Improved Passive Cell Balancing Strategy for Lithium-Ion Batteries Using Current Sensor-less DCIR Estimation

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ABSTRACT

This paper proposes an improved passive equalization algorithm based on real-time, sensor-less direct current internal resistance (DCIR) estimation to compensate for IR drops and accurately estimate the true open-circuit voltage (OCV) during balancing operations. Simulation results show that the DCIR-compensated algorithm efficiently mitigates switching chattering and minimizes the balancing gap between cells to below 2 mV. Additionally, the proposed method maintains high balancing accuracy across varying cell internal resistances (e.g., 0.01Ω to 0.09Ω), demonstrating robust adaptability to cell aging. Ultimately, this software-level OCV compensation approach significantly enhances the performance and reliability of conventional passive balancing circuits without adding hardware complexity.

1. INTRODUCTION

Lithium-ion batteries are essential for modern energy storage systems and electric mobility due to their high energy density and long working cycle life. In applications like electric two-wheelers and industrial energy systems, many cells must be connected in series to get the required voltage output. But manufacturing variations, different temperatures, and varying aging rates lead to cell imbalance within the multi-cell battery pack. This imbalance limits the usable capacity of the pack to that of its weakest cell and further degrades battery lifespan and increases the risk of thermal instability. Also, conventional methods for preparing and testing battery uniformity are complex, time-consuming, and require high-costs equipment[1].Passive cell balancing is mostly adopted in industrial sectors for its simplicity and low cost; But traditional voltage-based strategies often fall short in high-precision applications. These traditional methods depend on terminal voltage, which is affected by resistance effect and chemical polarization. This leads to balancing errors of 8-10 mV. While recent improvements have used fixed ohmic compensation to reduce these errors, they often fail to deal with the dynamic resistance changes found in aged battery pack[2]. Furthermore, many literatures suggest using SOC for better results. But estimating the SOC of each cell accurately is difficult and not practical[3]. This paper proposes an enhanced adaptive current sensor-less balancing approach that focuses on achieving balancing accuracy. Through rest-state diagnostics to estimate fresh direct current internal resistance (DCIR), the proposed approach eliminates the need for physical current sensors, reduces hardware costs, and ensures reliable balancing even in aged cells.

2. PROPOSED METHOD

The configuration of the proposed system uses passive balancing architecture, as shown in Fig. 1. Each cell in the series string is connected in parallel to a balancing branch consisting of a switch and a shunt resistor R_{bal}. To minimize the hardware size and costs, physical current sensors are eliminated. Instead, the balancing current I_{bal} is derived mathematically based on the terminal voltage measured by the battery management system (BMS). The proposed equalization algorithm works in three steps: first the microcontroller unit estimates the balancing current flowing through each balancing branch using the measured terminal voltage V_m and the known resistance of the parallel resistor R_{bal}:

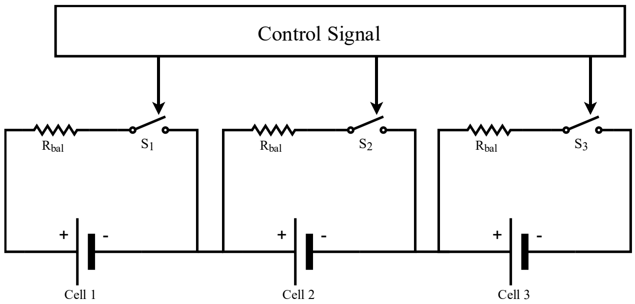

Fig.1 Schematic of passive balancing circuit.

