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Analysis of the internal temperature of the cells in a battery pack during SOC balancing

R Mizanur¹, M M Rashid¹, A Rahman², A H M Zahirul Alam³, S Ihsan² and M S Mollik¹

¹Department of Mechatronics Eng., International Islamic University Malaysia, Malaysia

²Department of Mechanical Eng., International Islamic University Malaysia

³Department of Electrical and Computer Eng., International Islamic University Malaysia

Abstract. Lithium-ion batteries are more suitable for the application of electric vehicle due to high energy and power density compared to other rechargeable batteries. However, the battery pack temperature has a great impact on the overall performance, cycle life, normal charging-discharging behaviour and even safety. During rapid charge transferring process, the internal temperature may exceed its allowable limit (46^oC). In this paper, an analysis of internal temperature during charge balancing and discharging conditions is presented. Specific interest is paid to the effects of temperature on the different rate of ambient temperature and discharging current. Matlab/Simulink Li-ion battery model and quasi-resonant converter base balancing system are used to study the temperature effect. Rising internal temperature depends on the rate of balancing current and ambient temperature found in the simulation results.

Keywords: SOC, temperature, quasi-resonant converter, EV.

1. Introduction

The battery technology is widely employed in the different applications, namely space vehicles, traction, hybrid powertrain, electric vehicle, and electronic utilities as the standard power source. Especially, in electric vehicle, it has a great impact to run long time and to reduce cost and fuel consumption which causes CO₂ emission [1]. The configuration and type of the battery technology are based on the power and energy demand. In the present market, there are different types of rechargeable batteries available, for example, NiMH, Li-ion, LiFeO₄, sodium-nickel chloride, nickel-cadmium (NiCd) and lead acid. The terminal voltage of a single cell is limited such as 2V for lead acid battery, 1.2V for NiMH, 3.6V for Li-Ion and 3.3V for LiFePO₄. To meet the high energy and power demand, battery cells are connected in series or parallel and both combinations. Among these types of batteries, Li-ion base batteries are more preferable for EV because of low self-discharge rate (6%- 10%), higher power density and energy capacity.

Ideally, each battery cell has unique characteristics, for example, voltage and current, so they can provide same power and energy. However, in reality, the characteristics of individual cell differ from cell to cell because of ambient temperature variation, manufacturing process, internal impedance and chemical degradation [2-4]. A battery pack always undergoes the charging and discharging process. During charging and discharging, battery capacity and lifecycle decrease gradually over time. Especially, high chemical reaction occurs throughout the discharging process (while a large amount of current drawing by the traction motor) and increases the battery cell internal temperature. Accordingly, state of charge (SOC) of the individual cell in a battery pack becomes unbalanced. Once this problem happens, some cells are charged faster than the other cells during charging and led to



overcharging (explosion and catch fire). Similarly, during the discharging process, cells are under discharged which led to permanent damage. It is indeed necessary that a charge balancing system is required to solve the unbalancing problem. During the quick and efficient charge balancing process, cell internal temperature is required to consider. Since, battery pack plays an important role for EV, the temperature of the battery pack which has a significant impact on the overall performance is a critical parameter. The operating temperatures of Li-ion battery are 0-46°C for charging and -20°C to 60°C for discharging [6]. Usually, at room temperature of 25°C, batteries are designed. Lower and higher temperatures than room temperature both have the effect on the power, energy and lifecycle of the battery cell.

Along with excellent properties, Li-ion cell has low mass density leads to lower thermal capacity, which allows rapid internal temperature rising during exothermic chemical reaction and joule heating (resistive heating, I^2R). Joule heating takes place while charging and discharging process and chemical reaction occurs during overcharge and under-discharge condition [7]. The performance of battery cell is influenced by temperature variation. Excessive temperature variation increases internal resistance, self-discharge rate and voltage. If cell internal temperature continues to increase, the eventual consequence may be an explosion and fire. Hence, many Li-ion manufacturer companies have implemented a wide range of techniques to ensure safety against rupture and fire at the point of view. They used conventional circuit breakers, thermal fuses and current interrupted device even the latest technology of thermal cooling system to manage the problem discussed. Nevertheless, it is undoubtedly necessary to understand the impact of internal temperature during charging and discharging which will be a constructive way of improving the design of the quick charge equalization system. Therefore, in this work, an investigation of the battery internal temperature during the charge balancing process and discharging process has been performed. Battery model and balancing system has been discussed as well to analyse the above mentioned problem for designing a quick charge balancing system.

