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Online DCIR Estimation for Series-connected Battery Cells using Matrix-Switched Capacitor Converter

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ABSTRACT

In the battery energy storage system, battery cells are connected in series to increase the operating voltage. Due to the difference in characteristics, the performance degradation of cells is dissimilar. This paper proposes an online DC internal impedance estimation for battery cells in the series string using a matrix-switched capacitor converter, which is already verified as useful for the series balancing of the cells. The simulation in the hardware in the loop test rig shows good accuracy and the feasibility of the proposed method.

Keywords: battery energy storage system, online DC internal impedance, hardware in the loop test rig, series-connected battery, Matrix-switched capacitor converter.

1. INTRODUCTION

To increase the operating voltage of the battery pack in electric vehicles or energy storage systems, multiple battery cells are connected in series. To ensure safety, the state of charge (SOC) and state of health (SOH) of battery cells are monitored regularly. When the SOC can be assessed by the degradation of battery impedance, the DC Internal Resistance (DCIR) of battery cells is monitored. Various impedance estimation methods are reported in [1], where the methods are classified into offline and online measuring techniques.

In [2, 3], a switched inductor converter is used to inject an AC signal into battery cells and the electrochemical impedance of the battery is estimated. However, it is hard to delimit the impedance value between 2 battery cells. On the other hand, the battery charger is utilized at the end of the charging process to scan the battery impedance [4]. Unfortunately, it only can apply for one battery at the time. To reduce the cost, an online impedance spectroscopy estimation using switched capacitor cell balancing is proposed [5]. Although the accuracy is high, the incurred cost for the voltage and current sensors is its disadvantage.

This paper proposes an online DCIR estimation for series-connected battery cells by utilizing the matrix-switched capacitor equalizer which is suggested in [6]. This paper introduces the operation principle of the DCIR estimation technique in section 2, hardware in the loop test results are performed in section 3, and the conclusion is made in section 4.

2. PROPOSED METHOD

The proposed method uses one matrix-switched capacitor converter as showing in Fig. 1. Besides, one current sensor and one voltage sensor are used to measure the balancing current and the capacitor voltage, respectively. To discharge the capacitor voltage to zero, a dummy load and a switch are used to discharge the capacitor in the second state of the measuring process. With the matrix-switch, the capacitor can connect with any battery cell in the series string. Based on the measured transferring current and the capacitor voltage, the DCIR of the battery is estimated.

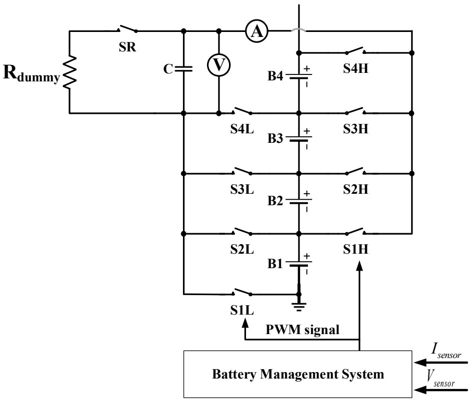
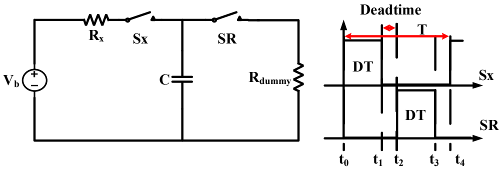
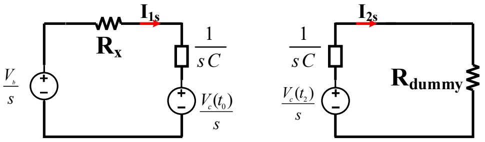


***Figure 1**: Matrix-switched capacitor converter*



(a) **(b)**

***Figure 2**: Equivalent circuit: (a) circuit topology; (b) complementary PWM signal.*



(a) **(b)**

***Figure 3**: Equivalent circuit in s-domain: (a) Phase A ($t_0 - t_1$); (b) Phase B ($t_2 - t_3$).*

The equivalent circuit of a measuring process is presented in Fig. 2(a) and the switches are controlled by a complementary PWM signal as in Fig. 2(b). The measuring process is divided into two states: measuring state – Phase A ($t_0 - t_1$) and recalibrating state – Phase B ($t_2 - t_3$). Between two-state, a small deadtime period is set to prevent the short-circuit. To analyze the operation of the circuit, the circuit is transformed to s-domain which is represented in Fig. 3, where R_l is the total resistance of the loop (on-resistance of the switch, $R_{d,on}$, battery impedance, R_b, and internal resistance of the capacitor, ESR), C is the capacitance of the measuring capacitor, and V_c is the voltage of the capacitor. In phase A, switch S_1 is turned on while S_2 is kept off. Denote the time constant, τ_1, of the switched capacitor is calculated by (1), where R_l is calculated by (2).