$$I_{bal} = \frac{V_m}{R_{bal}} \qquad (1)$$

Secondly, to improve the robustness against manufacturing variation and aging, which leads to cell imbalance, the proposed algorithm estimates the dynamic DCIR of each cell once during the initial balancing pulse by capturing the instantaneous voltage drop when the balancing switch is activated. This minimizes the error associated with fixed-parameter approach. The initial DCIR is estimated by using the following relationship:

$$DCIR_{est} = (V_{rest} - V_m)/I_{bal} \qquad (2)$$

where V_{rest} represent the terminal voltage during the rest state and V_m is the terminal voltage captured immediately after the balancing switch is turned ON. Through capturing this voltage delta $(V_{rest} - V_m)$, the control logic can accurately estimate cell aging and manufacturing variations that lead to internal resistance mismatch within the pack. At step third the MCU continuously updates the estimated open-circuit voltage (V_{ocv_est}) during equalization duration to prevent early termination due to ohmic drops. The compensation logic is defined as:

$$V_{ocv\_est} = V_m + (S_n \times I_{bal} \times DCIR_{est}) \qquad (3)$$

where S_n represent the switching state (1 for ON, 0 for OFF). This ensures that the passive balancing process continues until the actual open-circuit voltage of the cell is balanced within less than 2 mV threshold. The detailed algorithm flowchart of the proposed method is shown in Fig.2.

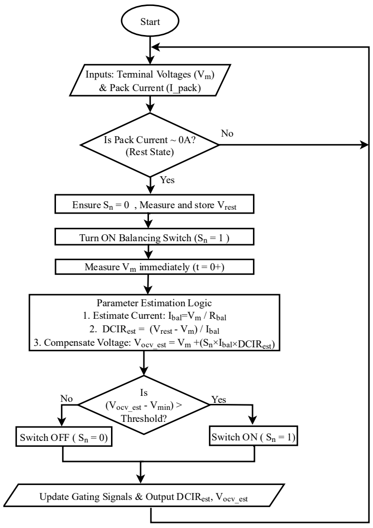

Fig.2 Flowchart of the proposed balancing algorithm.

3. SIMULATION & RESULTS

To assess the performance of the proposed equalization logic, simulation was carried out using PLECS software. The battery pack was composed of series-connected lithium-ion cells based on the 18650-type (3.7V/2.9Ah) parameters.

To validate the robustness of the proposed current sensor-less DCIR estimation algorithm, manufacturing variations and aging effects were emulated by intentionally increasing the internal resistance of the specific cell to 0. 0926Ω.

The results focus on the accuracy of the estimated open-circuit voltage (V_{ocv_est}) and the overall equalization accuracy under different internal resistance mismatches. The proposed algorithm estimates the OCV with a deviation of less than 2 mV, effectively minimizing the terminal voltage errors. The algorithm also maintains below 2 mV accuracy in simulation even under resistance mismatch, unlike traditional methods with up to 10 mV final difference, preventing early cutoff. Moreover, the system adapts to calculate fresh internal resistance every time balance is needed, ensuring reliable performance over the cell lifecycle without needing any additional sensors.

Table 1. Simulation parameters

Battery cell type	Lithium-ion (18650)
Nominal voltage	3.7 V
Rated capacity	2.9 Ah
Number of cells in series	3
Balancing resistor	27 Ω
Healthy cell IR (cell 1 & cell 3)	0.0426 Ω / 0.0327 Ω
Aged cell (intentional) IR (cell 2)	0.0926 Ω
Simulation software	PLECS

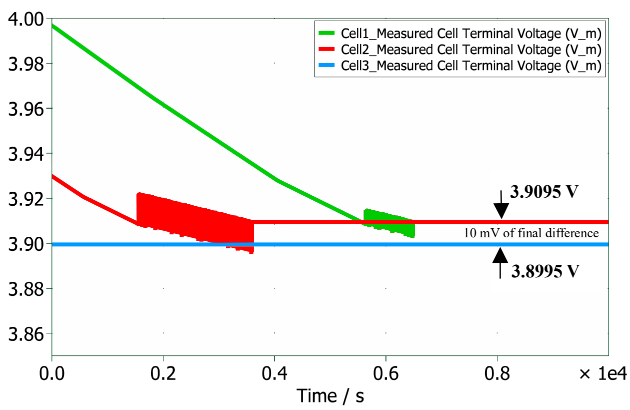

Fig.3 Terminal voltage chattering and 10mV final difference in conventional passive balancing method.