2. Battery Model

In terms of defining and studying of SOC, voltage, current, and temperature, a battery model is required. There are several battery models proposed in the preceding literatures [8-10]. The models are made of the equivalent circuit of combination of resistance and capacitance. For example, the RC model, internal resistance model, resistance capacitance model, thevenin equivalent circuit model, Shepherd model and the PNGV model [11-12]. In this study, the nonlinear battery model has been applied which is shown in figure 1. According to that model, figure 2 shows a typical battery discharging model.

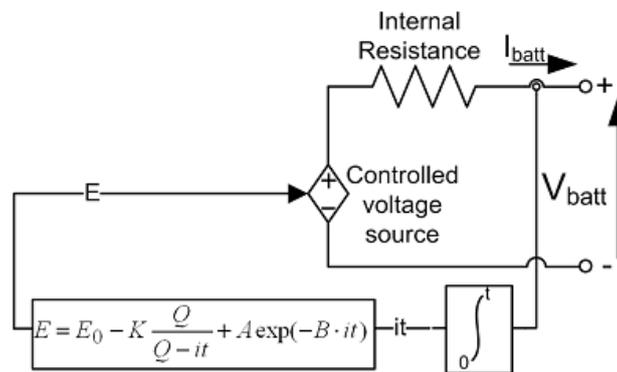


Figure 1. Nonlinear battery model [12].

The following parameters are found while defining this battery model.

Discharging ($i^* > 0$)

$$V_{batt} = E_0 - K \cdot \frac{Q}{Q - it} i^* - K \cdot \left(\frac{Q}{Q - it} \right) \cdot it + A \cdot \exp(-B \cdot it) \quad (1)$$

Charging ($i^* < 0$)

$$V_{batt} = E_0 - K \cdot \frac{Q}{Q - 0.1 \cdot Q} i^* - K \cdot \left(\frac{Q}{Q - it} \right) \cdot it + A \cdot \exp(-B \cdot it) \quad (2)$$

$$V_{batt(full)} = E_0 - R \cdot i + A \quad (3)$$

$$V_{batt(exp)} = E_0 - K \cdot \frac{Q}{Q - Q_{exp}} \cdot (Q_{exp} + i) - R \cdot i + A \cdot \exp\left(\frac{-3}{Q_{exp}} Q_{exp}\right) \quad (4)$$

$$V_{batt(nom)} = E_0 - K \cdot \frac{Q}{Q - Q_{nom}} \cdot (Q_{nom} + i) - R \cdot i + A \cdot \exp\left(\frac{-3}{Q_{exp}} Q_{nom}\right) \quad (5)$$

Where,

E is no load voltage,

E_0 battery constant voltage,

K polarization voltage,

Q battery capacity (Ah),

R internal resistance,

i battery current,

V_{Batt} nominal voltage (V),

exp(s) Exponential zone dynamics (V).

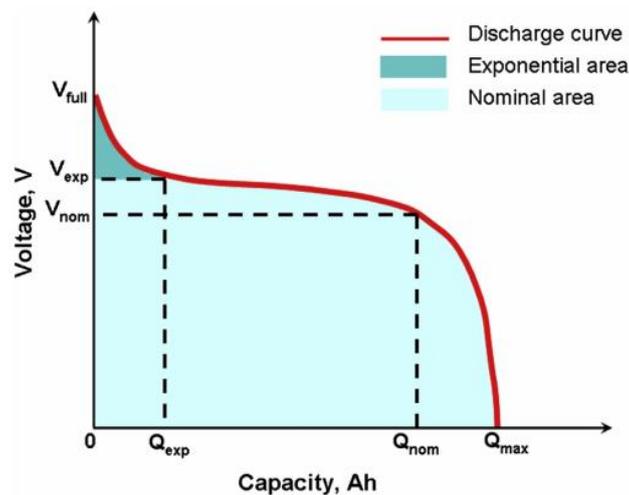


Figure 2. A typical discharging characteristic curve [13].

