Accurate Voltage Equalization of Supercapacitors with Online Identification Model

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***Abstract*—Voltage equalization scheme is used to solve the voltage imbalance problem between serial connected supercapacitors. The inner capacitor voltage instead of terminal voltage based balancing scheme has been proven to be more accurate. The inner capacitor voltage are traditionally deduced through offline identified model parameters, which are variable due to the effect of terminal voltage, interference, and temperature, which will cause undesirable balancing deviation. To address the problem, we propose an online identified model based voltage equalization scheme to improve the equalization accuracy. The scheme is achieved by identifying model parameters through recursive-least square (RLS) technique, which has the advantage of simplicity, easy practicability. Experimental results are given to verify the effectiveness and high accuracy of the proposed cell balancing method.**

I. Introduction

As a new energy storage device, supercapacitor has widely applied in high-power applications, such as public tranportation [1]–[3] due to its excellent characteristic in fast charging rate and long lifetime. Recently, the fast charging rate and long lifetime have also enable supercapacitors to be a promosing candidate for low-power applications, such as backup power supply for computer memory and portable power supplly [4]–[6].

The voltage of a supercapacitor cell is typically limited to 0-2.7 V, which implies that cells need to be connected in series to satisfy the voltage requirement of the specific applications. However, caused by the manufacturing process factors and environmental conditions, the different individual properties between each supercapacitor will lead to voltage imbalance problem during the charging process, which may result in overcharging of cells and and even explosion of supercapacitors in long time operation [7], [8]. Voltage equalization strategies are therefore used to overcome the problem.

Prior researches have proposed several passive balancing schemes which are specially used for low-power applications. Specifically, the switched resistor balancing circuit has been commonly used in low-power supercapacitor applications because of its simple and low-cost topology. Charge shunting method is the classic method for the switched resistor balancing circuit [9], [10]. A decentralized control strategy is applied in this method, i.e., if a cell is fully charged, its charging current will be shunted to the resistor which is chosen according to the expected voltage and charging current. It is further shown that the decentralized control method leads to voltage deviations due to the resistance variation effects. In [11], a consensus-based voltage equalization method is proposed to synchronize cell voltage during the charging process, and thus the proposed method is robust to resistance variations.

Voltage equalization scheme based on terminal voltage is the most general method in the literature. Many researches based on charge shunting method and consensus method determine cell balancing according to the terminal voltage. However, the terminal voltage cannot represent the true voltage of supercapacitor as the equivalent-serial-resistance (ESR) represents the power loss effect and voltage drop effect. This is, in the charging process, considerable energy will be consumed on the ESR. Moreover, when the charging process is finished, the terminal voltage suffers from a voltage drop effect when the charging current falls to zero. The terminal voltage includes the voltage on inner capacitor and inner resistor in charging process. Moreover, due to the manufacturing process factors and environmental conditions, the inner resistance of different cells are different. Therefore, the voltage of each cell is not only lower than the expected voltage but also different from each other.

We propose voltage balancing scheme based on inner capacitor voltage to achieve cell balance. First-order RC model is usually adopted as the equivalent model for supercapacitor due to its simplicity in analysis and computation. The inner capacitor voltage can be obtained by subtracting the inner resistor voltage from terminal voltage. However, the equivalent capacitance (EC) and equivalent series resistance (ESR) of supercapacitor vary with aging, operating temperature and terminal voltage, and the EC and ESR provided by manufacturers have 20% tolerance [12]–[15]. It is impractical to measure EC and ESR when a supercapacitor is in use. So, in many applications, the offline measured EC and ESR value or the rated value provided by manufacturer datasheet are adopted, which will lead to balancing error as the circumstance varies.

To overcome the problem mentioned above, in this paper, we propose an online identified model based supercapacitor voltage balancing scheme by considering internal voltage. The online estimation is achieved by using the technique of recursive-least squares (RLS), and no device temperature sensing is required to identify EC and ESR of supercapacitors.