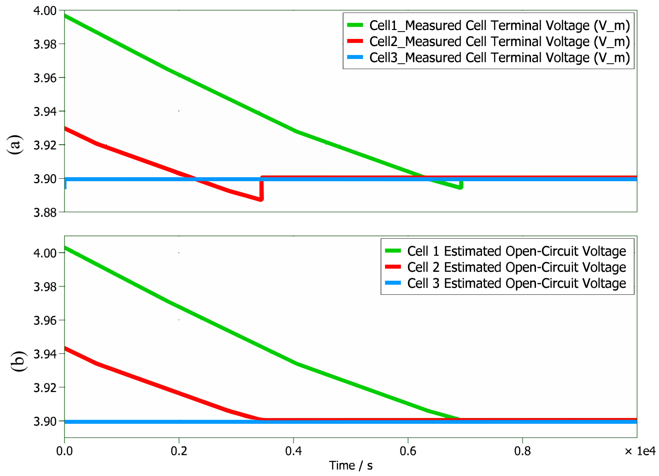

Fig.4 Simulation results of the proposed adaptive balancing algorithm: (a) measured terminal voltage V_m, and (b) estimated OCV V_{ocv_est}.

In Fig.3 the terminal voltages show chattering due to internal resistance, which can cause early cutoff in traditional balancing. These increase the electrical stress on MOSFETs and leave the cells with around 10 mV of final difference. Fig.4 shows the proposed algorithm dynamic response. Fig.4(a), the measure terminal voltage (V_m) experiences an instantaneous IR drop upon activation of the switch, which conventionally leads to chattering in traditional systems. To mitigate this issue, the MCU continuously calculates the estimated OCV (V_{ocv_est}), depicted in Fig.4(b). This real-time compensation of the IR drop yields a stable voltage profile. Consequently, it eliminates chattering and ensures continuous balancing without requiring complex MCU control logic.

4. CONCLUSION

This paper introduced sensor-less adaptive equalization approach for Li-ion battery packs. By applying dynamic compensation during rest condition, the algorithm reduces terminal voltage errors that cause premature cutoff in conventional passive balancing systems. The simulation results demonstrate that the method achieves a precision of less than 2 mV, reducing the cell-to-cell voltage deviation by over 75% as compared to 8-10 mV deviations found in traditional methods. The proposed system also adapts to cell aging and manufacturing variations during its lifetime. As no additional current sensors are required, it provides a cost-effective method for improving battery capacity and diagnostic reliability in industrial applications. Future work includes hardware implementation and real-time validation of the proposed algorithm on a low-cost microcontroller.

ACKNOWLEDGMENT

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1. Introduction

- Series-connected lithium-ion battery packs suffer from cell-to-cell imbalance due to manufacturing tolerances and aging.
- Passive balancing relies heavily on terminal voltage (V_m), which includes dynamic $I \times R$ drop and the polarization, causing an inherent balancing error.
- So, OCV compensation is required.
- Fixed ohmic compensation strategies fail to handle dynamic internal resistance changes in aged battery packs**[1]**, while SOC-based methods are too computationally complex for low-cost microcontrollers (MCUs) **[2]**.
- Proposed solution: A current sensor-less true OCV compensation algorithm using a dynamic, rest-state DCIR estimation to achieve high precision with zero added hardware cost.

2. Proposed method

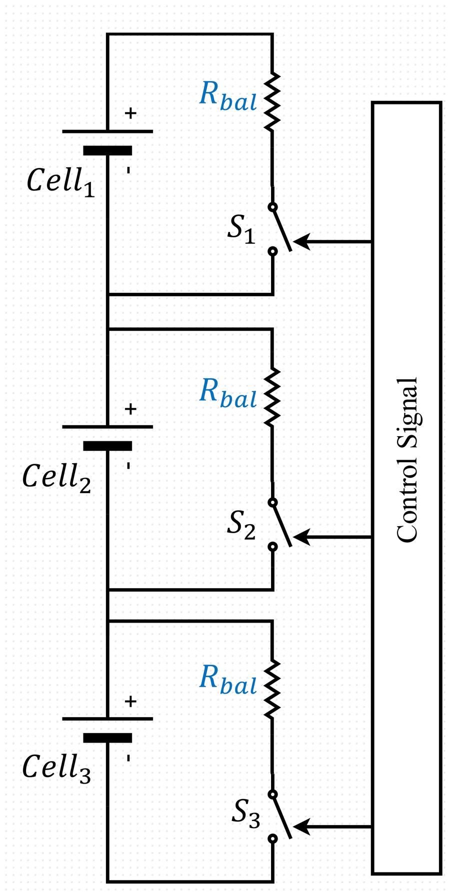
❖ Current and DCIR Estimation Logic

- Equation (1): Balancing current I_{bal} calculation without physical sensors:

$$I_{bal} = \frac{V_m}{R_{bal}} \qquad (1)$$

- Equation (2): Dynamic DCIR estimation during the initial balancing pulse (V_{rest} is captured at $I_{pack} = 0A$):

$$DCIR_{est} = \frac{V_{rest} - V_m}{I_{bal}} \qquad (2)$$



Schematic of passive balancing circuit

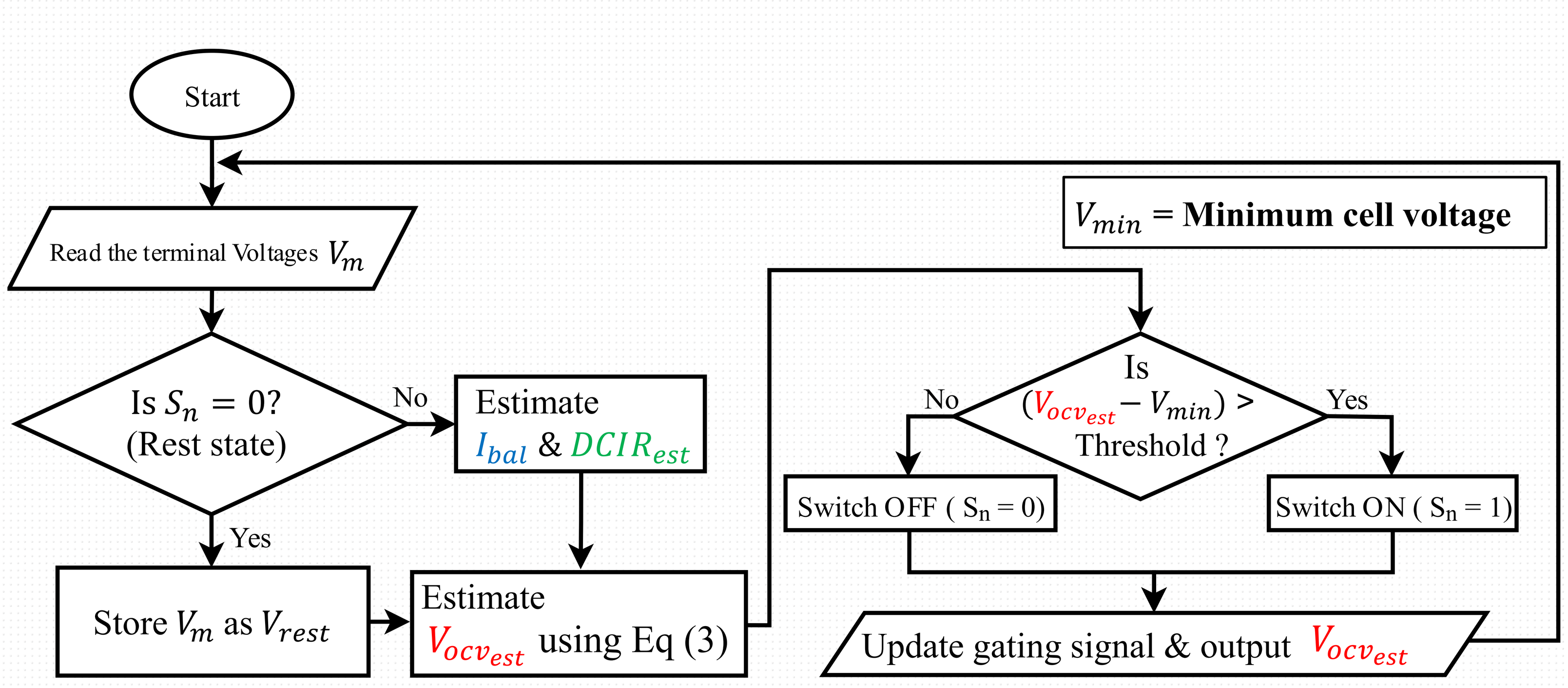
❖ True OCV Compensation

- Equation (3): Continuous software-level OCV calculation to eliminate voltage drops from the raw measured voltage and avoid premature cutoff:

$$V_{ocv_{est}} = V_m + S_n \times I_{bal} \times DCIR_{est} \qquad (3)$$

- $V_{ocv_{est}}$: Estimated true OCV (compensated for accurate balancing decisions).
- V_m: Raw measured voltage (distorted by internal resistance).
- S_n: Switch state (1 = ON, 0 = OFF) of the balancing circuit.
- I_{bal}: Balancing current (calculated without physical sensors) by equation (1).
- $DCIR_{est}$: Estimated internal resistance (adapts dynamically to cell aging) by equation (2).

❖ Proposed Balancing Algorithm Flowchart Logic



Flowchart of the proposed balancing algorithm.

3. Simulation Verification

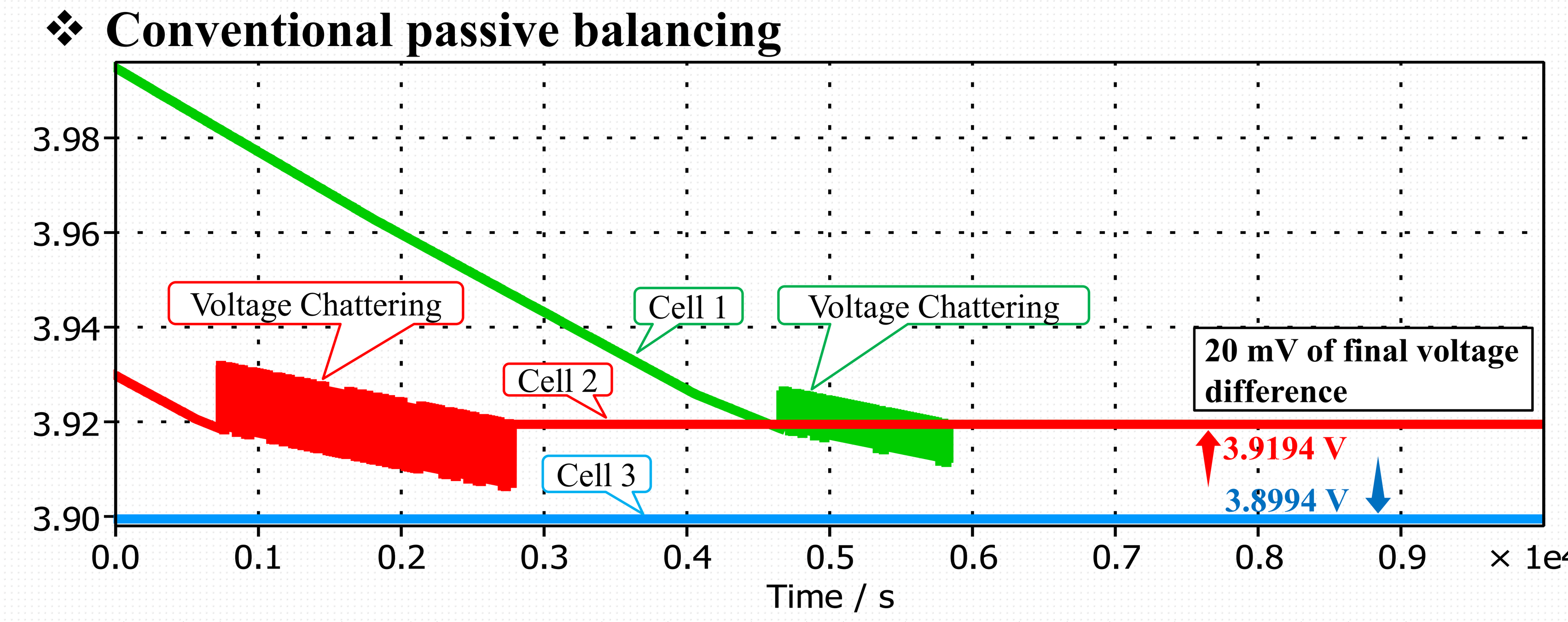