3. SOC Balancing Methods

Ideally, every cell in a battery pack has the same chemical reaction but in reality each cell has different chemical reaction due to manufacturing process, internal resistance, self-discharge rate, degradation and temperature. These various chemical reaction causes unbalance the SOC of the cell in a battery pack. For safety and long time performance, every cell needs to be the same SOC level in a battery stack. Based on charging, discharging and inoperative condition, various charge equalization methods have been designed, developed and implemented. The methods can be divided into two main methods: namely energy consuming or passive method and energy transferring or active methods. In the energy consuming method, resistor components are used across the battery cell with higher charge. On the contrary, inductor, capacitor and diode are used in energy transferring methods because of the non-consuming element. According to the use of non-consuming components, inductor base, capacitor base and different kinds of converter base equalization system have been presented for example buck-boost converter, flyback converter, quasi-resonant converter, resonant converter etc. [14-20]. In this

study, the quasi- resonant LC converter base charge equalization system for two series connected battery cell has been considered and shown in figure. 3.

Battery pack in an electric vehicle is made of sub modules to acquire high voltage and current mentioned before. Based on the above methods, the charge balancing operation is performed from module to cell, module to module, cell to module and cell to cell. The module to cell balancing system can charge a weakest cell efficiently but in cell to module, strong cell can charge a module inefficiently [21].

Most of the researches have been led on balancing with inoperative condition due to the most straightforward approach to transfer energy from strong cell or module to weak cell or module in a battery pack. If the cells are connected in series and both series- parallel combination, the strong and weak cells are found using efficient algorithm. Converter base equalization system with a high switching frequency holds the energy from strongest cell and releases to weakest cell for a while. In the charging and discharging condition, there is a need to think about bypass current to protect the overcharging and undercharging.

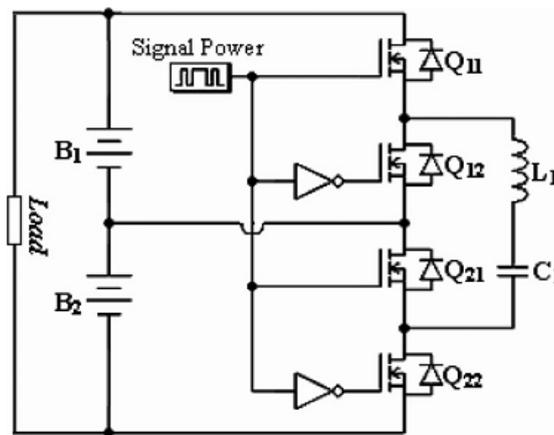


Figure 3. Equalization circuit based on quasi-resonant converter [19].

4. Temperature analysis

During charging and discharging cycle of charge balancing, cell temperature rises dramatically and may exceed its allowable limit (46°C). Battery cell performance depends on internal and ambient temperature. According to joule heating, temperature is generated inside a battery due to I^2R losses when current flows through its internal resistance shown in Eq. (7). Another two heat generation sources are the change of entropy and surrounding temperature of a battery [22]. Dynamic battery temperature is defined by a general energy balance equation shown in Eq. (6).

$$\rho C_{cell} \frac{dT_{cell}}{dt} = Q_{gen} - Q_p - Q_s \quad (6)$$

where

$$Q_{gen} = i(E_0 - V_{batt} + T \frac{dU}{dT}) + i^2 R$$

$$Q_p = hA_s(T_{cell} - T_{amb})$$

$$Q_s = E\sigma_{sb}(T_{cell} - T_{amb})$$

The internal temperature (T) can be found at any given time (t) and shown as follows

$$T(t) = L^{-1} \left(\frac{Q_{gen} R_{th} + T_{amb}}{1 + S.t_C} \right) \quad (7)$$

where C_{cell} is the heat capacity of a cell, t time, T_{cell} the battery temperature, Q_{gen} the overall heat generation inside the cell, i charging/Discharging current, T_{amb} ambient temperature, Q_p heat generation due to chemical reaction, AS the total surface area, h the heat temperature coefficient, Q_s

heat generation due to entropy changes, R_{th} thermal resistance, cell to ambient ($^{\circ}C/W$) and t_c thermal time constant, cell to ambient (s).

5. Simulation Results

To demonstrate the investigation of battery cell temperature with respect to time in second, a Li-ion (5.4AH, 3.7V) battery model and quasi-resonant converter base balancing circuit were chosen. The simulation time for discharging and the charge balancing operation is different due to limitation of simulation tool. The proposed work is simulated by Matlab-Simulink 2015b with the consideration of wide ambient temperature of 25-40 $^{\circ}C$, constant discharging current of 1-4Amp and SOC difference of 0.5%. In essence, the cell temperature is generated due to ambient temperature and current flowing through it during charging and discharging. Therefore, initially the ambient temperature and discharging current are assumed to be 25 $^{\circ}C$ as a room temperature and 1 Amp respectively.

