Adaptive Passive Balancing for Serial Battery Cells with Dynamic Current Control

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ABSTRACT

Battery energy storage systems (BESS) and electric vehicles (EVs) commonly use passive balancing that dissipates excess energy from battery cells by fixed resistors. The passive balancing method is simple and cost-effective but suffers from slow balancing speeds. Furthermore, attempts to increase balancing speed can lead to higher final voltage differences between cells due to the polarization effect. To address these challenges, an adaptive passive balancing method is proposed. This method retains the simplicity of passive balancing while dynamically adjusting the dissipated current through switch control using a duty cycle. This adaptive approach not only reduces the adverse impact of polarization but also improves power efficiency. Simulation results demonstrate that the adaptive circuit provides faster and more efficient balancing, with reduced final voltage discrepancies.

1. INTRODUCTION

Battery management systems (BMS) are essential for ensuring the safe, efficient, and reliable operation of battery packs used in EVs, BESS, and portable electronics. A critical function of the BMS is cell balancing[1-2], which maintains a uniform voltage among all cells in a battery pack. Effective cell balancing maximizes the performance, lifespan, and safety of the battery. Passive balancing is a common method for achieving voltage uniformity due to its simplicity and low cost [3]. It operates by dissipating excess energy from overcharged cells as heat through fixed resistors. When the difference voltage between cells exceeds a *deltaV*, a switch connects the higher energy cell to a resistor, discharging the cell. However, this method has a key limitation: slow balancing speed. The balancing current is constant, governed by the resistor value and voltage difference between cells, making the process inefficient, especially when large voltage discrepancies exist. While reducing resistor values can increase the current, it also raises the polarization effect, potentially resulting in greater final voltage differences between cells. To address this limitation, an adaptive passive balancing circuit is proposed. This circuit enhances the traditional passive approach by introducing the flexibility to dynamically adjust the dissipative current flow. By maintaining simplicity while improving power efficiency, the adaptive method achieves significantly lower final voltage differences.

2. PROPOSED METHOD

Fig.1 depicts a passive balancing circuit composed of a bleeding resistor, R_i, and a switch, S_i. In conventional implementations, the switch S_i is activated when the voltage differential between cells exceeds the target value, *deltaV*. The switch remains engaged until the voltage of the *i-th* cell aligns closely with that of the lowest voltage cell within the *deltaV* range. However, due to the inherent polarization effects, this approach often results in a final voltage that is higher than the voltage target. To improve this issue, the proposed method introduces duty cycle control, D_i, for the switch. The idea is to dynamically adjust the amount of current used for balancing, rather than relying on a fixed resistor value.

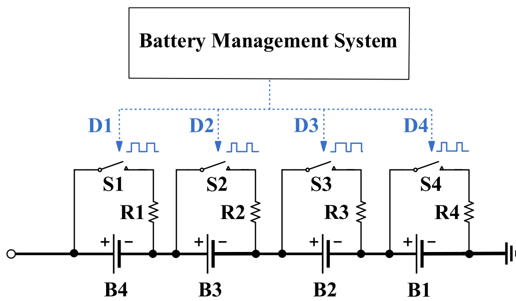


Fig.1 Passive balancing circuit

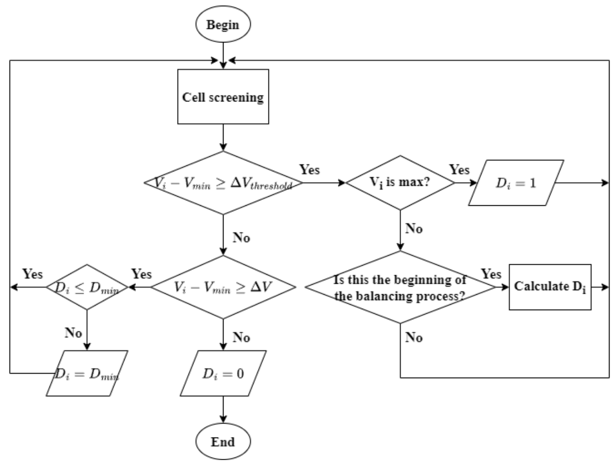


Fig.2 Flowchart of proposed method

The operation of the proposed method is depicted in Fig. 2. The process begins by monitoring the voltages of all cells within the battery pack. When a significant voltage disparity is detected, the balancing circuit activates, allowing current flow through the parallel resistor to quickly reduce these energy differences. As the voltage differences decrease to within the threshold voltage (V_{th}), the duty cycles of all switches are reduced to below D_{min}. This duty cycle allows for a smaller final *deltaV* without significantly extending the balancing process. The minimum duty can reduce dependence on trade off between balancing time and voltage difference in final. This adjustment lowers the balancing current, thereby minimizing the polarization effect and applying just enough current to achieve a final balance voltage smaller than *deltaV*. When a cell's voltage difference exceeds V_{th}, the duty cycle for the cell with the maximum voltage is set to 1, while the duty cycles for the remaining cells are calculated to equalize voltages within the maximum cell's balancing time. This process reduces thermal dissipation in both the switch and the bleeding resistor by optimizing the balancing current.

