Novel Battery Model Employing Variable Capacitor for Effective Description of SOC Behavior

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***Abstract*—High-capacity batteries connected in series and/or parallel in the battery energy storage system (BESS) and electric vehicle (EV) require cell balancing circuits to ensure their lifetime and safety. Conventionally, a sequence of circuit simulations or tedious hardware tests are the only ways to evaluate the performance of the balancing algorithm. However, since the battery capacity is large, it takes much time to examine the entire balancing process under various combinations of initial voltage conditions. Moreover, it is difficult to estimate the balancing time due to the non-linear relationship between the open-circuit voltage (OCV) and the state of charge (SOC). To mitigate the problem, this paper proposes a variable capacitor model to simplify the SOC-OCV curve for rapid evaluation of the balancing time. Compared to the conventional variable voltage-source model, it can provide a rapid estimation of the balancing time with high accuracy by simple calculation of the R-C time constant based on the concept of charge-equivalent capacitance. The proposed method is useful for active balancing circuits as well as passive balancing schemes. After validating the model accuracy by experimental results, a switched-capacitor active balancing circuit and passive cell balancing chip are implemented to verify the effectiveness of the proposed model.**

Keywords—battery modeling, battery SOC, variable capacitor.

I. INTRODUCTION

Due to the rapid evolution of BESS and EVs, the demand for high-capacity batteries continues to surge. Depending on application requirements, a hundred or even a thousand of these high-capacity batteries are connected in series and/or parallel in the battery energy storage system [1]-[3]. However, their utilization comes with a set of challenges in ensuring the longevity and safety of these systems. A critical challenge revolves around cell balancing - the process of ensuring that individual cells within a battery pack maintain uniform charge levels.

In conventional practice, evaluating the performance of cell-balancing algorithms has been a challenging task. Typically, this process involves a sequence of circuit simulations or hardware tests [4]-[5]. While effective, these approaches are often time-consuming, resource-intensive, and not well-suited for systems with large battery capacities. The scale and complexity of these systems necessitate an alternative approach that can provide rapid and accurate estimations of the balancing time.

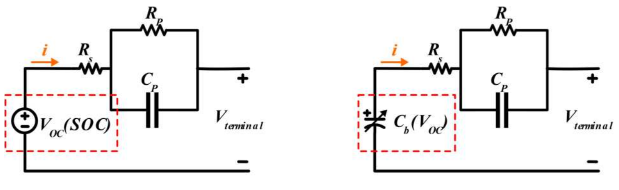
On the other hand, the behavior of the battery in the circuit cannot be predicted and optimized without having access to battery models. Various battery modeling approaches are mentioned [6], but equivalent circuit models (ECMs) [7]-[8] have a considerable amount of attention in real-time applications due to their simplified structure and less computational demand. ECMs utilize electrical elements such as voltage sources, resistors, and capacitors to imitate a battery's characteristics. Conventionally, ECMs consisting of a variable voltage source and Randles circuit as Fig. 1a are widely used, but it is hard to predict the balancing time of the equalizer circuit by that model without simulation. Another ECM is the resistance-capacitance battery model [9]. This model incorporates two capacitors for charge storage. The first capacitor, C_b, is notably large and symbolizes the battery's extensive chemical charge storage capacity. The second capacitor, C_c, is small and predominantly signifies the surface effects within a cell. This circuit configuration enables the capturing of hysteresis and polarization phenomena of the battery, but it is more complex.

To eliminate the issues, this paper proposes a variable capacitor model as a means to simplify the SOC-OCV curve and expedite the evaluation of balancing time. This approach provides a direct calculation of the balancing time through the R-C time constant, employing the foundational concept of charge-equivalent capacitance. The formulation of this novel model is expounded upon in Section II. Subsequently, Section III presents the application of the proposed model in the computation of balancing time, and the conclusion is made in Section IV.

