they are balanced to the same SOC [13].

This paper proposes a comparative analysis of current controlled switching algorithm, switch control algorithm with PI controller and FOPID controller. SOC based cell balancing is done which ensures cell voltage across each cell in a string. The proposed work is arranged as follows for further discussion: Section II and III presents the overall system design and control techniques used in cell balancing respectively. In Section IV, simulation results and their further outcomes were discussed. A comparative analysis of control techniques for cell voltage, and SOC balancing is explained in section V. The conclusion of proposed work is presented in Section VI.

TABLE I
COMPARISON OF TYPICAL EQUALIZATION CIRCUIT TOPOLOGIES

Circuit Topology	Equilibrium Speed	Control difficulty	Cost	Implementation Complexity	Volume	Energy efficiency
Switched Capacitor	Slow	Difficult	Low	Medium	Small	Higher
Cuk	Fast	Difficult	High	Complicated	Medium	High
Transformer	Fast	Difficult	High	Complicated	Huge	Low
Buck-Boost	Fast	Difficult	Medium	Simple	Medium	High

II. SYSTEM DESIGN

Fig.1 depicts the equalization topology of the inductor-based buck-boost circuit. Four cells were considered for cell balancing which were connected in series. For 'n' lithium-ion cells, (n-1) inductors and (2n-2) switches were utilized. The analysis was carried out in two layers. Each pair of cells (Cell1, Cell2) is grouped in the first layer (Cell3, Cell4) are grouped in second layer of the balancing circuit. Every layer is considered a single cell that will balance with its neighboring one. Thus, result in balancing of all cell voltage and SOC equally.

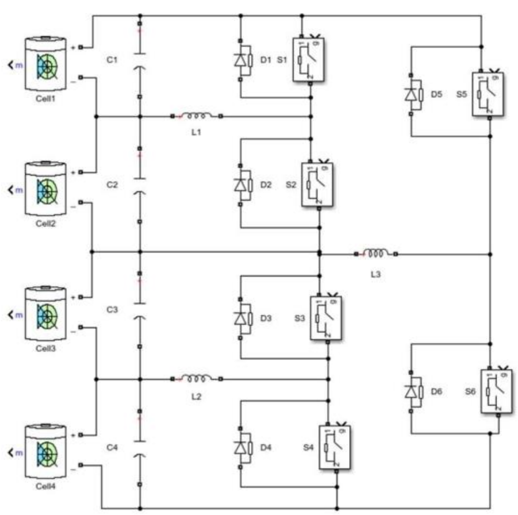


Fig. 1. Inductor-based buck–boost converter circuit.

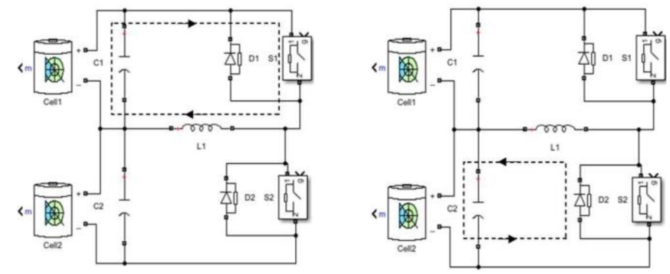
A. Modes of Operation

Fig. 2(a) shows the equivalent circuit during Mode 1. Considering the cell SOC if Cell1 SOC is greater, then switch S1 is closed to balance charge in circuit. The direction of current flow will travel from Cell1 via the switch and into the inductor. During this time, the inductor stores the energy $LI^2/2$, and the V/L ratio determines the rate of current flow. The inductor value and ON time duration were selected to prevent inductor saturation.

During Mode 2, Switch S2 is turned ON and Switch S1 is turned OFF. Cell2 will be charged by the energy held in the inductor during Mode 1. In Fig. 2(b), the current flow direction is depicted. To prevent a change in the direction of the current, the S2 ON period needs to be brief enough [14].

B. Switch Controlling algorithm for 4 cells

The flow chart of switch controlling algorithm is given in Fig.3. The algorithm initiates with reading SOC of all cells and checks for its balancing condition. The algorithm will find which cell is higher in SOC. If SOC1 of Cell1 is greater than SOC2 of Cell2 then PWM signal activates the switch associated with greater cell SOC. Thus, the energy will be flowing from Cell1 to Cell2, via inductor in stating the balancing process. The SOC is then read again in order to ensure that it is in a balanced state, and like this, the process is repeated until both cells are balanced. The benefit of this method is this algorithm runs continuously during the charge or discharge profile.