With the accurately identified model, inner capacitor voltage is accurately deduced to carry out the voltage balancing scheme.

The remainder of this paper is organized as follows. Section 2 illustrates the switched resistor balancing circuit used in this paper. Section 3 then shows the RLS online estimation algorithm. The experiment results are shown in Section 4. Section 5 concludes this paper.

II. System Modeling

In this section, we introduce the switched resistor circuit cell balancing circuit for a multi-cell module. Since only the charging process is considered, the simple first-order RC model is adopted as the equivalent model for supercapacitor, which can reduce the computational efforts. Hence, the resistor and the capacitor in RC model is represented by r_i and C_i, respectively. In switched resistor balancing circuit, the equalizing resistor R_i and the switch S_i are connected in series, and in parallel with a cell which is replace by a RC model, as shown in Fig.1. Whats more, all switches are controlled in order to achieve voltage balance [16].

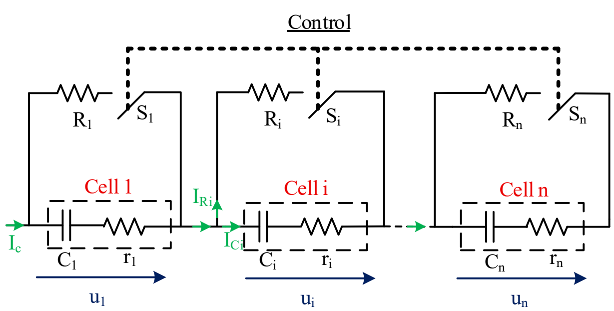


Fig. 1. The charging system of supercapacitors and its balancing circuit

When the $i^{th}(i=1,2,...,n)$ switch S_i is on, the charging current I_c will be divided into two flows for cell i and balance resistor R_i or transferred to the balance resistor R_i totally. When the i^{th} switch S_i is off, the charging current I_c will flows through the cell i totally.

The terminal voltage of cell i is given by formula (1).

$$u_i(t) = u_i(t_0) + \frac{1}{C_i}\int_{t_0}^{t} I_{C_i}(t)dt + r_i I_{C_i}(t) \quad (1)$$

Based on the Kirchhoffs current law (KCL), the formula (2) is obtained:

$$I_{C_i}(t) = I_c(t) - S_i(t)\frac{u_i(t)}{R} \quad (2)$$

where $u_i(t_0)$ is the initial voltage of i^{th} supercapacitor. I_{C_i} is the current flows through i^{th} supercapacitor and $I_c(t)$ is the charging current.

Because the voltage of each cell are equal to rated voltage V^* finally and the charging current I_c is constant, the value of balance resistor R_i should all be equal to $R^* = V^*/I_c$. What's more, $S_i(t)$ is used to represent the status of switch S_i.

If the i^{th} switch is on, $S_i = 1$. If the i^{th} switch is off, $S_i = 0$.

Therefore, formula (1) becomes:

$$\begin{aligned} u_i(t) = u_i(t_0) + \tfrac{1}{C_i}\textstyle\int_{t_0}^{t}\left(I_c(t) - S_i(t)\tfrac{u_i(t)}{R}\right)dt \\ + r_i\left(I_c(t) - S_i(t)\tfrac{u_i(t)}{R}\right) \end{aligned} \quad (3)$$

Then:

$$\begin{aligned} \frac{du_i(t)}{dt} = \frac{d\left(\frac{1}{C_i}\int_{t_0}^{t}\left(I_c(t)-S_i(t)\frac{u_i(t)}{R}\right)dt\right)}{dt} \\ + \frac{d\left(r_i\left(I_c(t)-S_i(t)\frac{u_i(t)}{R}\right)\right)}{dt} \end{aligned} \quad (4)$$