II. VARIABLE CAPACITOR MODEL

A. Model Formulation

The proposed model utilizes the relationship between the stored charge and the OCV of the battery to determine the incremental capacitance. The proposed model is very simple with only a variable capacitor and a Randles circuit as Fig. 1b, where the capacitance is a function of open circuit voltage



(a) (b)

Fig. 1. Battery model (a) Variable voltage source model
(b) Variable capacitor model

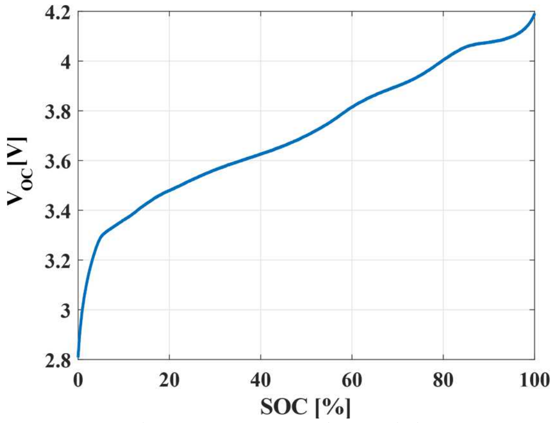


Fig. 2. SOC vs. OCV characteristic

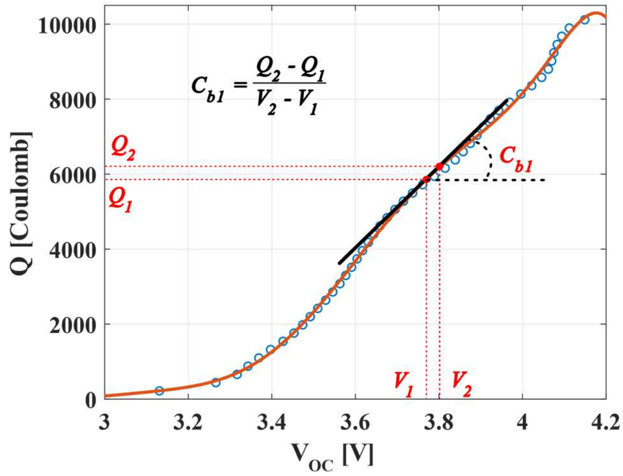


Fig. 3. Stored charge vs. OCV curve

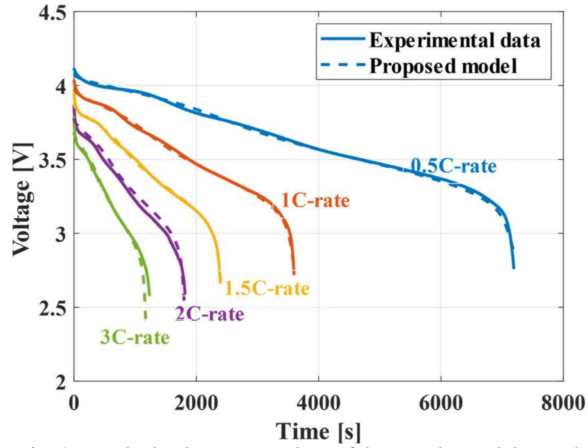


Fig. 4. Terminal voltage comparison of the experimental data and the proposed model simulation

V_{OC}. In this approach, the focus is to replace the variable voltage with a variable capacitor. The variable capacitor can combine with diverse battery impedance models depending on the specific application requirements. Here is how to transform the conventional variable voltage source model into the proposed model.

Conventionally, the initial voltage of the variable capacitor, $V_{OC\text{-}init}$, is identified by the polynomial function of SOC as shown in Fig. 2. From the V_{OC} versus SOC curve, the stored charge versus OCV curve in Fig. 3 is obtained by integrating the curve. Next, by applying polynomial curve fitting for the Q-V_{OC} curve, the Q(V_{OC}) function is determined. The capacitance of the battery at various OCV is obtained by the tangential slope at each point on the Q-V_{OC} curve in Fig. 3. As a result, the tangent capacitance function is defined by (1).

$$C_b(V_{OC}) = \frac{dQ(V_{OC})}{dV_{OC}} \tag{1}$$

B. Model validation

In order to verify the proposed model, a simulation schematic of the proposed model is built in the circuit simulation software PLECS [10]. Besides that, reference data is provided by the experiment. The 18650 Li-ion cell from Samsung SDI (3.6V/2.85Ah) is utilized for collecting charging/discharging data at 25^oC . The battery cells are fully charged by constant current at a 0.5C-rate and constant voltage at 4.2V with a 55mA cut-off current. After that, the battery cells are discharged by various constant current levels (0.5C, 1C, 1.5C, 2C, and 3C) at 25ºC ambient temperature with 2.5V cut-off voltage condition.