(a) (b)

Fig. 2. Working modes for two cells. a) Mode 1, when switch S1 is closed, S2 is open. b) Mode 2, when switch S1 is open and S2 is closed

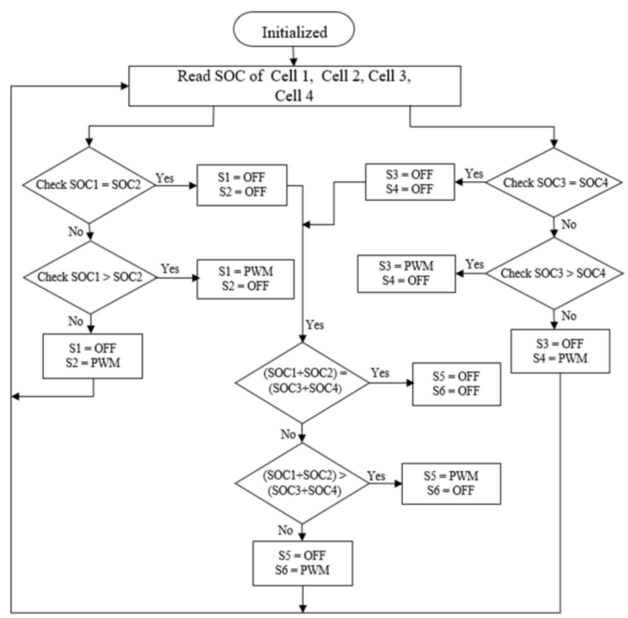


Fig. 3. Flow Chart of switch controlling algorithm.

III. CONTROL TECHNIQUES

A. PI Control Technique

The PI controller is incorporated into the system, in enhancing the controller's ability in cell balancing, by generating appropriate switching signals. The objective of controller is to equalize the State of Charge (SOC) across each cell, considering the difference between SOC as an error signal, as shown in equation (1). Due to the limitation of slow sampling rate of these errors, the error signal is sent via a PI controller which helps to enhance the steady-state error and prevent stability problems. The derivative component in controller is not employed, due to the inherent noise associated with SOC estimation, which would be amplified to unbearable levels [15].

SOC plays the dominant role in cell imbalance, with voltage as detuning parameter in affecting the parameters in PI control system. During battery charging SOC increases and decreases during the discharge. So, it is appropriate to use SOC as an input parameter for the PI-based system of control. In facilitating cell balancing, SOC error is determined as follows:

$$SOC_{error} = SOC_1 - SOC_2 \tag{1}$$

The PI controller output is the duty ratio, and during higher duty ratio, battery voltage will differ noticeably from their nominal levels. In order to avoid this unintended consequence, the duty ratio's growth rate is slowed down using the voltage difference as a detuning parameter. The voltage difference is described as follows:

$$V_{diff} = V_1 - V_2 \tag{2}$$

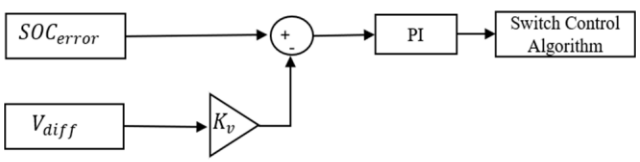


Fig. 4. PI controller for SOC-Voltage balancing.

Herewith, the modified final input to PI controller, as seen in Fig. 4, voltage difference is multiplied by K_v the detuning factor. The PI controller's input is described as

$$u(t) = i(t) + p(t) \tag{3}$$

were,

$$p(t) = K_P . (SOC_{error} - K_v . V_{diff}) \tag{4}$$

and

$$\mathrm{i(t)} = K^{\mathrm{i}} . \int_0^t (SOC \qquad - K \ . V \qquad) \ d \tag{5}$$

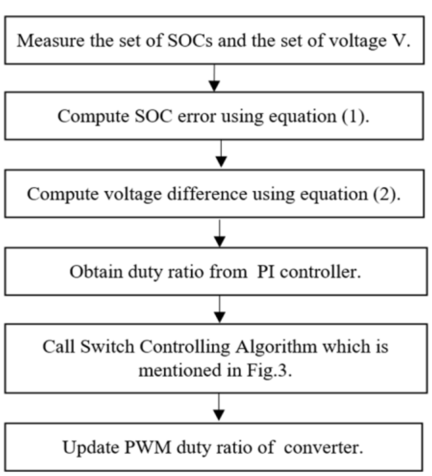


Fig. 5. SOC-Voltage Control Algorithm for PI Controller.