Formula (4) can be simplified to:

$$\frac{du_i(t)}{dt} = \frac{1}{C_i}(I_c - S_i\frac{u_i(t)}{R}) - r_i\frac{S_i}{R}\frac{du_i(t)}{dt} \quad (5)$$

III. Recursive-Least-Squares-Based Online Parameters Identify

A. Online estimation of RC model

The voltage balancing scheme based on inner capacitor voltage we proposed can avoid the phenomenon that the voltage of each cell is lower than the expected voltage and different from each other after voltage droop. The inner capacitor voltage can be obtained by subtracting the inner resistor voltage from terminal voltage. However, the equivalent capacitance (EC) and equivalent series resistance (ESR) of supercapacitor vary with aging, operating temperature and terminal voltage. Therefore, it is necessary to calculate the EC and ESR of each cell in real time. The RLS algorithms has been applied extensively in estimation and tracking of time-varying parameters in many fields [17].

In order to obtain the instantaneous ESR and EC of supercapacitor, instantaneous charging current and terminal voltage are measured and passed to RLS algorithm. RLS is an adaptive filter algorithm that recursively searches the coefficients that minimize a weighted linear least squares cost function which is related to the input signals. The principle of RLS algorithms can be summarized as follows: In the process of estimating the parameters, the latest observed data will be used to modify the last parameter estimation value based on recursive algorithm, the latest parameter estimation value is thus obtained. RLS algorithm can not only reduce the computation load and storage space, but also achieve online estimation [18]. The advantage of our method is that the initial voltage of supercapacitor is not required to know throughout the online parameters identification.

Because the RC model need to be transformed into regression form in the RLS algorithm, formula (1) can be represented by formula (6).

$$u_i(t) = \varphi(t)\theta(t) \quad (6)$$

With

$$\varphi(t) = [I_{C_i}(t) \ \int_0^t I_{C_i}(\tau)d\tau \ 1], \theta(t) = [r_i \ C_i^{-1} \ u_i(t_0)]^T \quad (7)$$

Formula (6) can be represented by formula (8) after discretization.

$$u_i[n] = \varphi[n]\theta[n] \tag{8}$$

The RLS algorithm estimates the weight vector $\hat{\theta}[n]$ in discrete domain at every iteration from

$$k[n] = \frac{\lambda^{-1}P[n-1]\varphi[n]}{1+\lambda^{-1}\varphi^T[n]P[n-1]\varphi[n]} \tag{9}$$

$$e[n] = u_i[n] - \hat{\theta}^T[n-1]\varphi[n] \tag{10}$$

$$\hat{\theta}[n] = \hat{\theta}[n-1] + k[n]e[n] \tag{11}$$

$$P[n] = \lambda^{-1}P[n-1] - \lambda^{-1}k[n]\varphi^T[n]P[n-1] \tag{12}$$

where $k[n]$ is the update gain vector, $e[n]$ is the error vector which representes the error between the autual output and the predicted output, $P[n]$ is normally referred to as the covariance matrix, $\hat{\theta}[n]$ is the estimated weight vector and λ is called the forgetting factor and $0 < \lambda \leq 1$. The forgetting factor λ operates as a weight which diminishes for the more remote data [17] [19].

B. Voltage balancing scheme based on online estimation of RC model

Fig.2 shows the block diagram of the voltage balancing scheme we proposed. The voltage balancing scheme based on online estimation of RC model is consist of RLS parameters estimation and equalization algorithm which is completed in the controller.

