Estimating Passive Balancing Time for Lithium Iron Phosphate (LiFePO4) Battery Using Nonlinear Capacitor-Based Modeling

Ngoc-Thao Pham*, and Sung-Jin Choi**
Department of Electrical, Electronic and Computer Engineering, University of Ulsan, Ulsan 44610, South Korea
*ptnthao1776@gmail.com, **sjchoi@ulsan.ac.kr

ABSTRACT

In Battery Energy Storage Systems (BESS) and Electric Vehicles (EVs), the use of high-capacity batteries connected in series or parallel requires cell balancing circuits for safety and battery longevity. Estimating the needed balancing time, whether for passive or active circuits, is challenging due to the nonlinear OCV-SOC relationship, especially in Lithium Iron Phosphate batteries with SOC-OCV hysteresis and flat plateaus. To tackle these issues, this study introduces a fast-balancing time estimation method using a nonlinear capacitor battery model. It employs a simplified R-C time constant calculation based on charge-equivalent capacitance. The simulation result for passive balancing is used to verify the proposed method.

1. INTRODUCTION

In the realm of Battery Energy Storage Systems (BESS) and Electric Vehicles (EVs), the integration of high-capacity batteries, whether in series or parallel configurations, stands as a pivotal enabler of enhanced energy storage capabilities[1]. However, the effective management of these high-capacity batteries necessitates the implementation of cell-balancing circuits. These circuits are indispensable in ensuring the safety, efficiency, and longevity of the battery systems. The accurate estimation of the required balancing time, be it for passive or active balancing techniques, remains a challenge in the field of battery technology. The intricacy of this challenge can be primarily ascribed to the non-linear relationship between open-circuit voltage (OCV) and state of charge (SOC) exhibited by batteries. This complexity becomes particularly pronounced in the case of Lithium Iron Phosphate (LiFePO4 or LFP) batteries, renowned for their unique hysteresis and flat plateau characteristics in the SOC-OCV profile[2]. Although a novel nonlinear double-capacitor model[3] can capture the nonlinear SOC-OCV relationship, it grapples with complexity.

On the other hand, the ability to predict and optimize battery runtime or circuit performance is dependent on battery models. Notably, Equivalent Circuit Models (ECMs)[4] in Fig.1(a) have gained prominence in real-time applications due to their simplified structure and less computational demand. ECMs incorporate a voltage source and battery impedance, which are commonly employed. Nevertheless, this model faces challenges in estimating the balancing duration of the equalizer circuit. Moreover, the need to simulate ECMs for determining operating times can be time-consuming, especially when dealing with a large number of cells. Addressing these intricacies, this research introduces a nonlinear capacitor battery model. The proposed model offers an expeditious approach to evaluating the essential balancing time and is easy to apply. R-C time constant is utilized in the rapid estimation of the balancing duration. To substantiate the utility and accuracy of this novel approach, the research employs simulations, with a particular focus on passive balancing methodologies.

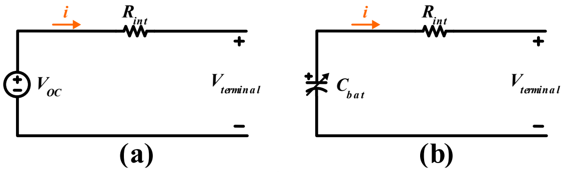

Fig.1 Battery model (a)Conventional model
(b)Nonlinear Capacitor model

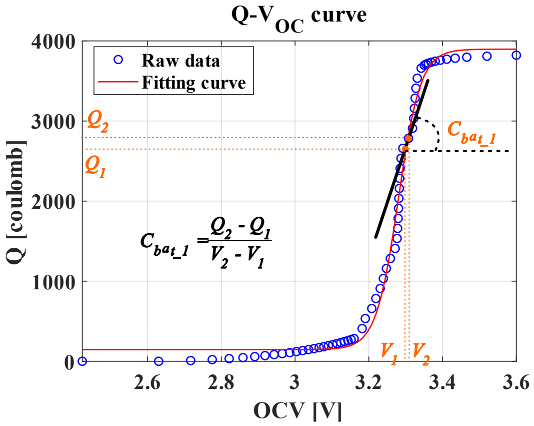

Fig.2 Q_V_{OC} curve of LFP battery

2. PROPOSED METHOD

This study proposes a nonlinear capacitor for the battery model. The proposed model is simple with a