$$\tau_1 = R_x C \tag{1}$$

$$R_x = R_{bx} + R_{d,on} + ESR \tag{2}$$

The current flowing into the measuring loop, I_{1s}, is calculated by (3), where the ΔV is the difference between the battery voltage and the initial voltage of the capacitor as in (4).

$$I_{1s} = \frac{V_b - V_c(t_0)}{R_x}\frac{1}{s+\frac{1}{\tau_1}} = \frac{\Delta V}{R_x}\frac{1}{s+\frac{1}{\tau_1}} \tag{3}$$

$$\Delta V = V_b - V_c(t_0) \tag{4}$$

By inverse-transforming to the time domain, the transferring current equation becomes (5). Thus, the stored charge in phase A is calculated by (6).

$$i_1(t) = \frac{\Delta V}{R_x} e^{\frac{-t}{\tau_1}} \tag{5}$$

$$Q_{in}(t_1) = \int_{t_0}^{t_1} i_1(t)dt = \Delta VC(1 - e^{\frac{-t_1}{t_1}}) \tag{6}$$

Next, the voltage of the capacitor at time t_1 can be calculated by (7), where $V_c(t_0)$ is expected to be zero.

$$V_c(t_1) = \frac{Q_{in}}{C} = \Delta V(1 - e^{\frac{-t_1}{\tau_1}}) + V_c(t_0) \tag{7}$$

By dividing (5) by (7), a function by R_1 is derived as (8). Denote G as the conductance of the circuit (9), the function becomes (10).

$$\frac{i(t_1)}{V_c(t_1)} = \frac{1}{R_x}\frac{e^{\frac{-t_1}{R_xC}}}{(1 - e^{\frac{-t_1}{R_xC}})} \tag{8}$$

$$G_x = \frac{1}{R_x} \tag{9}$$

$$f(G_x) = G_x \frac{e^{\frac{-G_xt_1}{C}}}{1 - e^{\frac{-G_xt_1}{C}}} - \frac{i(t_1)}{V_c(t_1)} \tag{10}$$

By applying the Newton-Raphson method with an initial guess value, the chosen G, which makes the function $f(G)$ become zero, is calculated by (11), where $f'(G_x(i))$ is the derivation of $f(G_x(i))$ and $G_x(i)$ is the i-th iteration value of G_x. As a result, the DCIR of the battery is calculated by (12).

$$G_x(i+1) = G_x(i) - \frac{f(G_x(i))}{f'(G_x(i))} \tag{11}$$

$$DCIR = \frac{1}{G_x(i+1)} - R_{d,on} - ESR \tag{12}$$

In phase B, the capacitor is discharged by a dummy load, R_{dummy}. To fully discharge the capacitor, the value of R_{dummy} is calculated as (13), where f_s is the switching frequency of the switched capacitor converter.

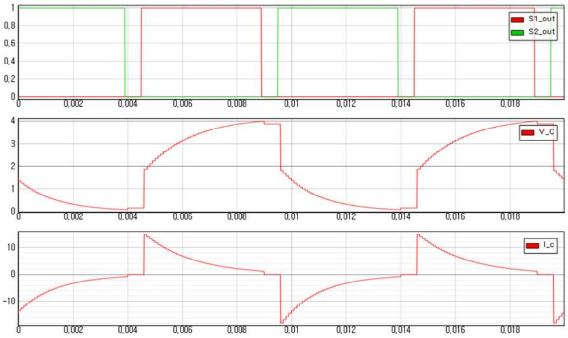


***Figure 4**: Captured waveform of capacitor voltage and current in the measuring process.*

***TABLE 1:** Actual and estimated value of DCIR*

	Cell 1	*Cell 2*	*Cell 3*	*Cell 4*
***ACTUAL* (mΩ)**	*34*	*40*	*42*	*50*
***ESTIMATION* (mΩ)**	*33*	*38*	*41*	*52*
ERROR (%)	*2.9*	*5.0*	*2.4*	*4.0*

$$R_{dummy} < \frac{1}{5f_sC} \tag{13}$$

When the measuring process of one cell is finished, the switching decision is changed to assess the next cell in the string. As a result, the DCIRs of all cells can be estimated.