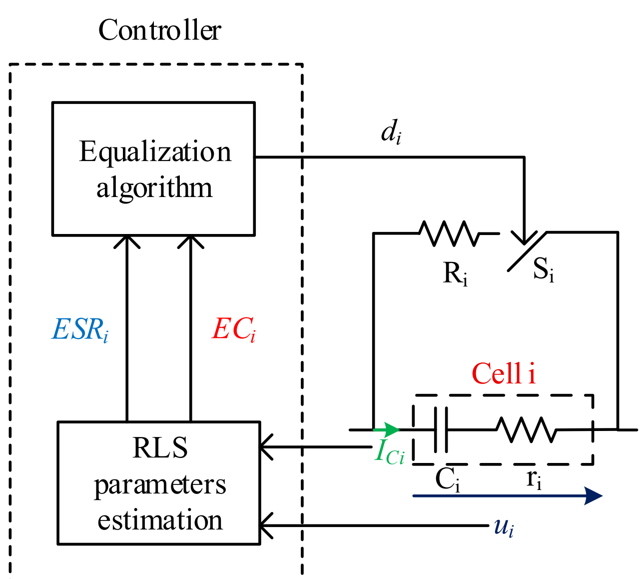


Fig. 2. The block diagram of the voltage balancing scheme

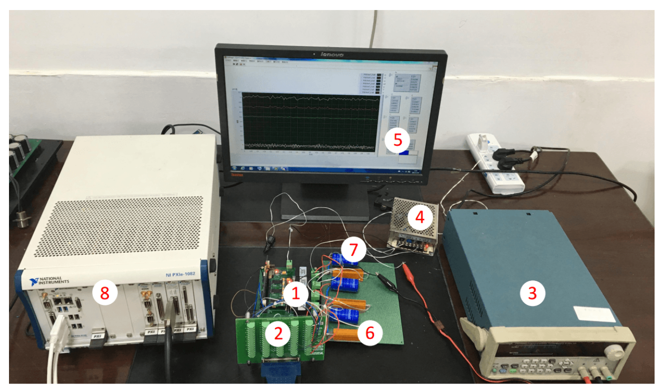
The current flows through cell i I_{C_i} and the terminal voltage of cell i u_i can be detected from current sensor and voltage sensor, and then passed to the RLS algorithm. The ESR and EC of cell i will be updated at every iteration of the RLS algorithm and passed to the equivalent algorithm. In equalization algorithm, we use charge shunting method to balance the voltage of each cell. The inner capacitor voltage of each cell is used to determine whether each cell is equal to each other. According to the RC model of cell i, the inner capacitor voltage of cell i u_{C_i} can be obtained from

$$u_{C_i}(t) = u_i(t) - r_i I_{C_i}(t) \tag{13}$$

If the inner capacitor voltage of cell i u_{C_i} is higher than the rated voltage, the i^{th} switch S_i should be turned on. Therefore, the control signal of the i^{th} switch $d_i = 1$. If the inner capacitor voltage of cell i u_{C_i} is lower than or equal to the rated voltage, the i^{th} switch S_i should be turned off. Therefore, the control signal of the i^{th} switch $d_i = 0$.

IV. Experimental Verification

In this section, experiments are conducted on a test platform as shown in Fig.3. Three supercapacitors, whose version is BCAP0150 of Maxwell Technologies, are used in our experiment. What's more, the value of three switch resistors is 1 Ω.



1. Equalization circuit 2. Data acquisition board 3. DC power supply 4. 24V power supply 5. Labview 6. Switched resisitor(1 Ω) 7. Supercapacitor(150F) 8. PXI platform

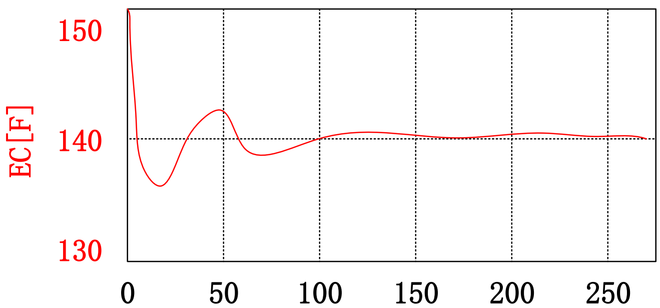
Fig. 3. Test platform

In our experiment, we compare the result of charge shunting method based on terminal voltage and charge shunting method based on inner capacitor voltage in two different charging current circumstances, 1.5 A and 2 A respectively. Note that the different charging current and constant switch resistance in our experiment represent the constant charging current and different switch resistance in practical application. Because the switch resistance cannot be equal to the desired value precisely due to the manufacturing tolerance, aging effect and environment factors.