The duty cycle of the cells can be calculated to achieve the desired voltage equalization within the specified balancing time, ensuring that the cells reach uniform voltage levels efficiently and safely. The duty cycle at the *i-th* cell is defined as

$$D_i = \frac{R_{eqi} - R_{bi}}{R_i}, \quad (1)$$

where R_i is the passive balancing resistance circuit; R_{bi} represents the internal resistance of the cell; and the equivalent circuit resistance, R_{eqi}, is calculated using the balancing time equation

$$t_{max} = R_{eqi} \times C_{eqi} \times ln\left(\frac{V_{i\_init}}{V_{th}}\right) \quad (2)$$

where C_{eqi} is the charge equivalent capacitance of the cell evaluated from V_{i_init} to $V_{th} = V_{min} + \Delta V_{threshold}$, based on the method in [4]

$$C_{eqi} = \frac{\int_{V_i}^{V_{th}} C_{bi}(V_{OCi})dV_{OCi}}{V_{th} - V_{i\_init}}, \quad (3)$$

where C_{bi} is capacitance function of the *i-th* cell variable capacitor; V_{OCi} represents the *i-th* battery open circuit voltage.

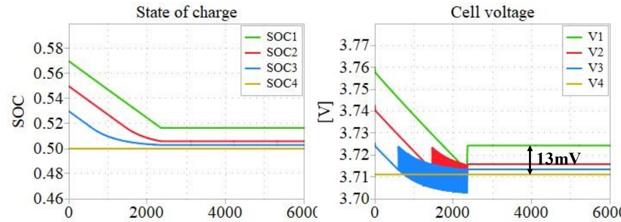
3. SIMULATION RESULT

To validate the effectiveness of the adaptive passive balancing method, a PLECS simulation of a 4-cell battery string was conducted in idle mode, based on an 18650 Li-ion Samsung SDI 3.6V/2.85Ah battery model. The initial SOC levels for the cells were set to $SOC_1 = 57\%$, $SOC_2 = 55\%$, $SOC_3 = 53\%$, $SOC_4 = 50\%$. The voltage difference threshold ($\Delta V_{threshold}$) is set at *3mV*, and it stops the balancing process when *deltaV* reaches *2mV*. The switching frequency is fixed at *100Hz*, the resistances R_i are tested either with *16*Ω and *33*Ω, and R_{bi} *is 42.6m*Ω. The minimum duty cycle (D_{min}) of 0.5 is applied to all cells when its cell voltage is lower than V_{th}.

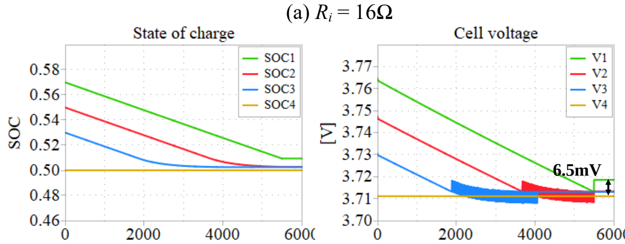
In the conventional method, it took *5501* seconds with a *33*Ω resistor to reach a 7.*5mV* voltage difference, and *2382* seconds with a *16*Ω resistor to achieve a *13mV* difference (Fig. 3). In contrast, the proposed method required *3098* seconds using a *16*Ω resistor to reach a significantly lower voltage difference of 3.*8mV* (Fig. 4). The proposed method achieves a smaller final voltage difference with only a modest increase in balancing time. Furthermore, even with the same bleeding resistor value, the proposed method shows less total power loss (P_Σ) compared to the conventional method (as seen in Table 1). This reduction in power dissipation is achieved by lowering the current through resistors R_2 and R_3 owing to duty cycle adjustments ($D_2 = 0.7$, $D_3 = 0.4$), without affecting the whole balancing process, reducing the overall power dissipation without affecting the overall balancing time.

4. CONCLUSION

This paper presents an adaptive passive balancing method that improves upon conventional techniques by introducing dynamic duty cycle control. Simulation results demonstrate that this method achieves significantly lower final voltage differences, minimizes polarization effects, and improves power efficiency. Future work could investigate further optimization of this approach, including a deeper analysis of its thermal impact of this method and long-term effects on battery performance.



(a) $R_i = 16\Omega$



(b) $R_i = 33\ \Omega$

Fig.3 Conventional passive balancing waveform

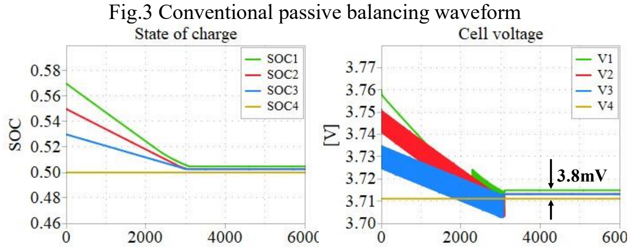


Fig.4 Proposed passive balancing waveform with $R_i = 16\ \Omega$

Table 1. Power loss of passive balancing with 16Ω bleeding resistor

Power loss [W]	P_1	P_2	P_3	P_Σ
Conventional method	0.866	0.714	0.436	2.015
Proposed method	0.803	0.583	0.337	1.723

This research (P0025291) was supported by the Ministry of Trade, Industry & Energy (MOTIE), Korea Institute for Advancement of Technology (KIAT) through the Encouragement Program for The Innovation Cluster Development of Region, and by Regional Innovation Strategy (RIS) through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (MOE) (2021RIS-003).

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