K_v is the detuning factor, where K_P and K_i stands for proportional gain and integral gain respectively. The duty ratio output is established by PI controller which is taken as input for switch controlling algorithm as explained in Fig. 3, to account for requirement of SOC balancing and to minimize fluctuation in battery voltage [16]. For both first and second grouped switches of Inductor based buck–boost circuit, this technique generates PWM pulses. The PWM pulse is sent to switch depending on switch control algorithm. The overall system control algorithm with PI controller, shown in Fig. 5, is known as SOC-Voltage Control Algorithm.

B. *FOPID Control Technique*

The extended version of conventional PID controller, is the Fractional order PID (FOPID) controller, which is more adaptable and reliable and adaptable with the benefits such as reduced steady-state error, decrease in oscillation and overshoots, faster response, insensitivity to disruptive influences and so on. The synchronization and control of chaotic systems, magnetic levitation systems, asynchronous motor drive systems, direct current (DC) motor control, and DC-DC amplifier converters are a few examples of applications that make use of FOPID controllers [17]. The generalized transfer function of FOPID controller is,

$$G_{FOPID}(s) = K_P + K_I s^{-\lambda} + K_D s^{\mu} \ (\lambda, \mu > 0) \tag{6}$$

Fig.6 shows FOPID controller for SOC-Voltage balancing, which replaces only the PI controller in the same SOC-Voltage Control Algorithm as depicted in Fig. 5.

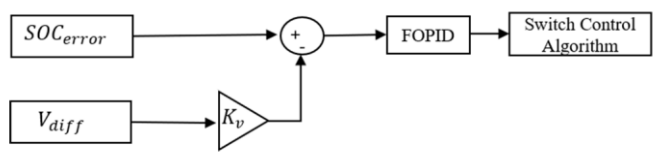


Fig. 6. FOPID controller for SOC-Voltage balancing.

There are five parameters K_P, K_I, K_D λ, μ ,where K_P, K_I, and K_D are the proportional, integral, and derivative gain constants, and λ and μ are the fractional order of integral and derivative terms respectively. These two additional tuning parameters allow the controller in greater customization, improving the accuracy and robustness of its control action [18]. The FOPID control technique provides faster settling time in cell SOC and voltage balancing, compare to the conventional PI controllers.

C. *Current controlled switching algorithm*

To mitigate the risk of cell damage due to excessive current flow in a string of cells, it is crucial to ensure the cell current is within safe limits. This limitation of current enhances the battery health and avoids the premature failure of cells. Concern with addressing the above issue, a new algorithm with current control is proposed which limits the excess current flow through the cell and operates independently in regulating the switching in cell SOC and voltage balancing. Fig. 7 depicts the flow chart of the current controlled switching algorithm.

The proposed algorithm determines when to turn the switches ON and OFF based on the condition of current and SOC of each cell. First, algorithm check for the absolute difference between the SOC values of the two cells. If the difference is greater than the specified threshold of 0.001, the algorithm proceeds to the next condition. It evaluates whether SOC1 of Cell1 is greater than SOC2 of Cell2. If this condition holds true, algorithm examines the current values. If the current I_1 is less than or equal to threshold value I_{TH}, it turns ON Switch S1 and Switch S2 will remain OFF. This configuration results in charging of inductor L1 through Switch S1 as shown in Fig. 2(a). If SOC1 is greater than SOC2 and the current I_1 exceeds or equal to I_{TH}, algorithm check for the next condition, whether the current is greater than or equal to string current k_S. If this criterion satisfies, it turns OFF Switch S1 and turns ON Switch S2 as shown in Fig. 2(b). This algorithm maintains the current through the string of cells, within the safe limit, and promptly turns off the respective cell switch, in preventing overcharging. This algorithm works in the same way for all other connected cells and continued to be functioning until all the cell SOC is balanced and the current is maintained at a safer limit.

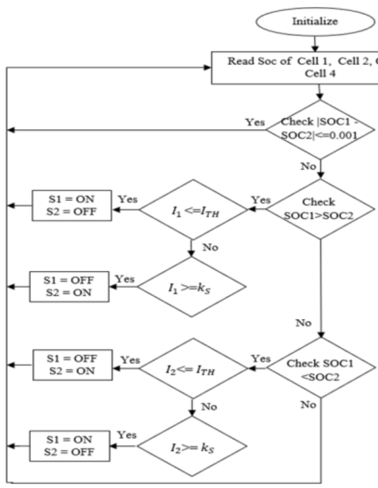


Fig. 7. Current control switching algorithm flow chart.