The comparison results in Fig. 4 illustrate the discharging voltage profile of the battery calculated from the variable capacitor model and the experimental data are well-fitted to each other. At the end of the discharging process, the difference in voltage between the proposed model and the reference is trivial. The result proves that the variable capacitor model can effectively describe the battery operation.

III. Balancing Time Estimation

A. Case study #1: active cell balancing

For the purpose of active cell balancing, the various structures of the switched-capacitors (SC) [11] are promising due to their high efficiency and relatively reasonable cost. In this paper, the proposed model is applied for the rapid evaluation of a single switched-capacitor (SSC) equalizer [4] presented in Fig. 5. The battery cells in a string are balanced by the autonomous switching of the balancing capacitor, $C_{balancing}$ as shown in Fig. 5a. In this scheme, the energy from the higher voltage cell is gradually transferred to the lower

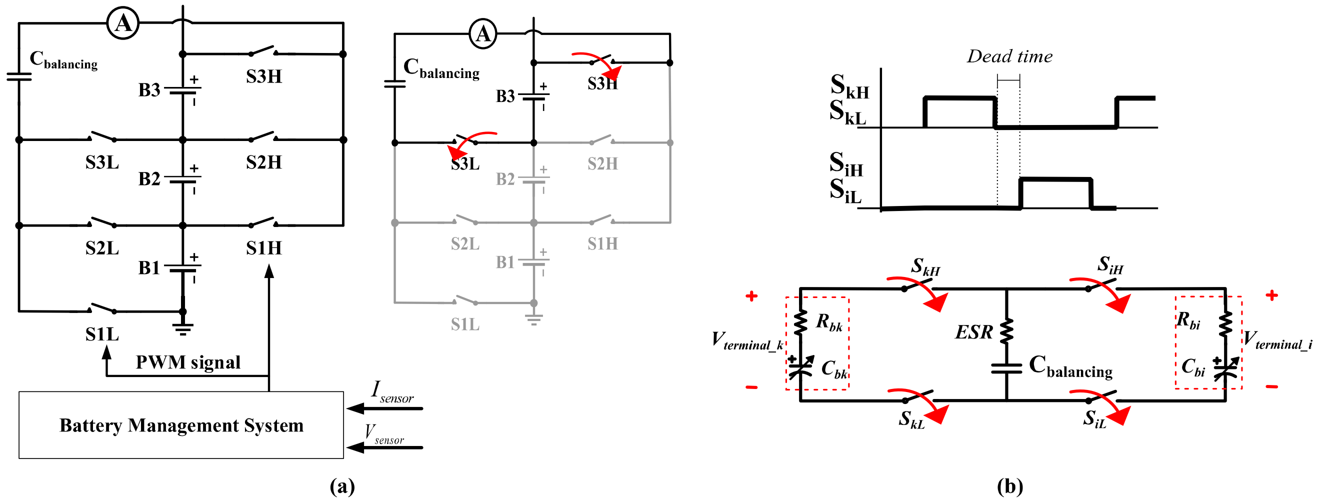


Fig. 5. Single switched capacitor equalizer (a) Topology structure and operation (b) Its equivalent circuit

voltage cell. Fig. 5b shows the equivalent circuit of the balancing process.

If the proposed variable capacitor model with a single internal resistor is applied to this balancing circuit, the charging or discharging time can be determined by the R-C time constant via simple calculations. Even though the charge stored in the variable capacitor is a nonlinear function of the open circuit voltage, from the incremental capacitance function defined in (1) $C_b(V_{OC})$, a linear charge-equivalent capacitance for a cell, C_{eq} is obtained as in (2).

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

where $V_{OC}(t_0)$, $V_{OC}(t_1)$ is the open circuit voltage at t_0, and t_1, respectively. The resulting C_{eq} is a function of V_{OC}. The charge-equivalent capacitance will be very useful in the calculation of the balancing time.