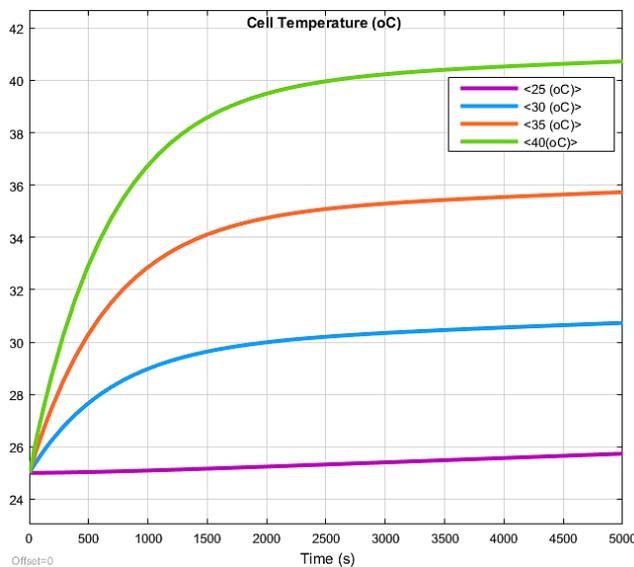


Figure 4. Internal temperature on different ambient temperature and constant discharging current (1A).

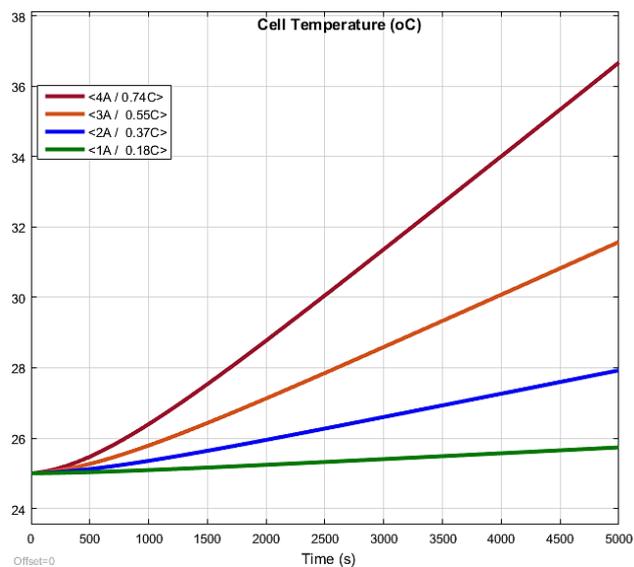


Figure 5. Internal temperature based on constant ambient temperature (25 $^{\circ}C$) and discharging current variation (1-4A).

Ambient temperature and constant discharging current variation have been considered to reflect the internal cell temperature. Cell temperature was rising as varying ambient temperature from 25-40°C where the discharging current were constant (1 Amp) shown in figure 4. From the figure, it can be seen that the temperature reached at 26°C after a certain time of 5000sec when the ambient temperature was 25°C. Again, ambient temperature was changed from 20°C to 25°C, 30°C and 35°C respectively to observe the effect of internal cell temperature. Accordingly, it is noticed that the rate of temperature rising was significant and proportional. When the ambient temperature was settled on 40°C, cell temperature changed from 25°C to around 41°C which was close to the maximum allowable operating range of 46°C. If the temperature exceeds the maximum range, Li-ion battery is unable to perform its normal behaviour during charging and discharging.

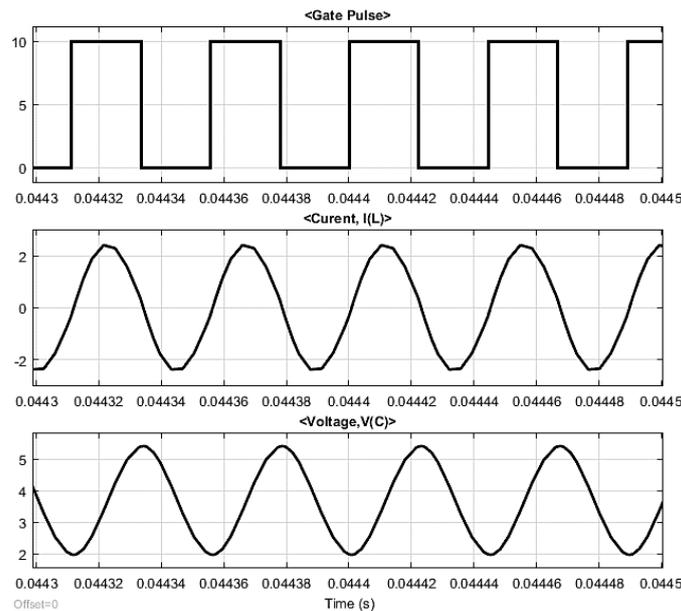


Figure 6. Resonant current and voltage curve in LC network.