3. VERIFICATION OF THE PROPOSED METHOD

To verify the proposed method, hardware in the loop test for four series-connected 18650 battery cells (3.7V/2.6Ah) has been implemented. Assume that all cells are fully charged but the DCIRs of them are different as in Table I. The capacitance is set at 6800uF, the sum of $R_{d,on}$ and ESR is set at 100mΩ. Besides, the Rdummy is set as 20mΩ to discharge the capacitor voltage to zero. The estimated DCIRs of battery cells are summarized in Table I. The results show that the proposed method can estimate the individual DCIR of battery cells within 5.5% tolerance.

4. CONCLUSION

This paper proposes an online DCIR estimation technique based on the matrix-switch capacitor converter for series-connected battery cells. With the matrix-switch structure, the proposed method can estimate the individual DCIR value of battery cells and equalize the energy between cells. The HIL test shows that the tolerance of the method is within 5.5%. A hardware experiment is under preparation for further verifying of the proposed method.

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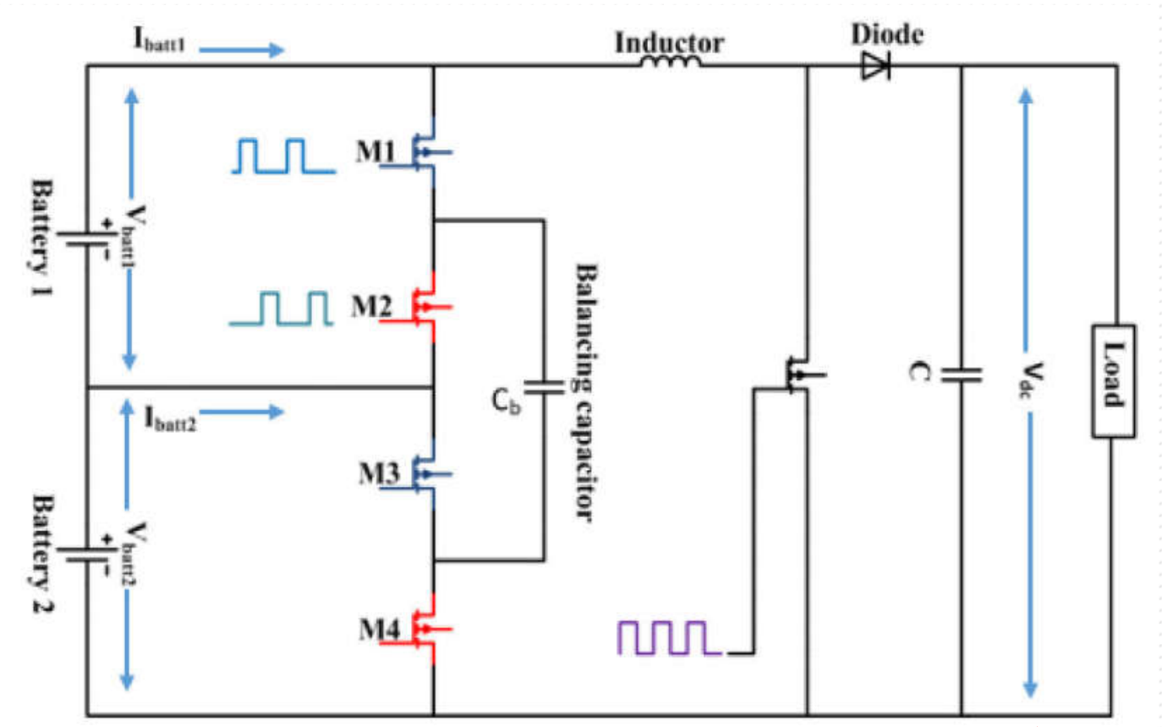
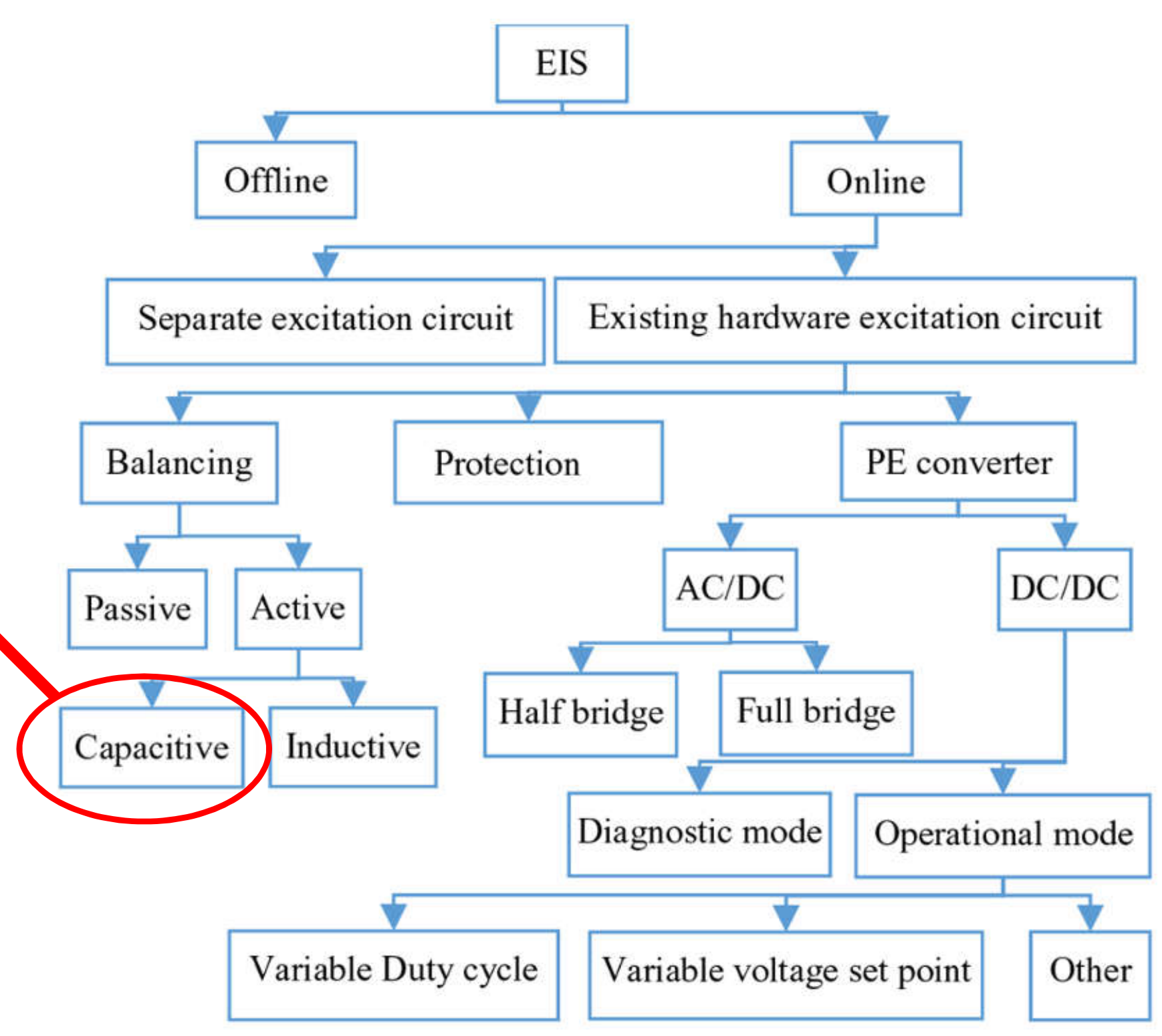
Summary

- The cell inconsistency in the series-connected battery configuration causes more risk of over-charge or over-discharge issues.
- The battery aging can be assessed by degradation of the battery internal impedance.
- The conventional researches are only applied for single battery cell.
- An online DCIR estimation for series-connected battery is proposed with the following advantages:
    - It utilizes the existing battery cell balancing circuit.
    - It can estimate the individual impedance of cells in series string.
    - It shows a high accuracy and easy to implement.