On the other hand, the equivalent resistance [4] of the SSC balancing circuit in Fig. 5 is found by (3).

$$R_{eq} = \frac{1}{f_s C_{balancing}} \frac{1 + e^{\frac{-D}{f_s \tau}}}{1 - e^{\frac{-D}{f_s \tau}}} \qquad (3)$$

$$\tau = C_{balancing}(ESR + R_b)$$

where f_s is the switching frequency of the balancing circuit, D is the duty ratio, and τ is the time constant, which can be obtained by multiplying the balancing capacitor, $C_{balancing}$, and the total resistance (the series connection of ESR and the battery resistance of the cell, R_b).

Based on the equivalent charge transfer analysis, the voltage after completing the balancing process is identified by (4).

$$V_b = V_{0,i} + \frac{C_{eq,k}(V_{0,k} - V_{0,i})}{C_{eq,i} + C_{eq,k}}\left(1 - e^{\frac{-t}{\tau_b}}\right) \qquad (4)$$

$$\tau_b = \frac{R_{eq} C_{eq,i} C_{eq,k}}{C_{eq,i} + C_{eq,k}},$$

where the subscripts i and k denote the lower and higher voltage cell, $V_{0,i}$ and $V_{0,k}$ denote the battery initial voltages, $C_{eq,i}$ and $C_{eq,k}$ represent energy equivalent capacitances, R_{eq} is the equivalent resistance of equalizer circuit given in (3).

With a given target voltage difference between the two cells, ΔV_b, defined by (5), the operation time to achieve that balancing state is referred to as the balancing time. This total balancing time should be calculated by (6).

$$\Delta V_b = V_{b,k} - V_{b,i} = (V_{0,k} - V_{0,i})e^{\frac{-t}{\tau_b}} \qquad (5)$$

$$t_b = \tau_b \, ln\left(\frac{V_{0,k} - V_{0,i}}{\Delta V_b}\right) \qquad (6)$$

To verify the proposed calculation method, two batteries at 80% and 60% initial SOC levels are connected in series. This battery string is connected to the SSC balancing circuit in PLECS simulation platform. The proposed battery model is constructed for 18650 Li-ion Samsung SDI (3.6V/2.85Ah) cylindrical cell. The parameters are set as follow: The battery initial voltages are 4.0089V and 3.7970V, respectively. The balancing capacitance is 2200μF, f_s is chosen at 20kHz with 0.45 duty, ESR is 0.15Ω, and the internal resistance of the battery is 0.035Ω.

Fig. 6 illustrates that the voltage of the two cells gradually converge to the balancing state. The calculated balancing time is also compared to the simulation at various elapsed time and detailed in Table I. Specifically, the equivalent resistance (R_{eq}) of this circuit is computed as 0.8224Ω. Subsequently, the charge equivalent capacitance of each cell determined by (2)

TABLE I. ACCURACY OF ACTIVE BALANCING TIME CALCULATION

Elapsed time [s]	$V_{b,k}$ [V]	$V_{b,i}$ [V]	$C_{eq,k}$ [F]	$C_{eq,i}$ [F]	ΔV_b [mV]	t_{sim} [s]	t_b [s]	t_{error} [%]
2000	3.975	3.841	12002.63	9283.09	134.43	2000	1959.11	2.04
4000	3.952	3.869	11490.82	9100.40	82.32	4000	3949.03	1.27
6000	3.936	3.887	11183.37	9039.34	49.58	6000	5971.65	0.47
8000	3.927	3.897	11004.61	9022.76	29.67	8000	8016.20	-0.20
10000	3.921	3.903	10900.80	9020.14	17.72	10000	10073.07	-0.73
12000	3.917	3.907	10840.22	9021.14	10.57	12000	12140.47	-1.17
14000	3.915	3.909	10804.68	9022.64	6.31	14000	14209.55	-1.50