IV. Simulation Result And Discussion

The MATLAB simulation is carried out in inductor-based buck-boost converter circuit, 4 cells have identical capacity and nominal voltage but different SOC which were given in Table II.

TABLE II
Simulation Parameters

Simulation Parameters	Values
Nominal voltage	3.7 V
Rated capacity	3.5 Ah
SOC1 of Cell1	62%
SOC2 of Cell2	61%
SOC3 of Cell3	60%
SOC4 of Cell4	59%

A comparative analysis of cell balancing is carried out with conventional PI controller, FOPID controller, and current controlled switching algorithm-based active cell balancing techniques. The results obtained were discussed further.

A. PI Control Technique Results

The simulation results of 4 cells equalization process using conventional PI control technique in inductor based buck boost converter circuit is presented in Fig. 8. It is observed in Fig. 8(a) that the SOC levels of all 4 cell balances at 140.054 seconds reaching the value of 60.32% from their initial values. In further Fig. 8(b) and 8(c) shows the voltage of all cells balance at 3.994V. After the SOC is balanced, the cell current decreases to zero.

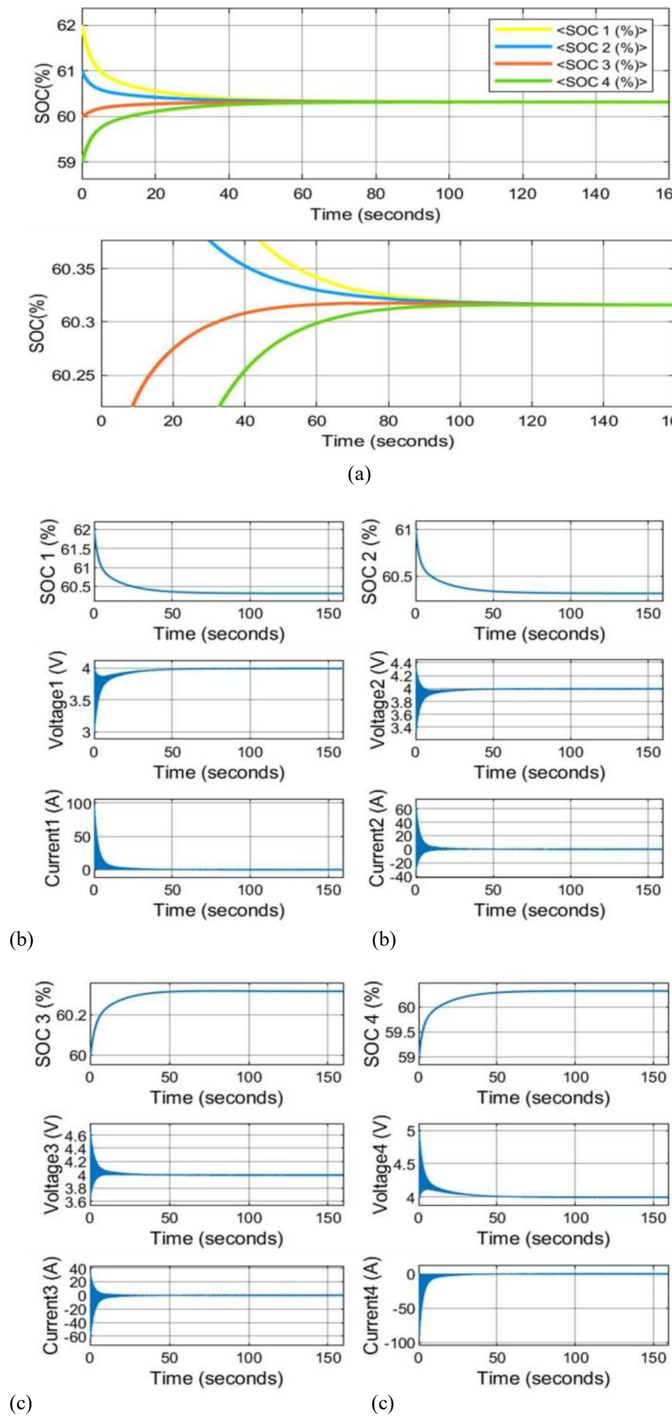
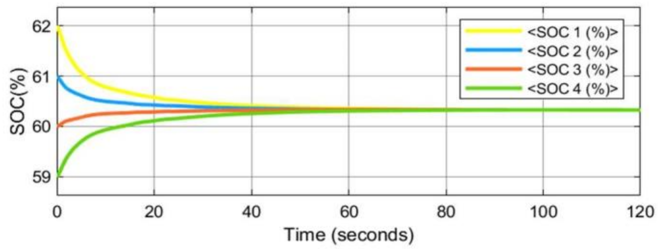