Table 1. Simulation parameters

Battery cell type	Li-ion (18650)
Nominal voltage	3.7 V
Rated capacity	2.9 Ah
Pack Configuration	3S
Balancing resistor	27 Ω
Healthy cells IR (cell 1 & cell 3)	42.6 mΩ, 32.7 mΩ
Aged cell IR (cell 2)	92.6 mΩ
Cell equivalent model	R_{int}
Simulation software	PLECS

Table 2. Balancing Performance Comparison

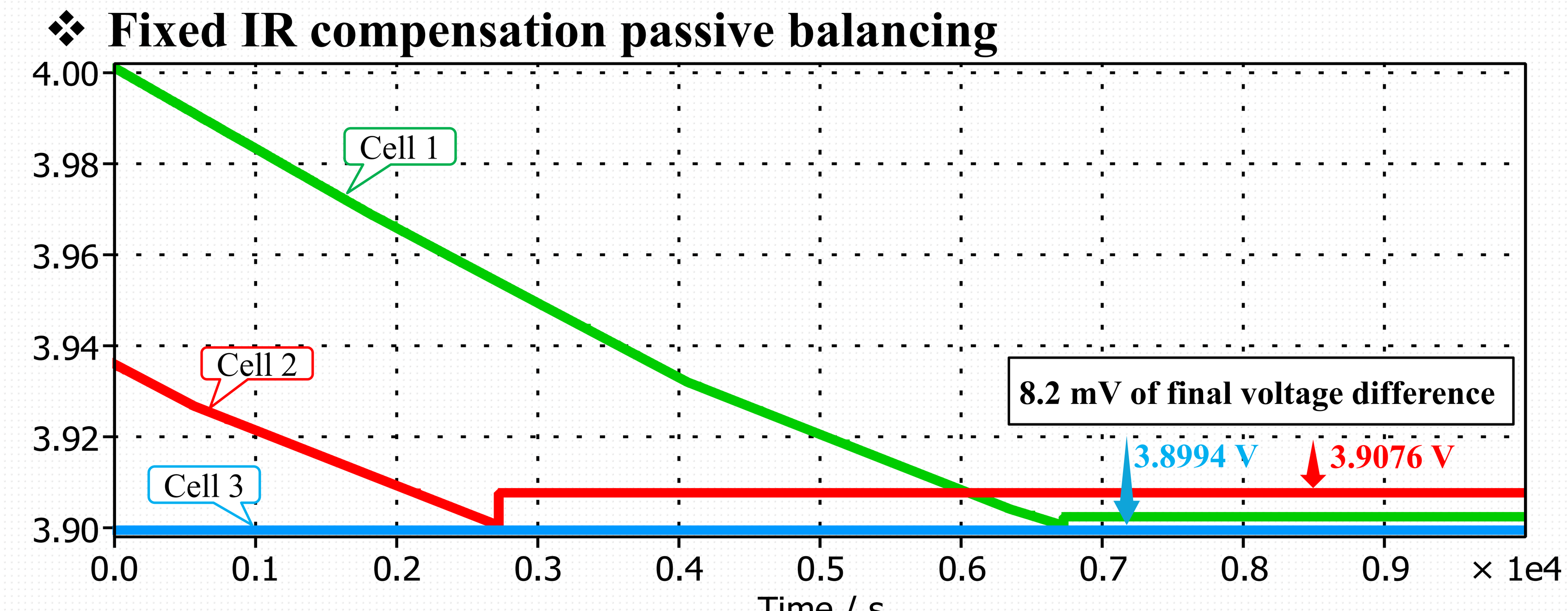
Evaluation Parameter	Conventional	Fixed ohmic compensation	Proposed Method
Final Cell Voltage Difference	20 mV	8-10 mV	< 2 mV
Adaptability to Cell Aging	None	Fails under dynamic DCIR	Calculates fresh dynamic DCIR
Voltage Deviation Reduction	N/A	Baseline	Over 75% Improvement