TABLE II. ACCURACY OF SOC CALCULATION IN ACTIVE BALANCING TIME CASE STUDY

	SOC_{init}	V_0 [V]	t = 2000 [s]			t = 8000 [s]			t = 12000 [s]		
			SOC_{cal}	SOC_{sim}	SOC_{error}[%]	SOC_{cal}	SOC_{sim}	SOC_{error}[%]	SOC_{cal}	SOC_{sim}	SOC_{error}[%]
B_k	0.8	4.0089	0.767	0.760	-0.962	0.717	0.710	-1.028	0.708	0.701	-1.028
Bi	0.6	3.797	0.640	0.641	0.094	0.690	0.690	0.085	0.698	0.699	0.072

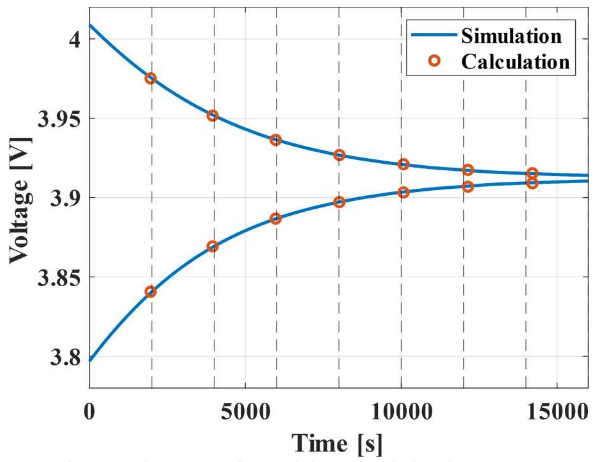


Fig. 6. Voltage waveform of the active balancing process

facilitates the calculation of the balancing time through (6). The calculated balancing time, t_b, matches well with the simulation result, t_{sim}, within *2.04%* error, which proves that the variable capacitor model is useful for predicting the balancing time of the active balancing circuits. Furthermore, battery SOC can be accurately calculated by using the charge-equivalent capacitance, as can be seen from Table II, where the SOC error margin remains bounded within *1.028%*.

B. *Case study #2: passive cell balancing*

Although active balancing is more efficient than passive balancing, passive balancing is still popular in the industry because of its simplicity and outstanding cost-effectiveness. Fig. 7a shows the battery passive cell balancing structure. The balancing resistors discharge the cell with the highest voltage, reducing its voltage to match the other cells in the pack. This process continues until all the cells are balanced. The equivalent circuit incorporated with the proposed variable capacitor model in Fig. 7b includes only a capacitor and resistors. It means that the balancing time can be directly determined by the R-C time constant. In this calculation, the charge equivalent capacitance is found by (2) and the equivalent resistance of this circuit is just the sum of the discharging resistance, R_i, and the internal resistance of a battery, R_{bi}, for each cell.

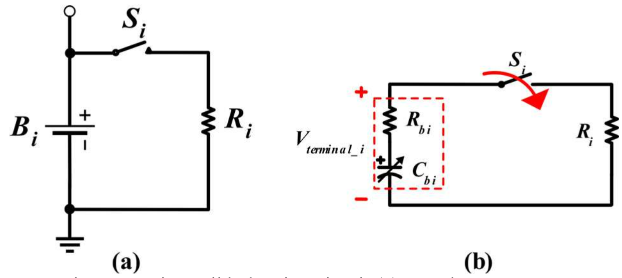


Fig. 7. Passive cell balancing circuit (a) Topology structure (b) Equivalent circuit

In order to validate this approach, the experiment of the passive balancing process was implemented, as illustrated in Fig. 8. Eight batteries, each with various SOC level, are implemented into a passive balancing chip (Analog Device, LTC6804) with a *27Ω* discharging resistor. Battery voltage data during operation is logged using a data logger (HIOKI, LR8420). For the battery model, the internal resistance of a battery is measured as *35mΩ* by an EIS equipment (ZIVE, SP10). In this test, Samsung SDI's 18650 cylindrical cell is also used. By summing the series resistances, the equivalent resistance (R_{eq}) is obtained as *27.355Ω*, inclusive of *0.32Ω* for a switch on-resistance and a wiring resistance. In this configuration, due to the lower voltages of cells #7 and #8, they are exempt from connection to the discharge resistor. The remaining batteries, with voltages exceeding those of cells #7 and #8, are connected to the discharging resistor until ΔV become less than *0.13V*.