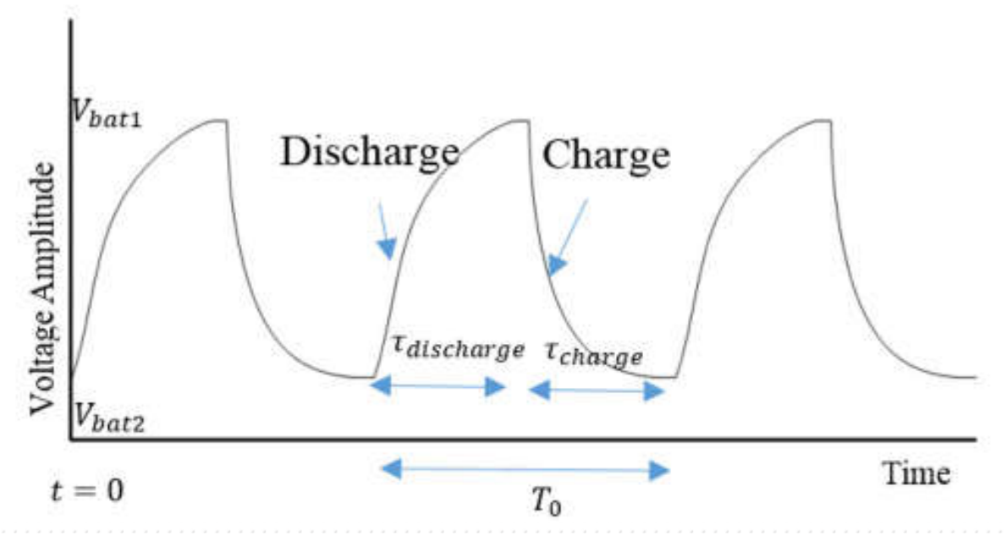
Conventional EIS Estimation Methods



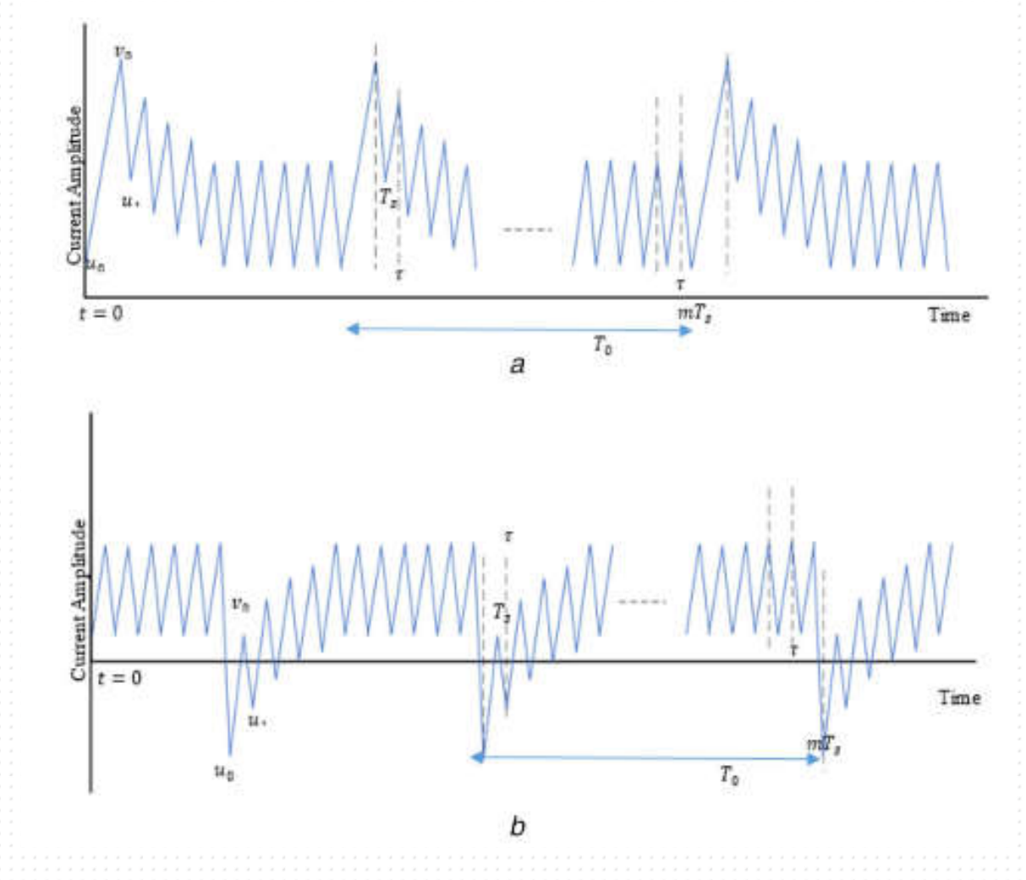
Switched Capacitor Cell Balancing



Summarize of EIS Estimation Methods



Capacitor voltage waveform



Battery current: (a) discharging mode; (b) charging mode

- Utilize the existing switched capacitor cell balancing circuit.
- Capacitor voltage and current are measured to calculate the battery impedance.

$$z(t)=\frac{v(t)}{i(t)}$$

- It needs a lot of sensors to measure the individual impedance of cells.