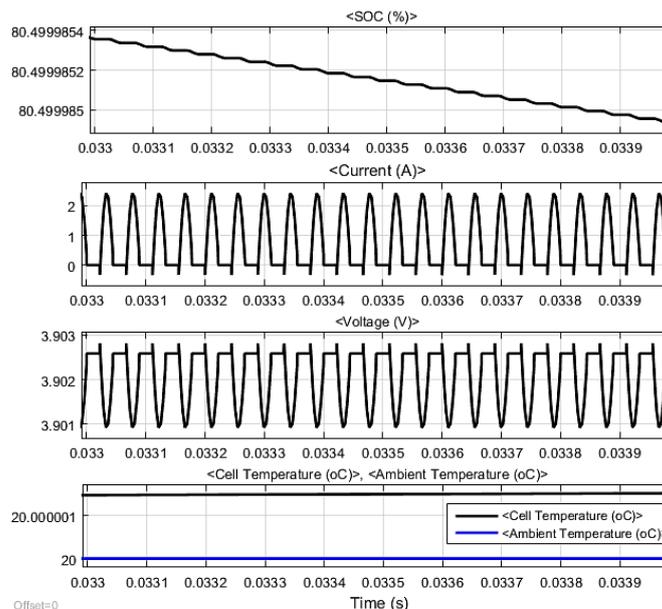


Figure 7. Battery cell (B1): SOC, Voltage, Current and internal temperature during balancing

Usually, temperature rising of the battery cell depends on battery C rate or discharging current and AH (ampere hour) rating. It is suggested that, C rate should be less than 1C to get the best performance [23-25]. In figure 5, discharging current was varied and ambient temperature were constant. Maximum current for discharging were 4Amp/ 0.74C in this case. The figure shows that the cell temperature gradually increased to nearly 26oC at a certain time of 5000sec when discharging current were 1Amp. In the similar manner, temperature reached to almost 37oC at a discharging current of 4Amp. During the charge balancing operation, both charging and discharging is occurring. The charge balancing circuit for two series connected cells, which has been exposed in the figure 3 where one cell is assumed to be a strong cell and another to be a weak cell. In addition, the charge transferring process was performed by dint of the LC network. This LC network was controlled by at a constant frequency of 22KHz and 50% duty ratio. The resonant current and voltage in the LC network was shown in figure 6. During the charge equalization process, higher cell was discharged from 80.5% and lower cell was charging from 80%. For both discharging and charging condition, cell temperatures were increasing from 20°C to 20.0002°C for B1 and 20.001°C for B2 respectively presented in figure7 and 8 respectively.

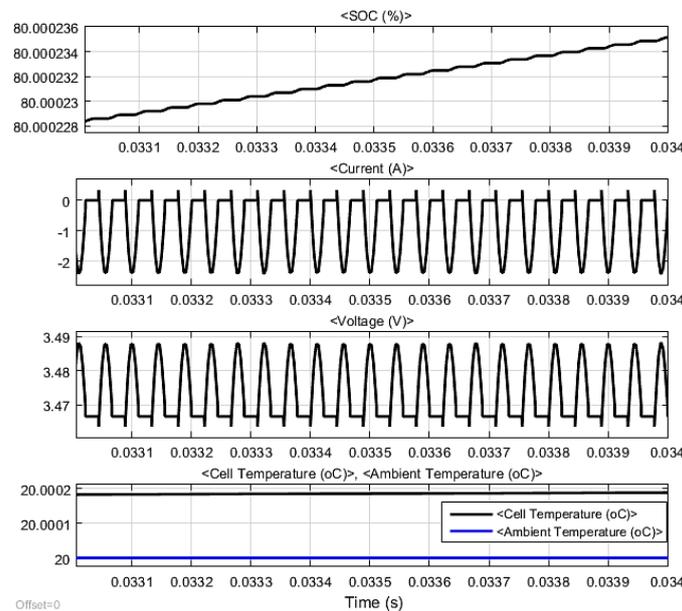


Figure 8. Battery cell (B2): SOC, Voltage, Current and internal temperature during balancing