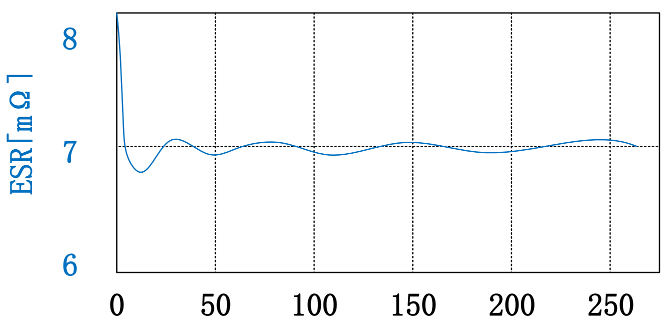
The initial voltage of three cells are 2.7 V, and then we discharged the three supercapacitors with arbitrary current till the voltage of cell 1, cell 2 and cell 3 are 1 V, 0.8 V and 0.6 V respectively. In order to avoid overcharge for supercapacitor, the rated voltage of three supercapacitors is set as 2 V. Therefore, the nominal charging current should be set as 2 A.

TABLE I
THREE SUPERCAPACITOR DATA

Supercapacitor	EC		ESR	
	Rated(F)	Measured(F)	Rated(mΩ)	Measured(mΩ)
Cell1	150	∼140	10	∼7
Cell2	150	∼143	10	∼13.8
Cell3	150	∼135	10	∼9.2



(a) EC of Cell1



(b) ESR of Cell1

Fig. 4. EC and ESR online estimation result of cell1

A. *Online parameters estimation*

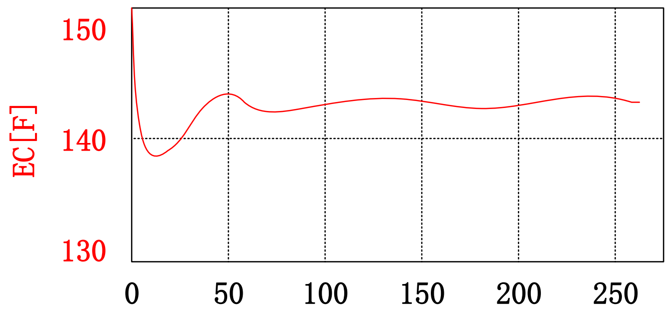
In the experiment, EC and ESR estimation was executed in real time. The relevant data of supercapacitor is summarized in Table 1. The initial conditions were chosen as

$$\hat{\theta}[0] = [0\ 0\ 0], P[0] = 10^{10} I \tag{14}$$

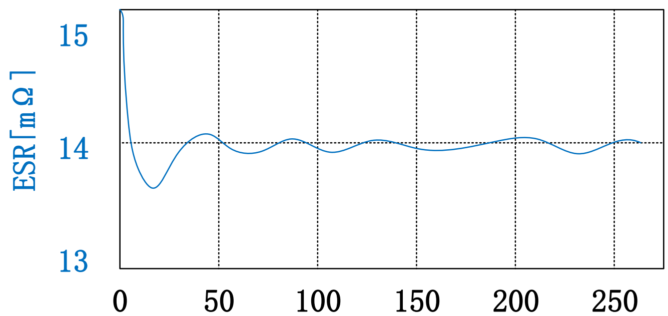
with I denoting a unity matrix. The forgetting factor was selected as $\lambda^{-1} = 0.995$. Fig.3, Fig.4 and Fig.5 shows the results of ESR and EC of cell1, cell2 and cell3 when charging current is 1.5 A, respectively.