Table III offers a comparative analysis of the results obtained from the balancing time measurements and the proposed calculations, denoting t_{exp} and t_{cal} as the balancing times in the experiment and the calculation, respectively. The results substantiate that the calculation of the passive balancing time closely aligns with the actual results, with a minor error margin of *2.011%*. Fig. 9 further illustrates the battery voltage profiles observed throughout the balancing process.

TABLE III. ACCURACY OF PASSIVE BALANCING TIME CALCULATION

Cell no.	SOC_{init}	SOC_{target}	V_{init} [V]	V_{target} [V]	C_{eq} [F]	R_{eq} [Ω]	t_{cal} [s]	t_{exp} [s]	t_{error} [%]
#1	0.49	0.32	3.698	3.57	13731.574	27.355	13232.046	13473.2	1.790
#2, #3, #4	0.42	0.32	3.643	3.57	14029.867	27.355	7768.587	7848.2	1.014
#5, #6	0.34	0.32	3.59	3.57	14031.207	27.355	2144.272	2102	-2.011
#7, #8	0.30	-	3.557	-	-	-	-	-	-

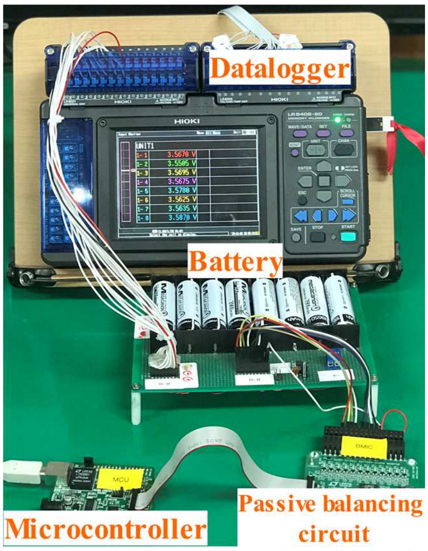


Fig. 8. Experimental setup of the passive cell balancing test

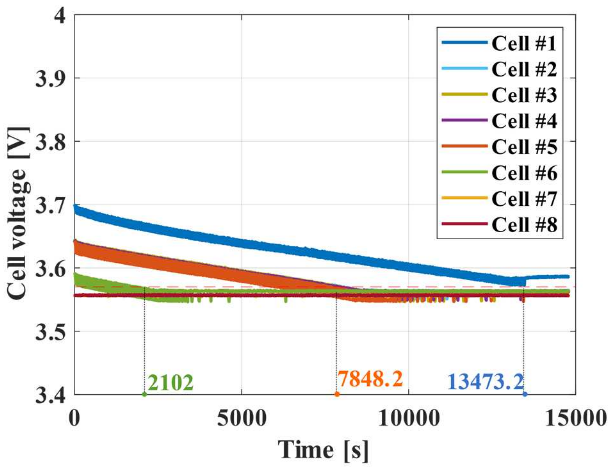


Fig. 9. Cell voltages of the passive balancing experiments

C. Discussion

Overall, the results obtained from the two case studies of active and passive cell balancing demonstrate the efficacy of the proposed approach in providing a quick and precise estimation of balancing speed. Despite of its apparent simplicity, the proposed model proves to be a valuable tool in evaluating the performance of balancing circuits. Moreover, the model offers the determination of SOC through the utilization of the polynomial function governing the SOC-OCV relationship. As batteries degrade, the SOC-OCV relationship changes, necessitating a periodic update of both the capacitance equation and the battery impedance parameters to accurately capture and reflect the changing characteristics. This consideration is vital for ensuring the continued relevance and accuracy of the proposed model over the lifespan of the battery.

IV. CONCLUSION

This paper introduces a novel battery model employing a variable capacitor. By combining the variable capacitor model with both active and passive cell balancing circuits, the balancing time is directly derived from the R-C time constant. Additionally, the SOC can be determined based on the SOC-OCV relationship. The successful integration and operation of these circuits validate the simplicity and practical effectiveness of the proposed model. Consequently, the model proves valuable for estimating and assessing battery behavior across various balancing circuits. Future research directions may delve into exploring temperature dependencies to enhance the model's applicability and predictive accuracy across a broader range of real-world scenarios.

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