The rising temperature depends on SOC difference, charging-discharging current and ambient temperature. The simulation time was setup around 1 sec and 2 secs for 2% and 5% respectively due to the limitation of simulation tools. Figure 9 shows the result of SOC charge equalization with temperature where the initial temperature was nearly 25oC and SOC for two cells were almost 80% and 80.2% individually. After 2sec, both SOC become equal to 80.125% and the temperature increased to just over 20.1°C. At this moment, it seems that rising temperature is not so much. In this case, if the SOC difference is large, growing temperature will be high. From the Figure 10, it can be said that, internal temperature increased more than the 2% difference.

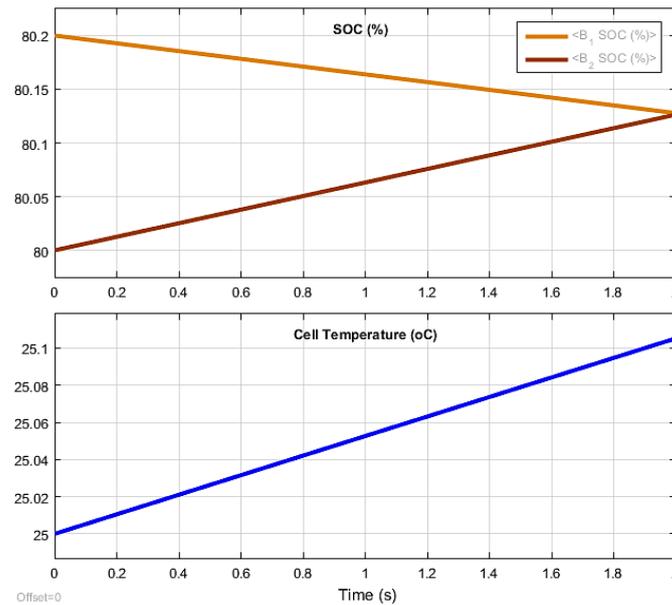


Figure 9. Battery cell (B1 and B2): SOC of 2% variation and internal temperature during balancing.

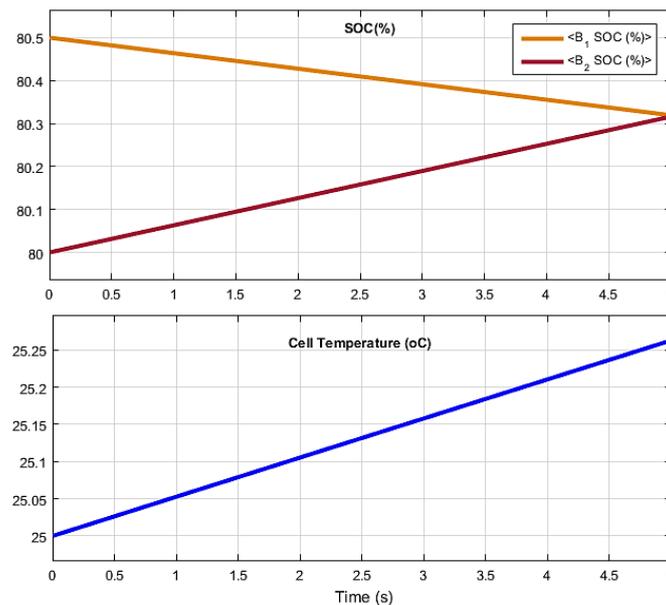


Figure 10. Battery cell (B1 and B2): SOC of 5% variation and internal temperature during balancing.

6. Conclusion

This paper has presented the analysis of the internal temperature of the individual cell during the charge balancing process. Among the charge equalization methods, quasi-resonant base charge balancing method has been applied for analysing the internal temperature. The analysis clearly shows that the rate of increasing internal temperature is influenced by ambient temperature and charging-discharging current (C-rate). In addition, it is obviously true that the highest peaks of the internal temperature of the battery cells depend on SOC difference. During the charge balancing process, the internal temperature may exceed its allowable limit if the SOC difference of the cells is 60%-80% (one is almost full and another is almost empty). In future, experimental work on different balancing

methods to analyse battery cell and pack temperature and to design an efficient charge equalization system.

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