Table 1. The passive balancing time comparison

SOC_{ini} [%]	SOC_{fin} [%]	V_{ini} [V]	V_{fin} [V]	C_{eq} [F]	R_{eq} [Ω]	t_{cal} [s]	t_{sim} [s]	t_{error} [%]
86.87	80.44	3.335	3.321	17589.533	27.01	2067.2	2011.9	2.75
84.33	74.17	3.329	3.310	20954.567	27.01	3274.0	3200.6	2.29
55.55	43.17	3.284	3.268	30768.539	27.01	4044.0	4054.2	-0.25
46.04	37.19	3.272	3.260	29294.509	27.01	2900.3	2926.3	-0.89
44.18	19.81	3.268	3.227	23327.847	27.01	7881.1	8017	-1.70

variable capacitor connected to the internal resistor as Fig. 1b. The variable capacitor has capacitance as a function of open circuit voltage V_{OC}. Therefore, the capacitance function value is constructed by the stored charge and voltage curve. However, conventional polynomial curve fitting methods fall short when applied to LFP batteries, primarily due to the voltage stability in the wide range (20% to 80% SOC) as Fig.2. To eliminate this issue, the sigmoid function is employed.

For this analysis, an LFP battery (1100mAh)[5] tested at 25°C is selected. Through the application of sigmoid curve fitting to the Q-V_{OC} curve, the Q(V) function is determined. The battery's capacitance at various voltages is interpreted as the tangent capacitance value, representing the slope of the tangent equation at each point on the Q-V_{OC} curve (Fig.2). The tangent capacitance function is mathematically defined as (1).

$$C_{bat} = \frac{dQ(V_{OC})}{dV_{OC}} \qquad (1)$$

3. SIMULATION RESULT

Passive balancing (Fig.3), a widely adopted technique in the industry, has gained popularity owing to its simplicity and cost-effectiveness in managing multi-cell battery systems. The balancing resistors discharge the cell with the highest voltage. The discharge process persists until equilibrium is attained, ensuring that all cells within the battery pack are balanced.

The duration of the discharging procedure can be effectively determined by considering the R-C time constant, a parameter associated with a nonlinear capacitor-based battery model. In this context, a charge equivalent capacitance, denoted as C_{eq}, is introduced to simplify and approximate the complex behavior of the nonlinear capacitor-based model.

$$C_{eq}(V_{OC}) = \frac{\int_{V_{OC}(t_0)}^{V_{OC}(t_1)} C_{bat}(V_{OC})dV_{OC}}{V_{OC}(t_1) - V_{OC}(t_0)} \qquad (2)$$

where $V_{OC}(t_0)$, $V_{OC}(t_1)$ is the open circuit voltage at t_0, and t_1 respectively.

The balancing time, Δt, of the battery is calculated by

$$\Delta t = C_{eq}R_t ln\left(\frac{V_{OC}(t_0)}{V_{OC}(t_1)}\right) \qquad (3)$$

where R_t is the total of the battery internal resistance and balancing resistance (27Ω).

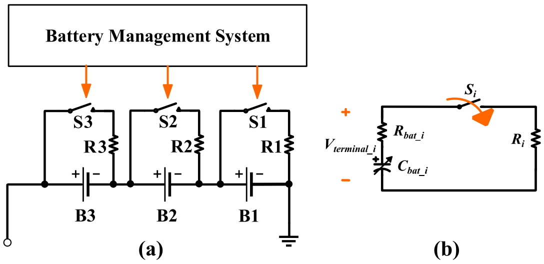

Fig.3 Battery passive balancing structure
(a) Topology structure (b) Equivalent circuit

Table 1 depicts that balancing time from the calculation can reach the accuracy with 2.8%, where t_{sim} and t_{cal} are the balancing time in simulation and calculation respectively.

4. CONCLUSION

A nonlinear capacitor-based battery model for LFP battery is proposed. The capacitance function is calculated using the open circuit voltage and the stored charge. The terminal voltage comparison results show that the proposed model is accurate. The proposed model is useful for quickly and simply estimating battery balancing time with an error of no more than 2.8%.

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.

REFERENCE

[1] M. Einhorn, W. Roessler, and J. Fleig, “Improved performance of serially connected li-ion batteries with active cell balancing in electric vehicles,” IEEE Transactions on Vehicular Technology, vol. 60, no. 6, pp. 2448–2457, 2011.

[2] Roscher, Michael A., and Dirk Uwe Sauer. "Dynamic electric behavior and open-circuit-voltage modeling of LiFePO4-based lithium ion secondary batteries." Journal of Power Sources 196.1 (2011): 331-336.

[3] Tian, Ning, Huazhen Fang, and Jian Chen. "A new nonlinear double-capacitor model for rechargeable batteries." IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2018.

[4] Wang, Yujie, et al. "A comprehensive review of battery modeling and state estimation approaches for advanced battery management systems." Renewable and Sustainable Energy Reviews 131 (2020): 110015.

[5] CALCE battery research group homepage.
URL https://calce.umd.edu/battery-data.