❖ Conventional passive balancing



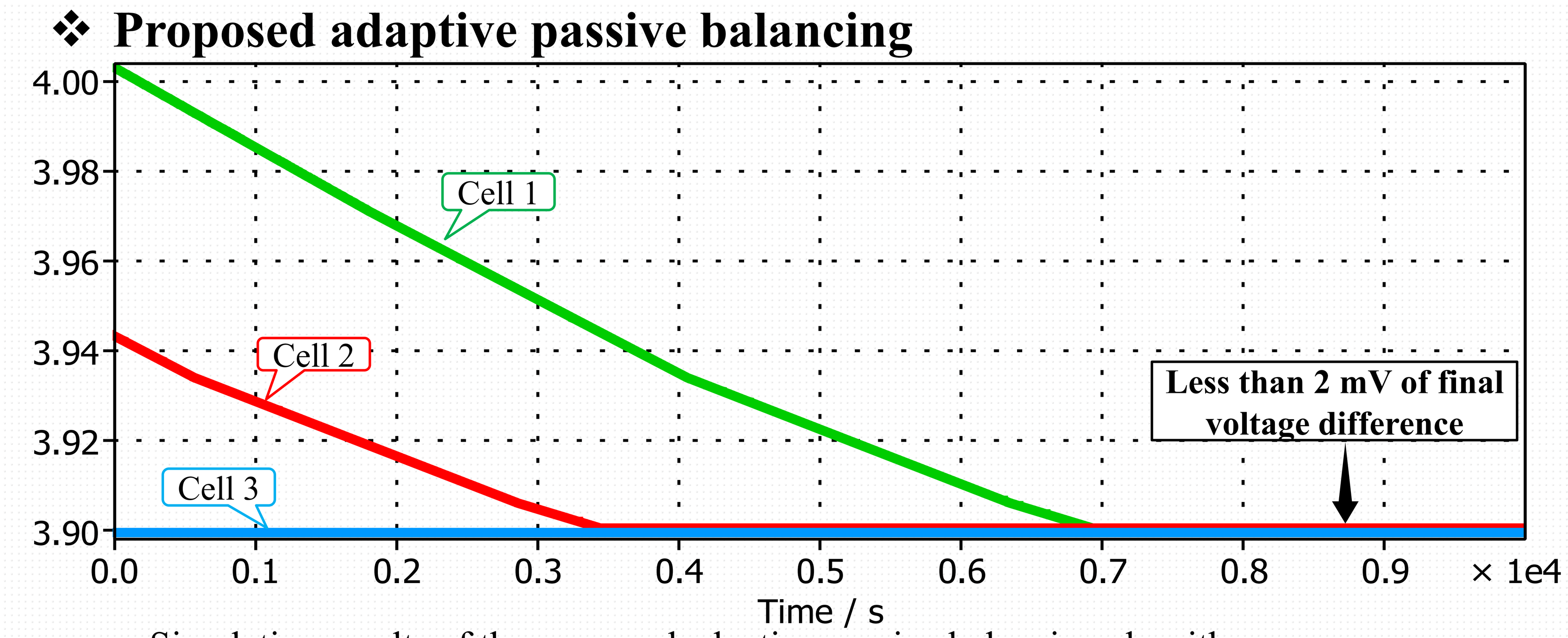
Simulation results of the conventional passive balancing method, showing terminal voltage chattering and a 20 mV final voltage difference.

❖ Fixed IR compensation passive balancing



Simulation results of the fixed compensation passive balancing algorithm.

❖ Proposed adaptive passive balancing



Simulation results of the proposed adaptive passive balancing algorithm.

4. Conclusions

- An improved passive balancing strategy based on real-time, sensor-less direct current internal resistance estimation has been presented to accurately compensate for dynamic IR drops.
- Simulation results show a cell-to-cell voltage deviation of below 2 mV, achieving an error reduction of over 75% compared to conventional methods.
- By updating parameters in real time without physical current sensors, this method provides a cost-effective and aging-adaptive solution for commercial BMS.
- Experimental verification will be added as a subsequent study.

5. Reference

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