B. $R < R^{*}$*Case*

In this section, the charging current I_c is set as 1.5 A to simulate the circumstance that the true value of switch resistor is smaller than the nominal value. Fig.7 shows the results of charge shunting method based on terminal voltage and inner capacitor voltage. When cell voltage reaches the rated voltage 2 V, resistors are switched on and the current flows through the switch resistor should be 2 A, which implies that cell will be discharged through the switch resistor with 0.5 A due to the charging current is 1.5 A; while when cell voltages become less than 2 V, resistor are switched off and cell are charged

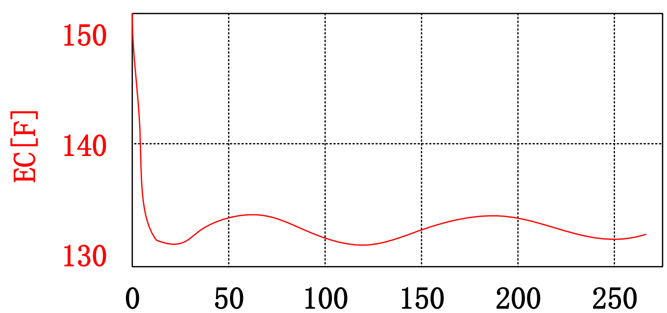


(a) EC of Cell2

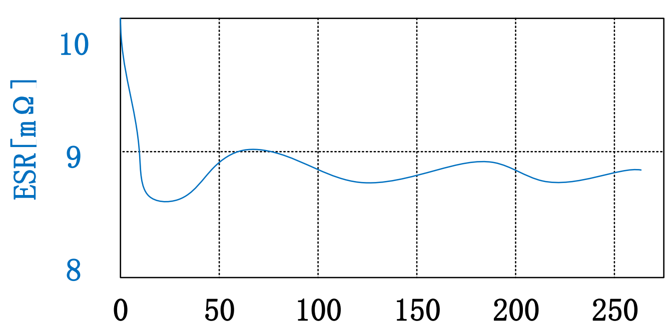


(b) ESR of Cell2

Fig. 5. EC and ESR online estimation result of cell2



(a) EC of Cell3

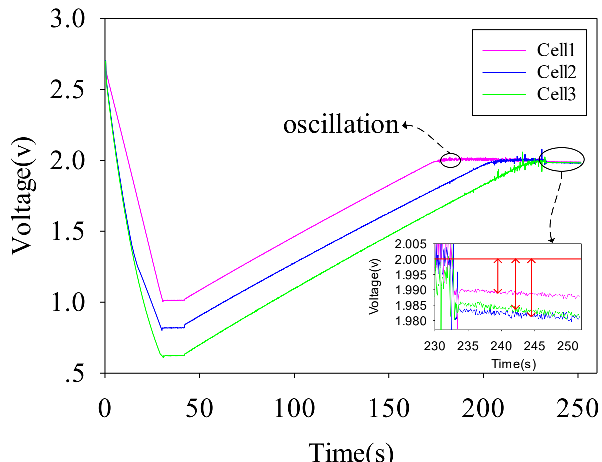


(b) ESR of Cell3

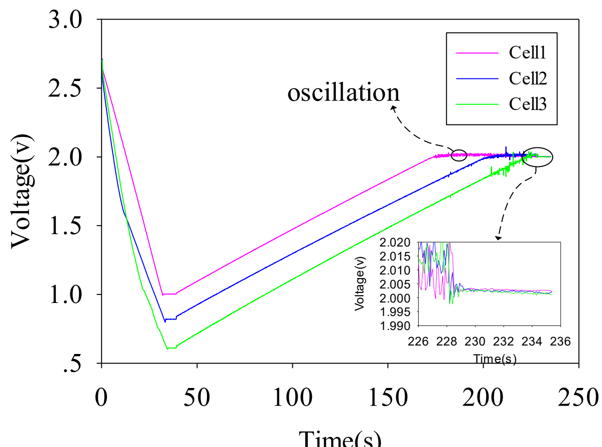
Fig. 6. EC and ESR online estimation result of cell3

again. This process will repeat, and the oscillation therefore occurs in the cell voltage, as shown in Fig.7.