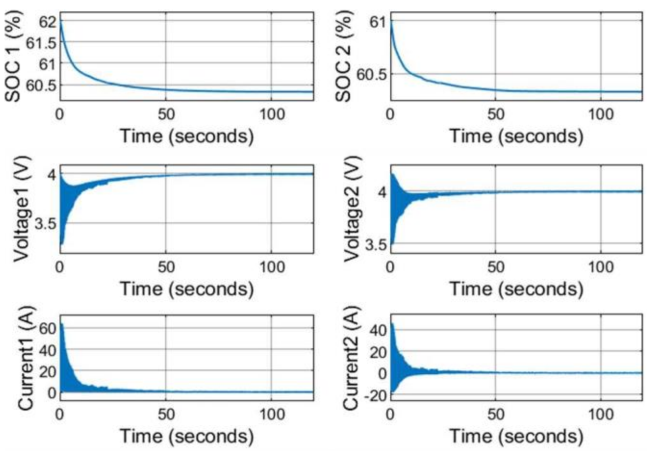
Fig. 8. Simulation results of equalization process using PI controller. (a) SOC response. (b) SOC, Voltage, & Current of Cell1 & Cell2. (c) SOC, Voltage, & Current of Cell3 & Cell4.

B. FOPID Control Technique Results

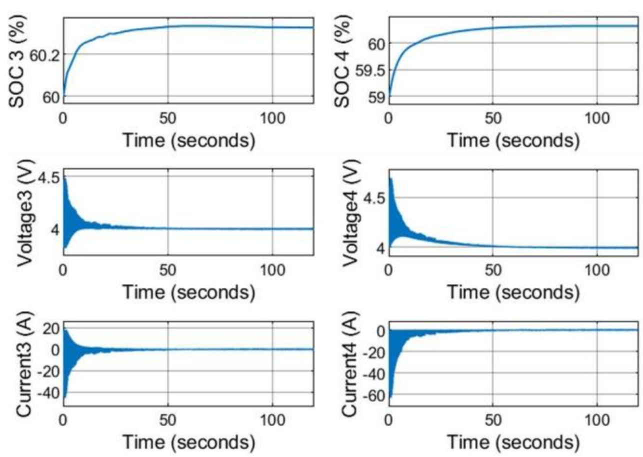
The simulation results of 4 cells equalization process using FOPID control technique in inductor based buck boost converter circuit is presented in Fig. 9. Fig. 9(a) shows the SOC levels of all 4 cell balances at 98.051 seconds reaching the value of 60.32% from their initial values. Similarly, Fig. 9(b) and Fig. 9(c) show the voltages of all 4 cells balances at 3.994V. After the SOC is balanced, the cell current decreases to zero.



(a)



(b)

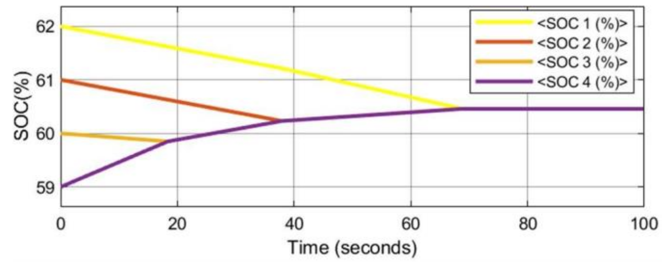


(c)

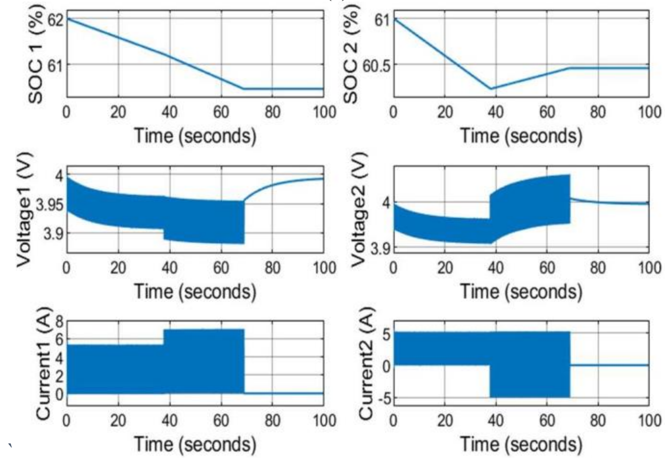
Fig. 9. Simulation results of equalization process using FOPID controller. (a) SOC response. (b) SOC, Voltage, & Current of Cell1 & Cell2. (c) SOC, Voltage, & Current of Cell3 & Cell4.