The cell voltages of charge shunting method based on terminal voltage after voltage drop are not only lower than 2 V, but also imbalance between each other, as shown in Fig.7(a). On the contrary, the cells voltage of charge shunting method based on inner capacitor voltage after voltage drop are balancing and equal to 2 V, as shown in Fig.7(b).



(a) based on terminal voltage



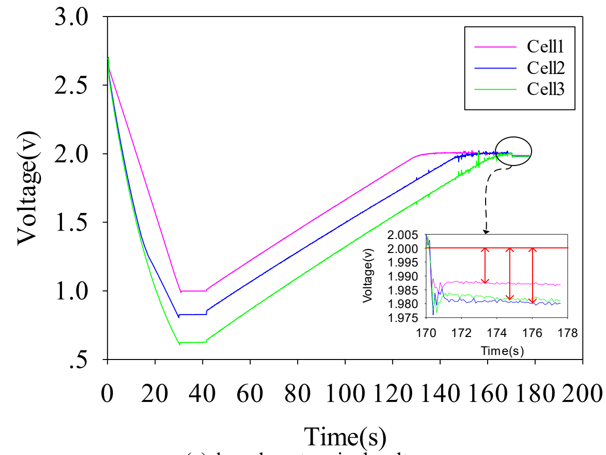
(b) based on inner capacitor voltage

Fig. 7. Experimental result with $R < R^{*} Case$

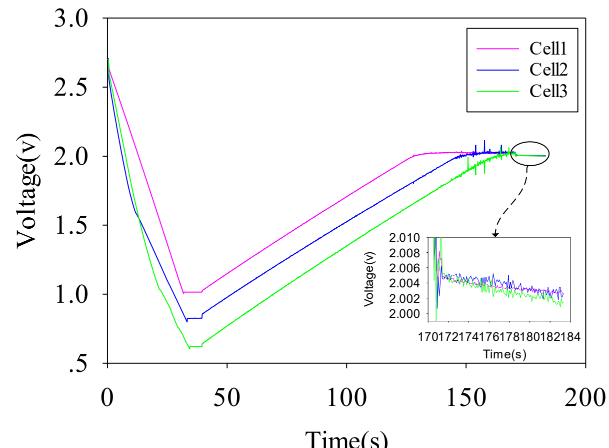
C. $R = R^{*} Case$

In this section, the charging current I_c is set as 2 A to simulate the circumstance that the true value of switch resistor is equal to the nominal value. Fig.8 shows the results of charge shunting method based on terminal voltage and inner capacitor voltage. When cell voltage reaches the rated voltage 2 V, the correspondingswitch resistor will be switched on. The current flows through the switch resistor is equal to 2 A. Because the charging current is 2 A, the current flows through the supercapacitor is equal to 0 A. Therefore, the voltage on supercapacitor will remain stable, and will not appear oscillation as shown in Fig.7 in this circumstance.

As shown in Fig.8(a), the cell voltage of charge shunting method based on terminal voltage after the voltage drop are lower than 2 V, and the imbalance problem also exist in this circumstance. The cells voltage of charge shunting method based on inner capacitor voltage are also balancing and equal to 2 V too after the voltage drop, as shown in Fig.8(b).



(a) based on terminal voltage



(b) based on inner capacitor voltage

Fig. 8. Experimental result with $R = R^{*} Case$

V. Conclusion and Future Work

In this paper, an online identify model based cell balancing scheme is proposed to balance cell voltages. We analyze the switched resistor circuit first. The accurately identified model is used in order to calculate the inner capacitor voltage. The proposed scheme was successfully verified by experimental results. In the future work, we will combine consensus method and RLS online parameters estimation to achieve cell balancing.

Acknowledgment

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