C. Current controlled switching algorithm Results

The simulation results of the proposed current controlled switching algorithm in inductor based buck boost converter for 4 cell balancing is depicted in Fig. 10. It is observed in Fig. 10(a), the SOC levels of all 4 cells balances at 69.872 seconds reaching the value of 60.46% from their initial values. In further Fig.10(b) and Fig.10(c) show the voltages of all 4 cells balances at 3.994V. After the SOC is balanced, the cell current decreases to zero.



(a)



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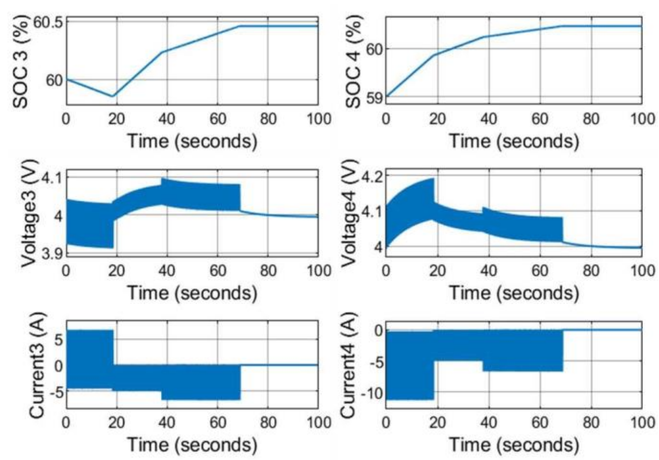

(c)

Fig. 10. Simulation results of the proposed equalization process using the Current Controller Algorithm. (a) SOC response. (b) SOC, Voltage, & Current of Cell1 & Cell2. (c) SOC, Voltage, & Current of Cell3 & Cell4.

From the above simulation results it is observed that, every control technique is taking a different settling time in balancing the cell SOC and voltages. SOC balancing helps in ensuring the charge and discharge rates of all cells in the battery pack are consistent, thereby increasing its total capacity and longevity. This is done by diverting charge from cells with highly charged to those with less charged, or by adjusting the charging rate for specific cells to attain cell balancing.

V. Comparative Analysis

TABLE III
COMPARATIVE ANALYSIS OF CONTROL TECHNIQUES

Parameters	PI Control Technique	FOPID Control Technique	Current Control Algorithm
SOC Settling Charge	60.32%	60.32%	60.46%
Settling Voltage	3.9V	3.9V	3.9V
SOC Settling Time	140.054 sec	98.051 sec	69.872 sec

The comparative analysis of control techniques is shown in Table III. When three control techniques are compared it is obtained that the proposed current controlled switching algorithm performs best with respect to three parameters they are; SOC settling charge which is obtained at 60.46%, SOC settling time which is obtained at 69.872 sec, and the settling voltage which is obtained at 3.9V. The algorithm limits the flow of cell's current to string current k_S . The SOC settling time is comparatively faster which allows better control over battery packs. SOC settling charge is also greater which shows less wastage of energy in the cells. When the conventional PI control technique and FOPID control technique are compared it is obtained that FOPID control technique provides faster response times compared to PI control technique. FOPID control technique performs well with respect to the SOC settling charge which is obtained at 60.32%, SOC settling time which is obtained at 98.051 sec for balancing 4 cells. PI control technique which SOC is balanced at 140.054 sec and SOC settling charge is settled at 60.32%. The voltage of all the control techniques is settle at 3.9V. The current for PI control and FOPID control technique rises at the beginning to charge the cells and gradually decreases when the cell SOC and voltage are balanced.

VI. Conclusion

The simulation results indicate that the proposed current controlled switching algorithm achieves a SOC settling time of 69.872 seconds which is significantly faster than FOPID & PI control technique whose settling time is 98.051 seconds and 140.054 seconds, respectively. This demonstrates the current controlled switching algorithm outperforms than the other two control with respect to SOC settling time, and cell SOC and voltage equalization. To ensure the SOC of all cells eventually settles, this control mechanism may be extended to battery systems that comprise of a larger number of cells.

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