Simulation Results

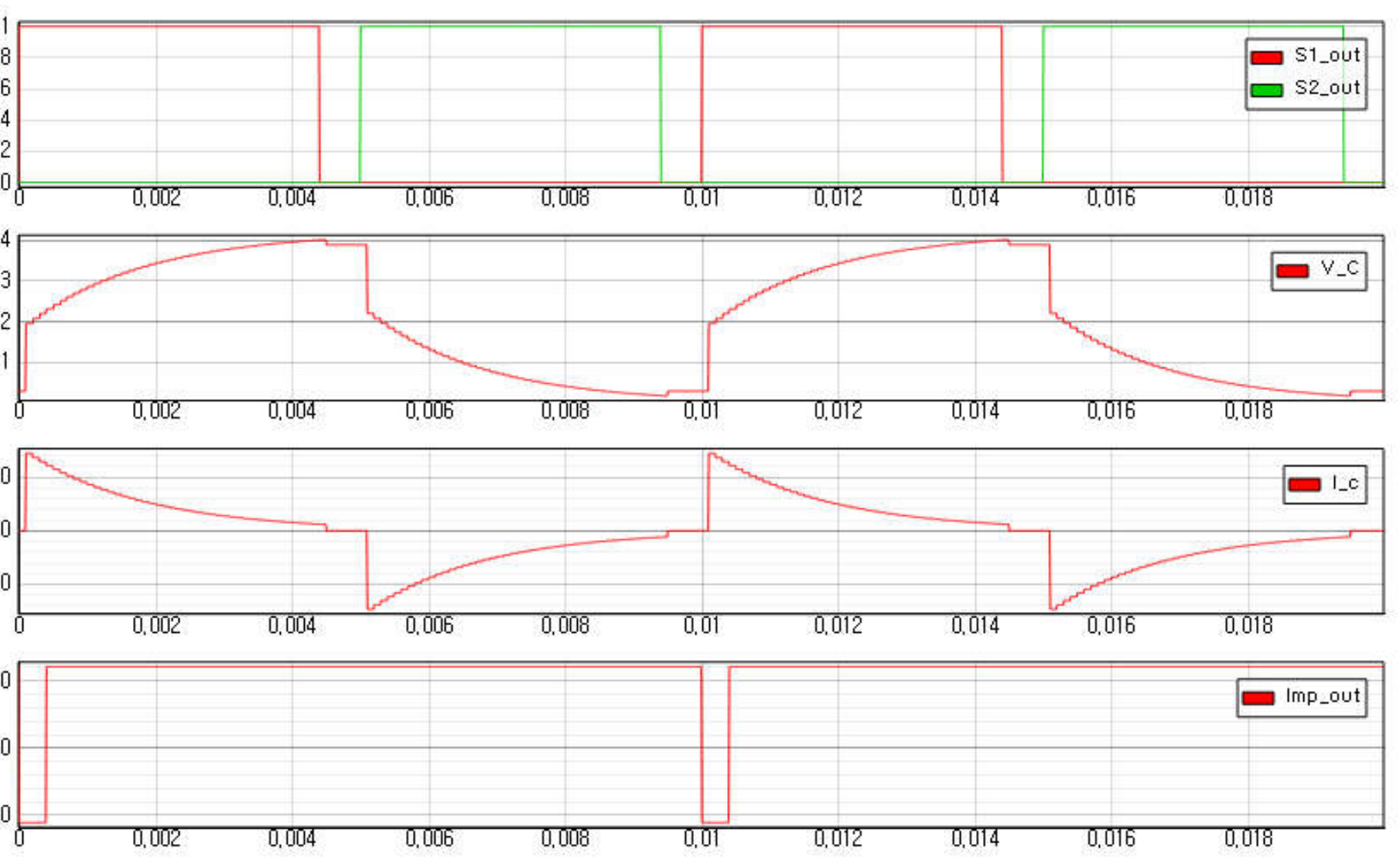


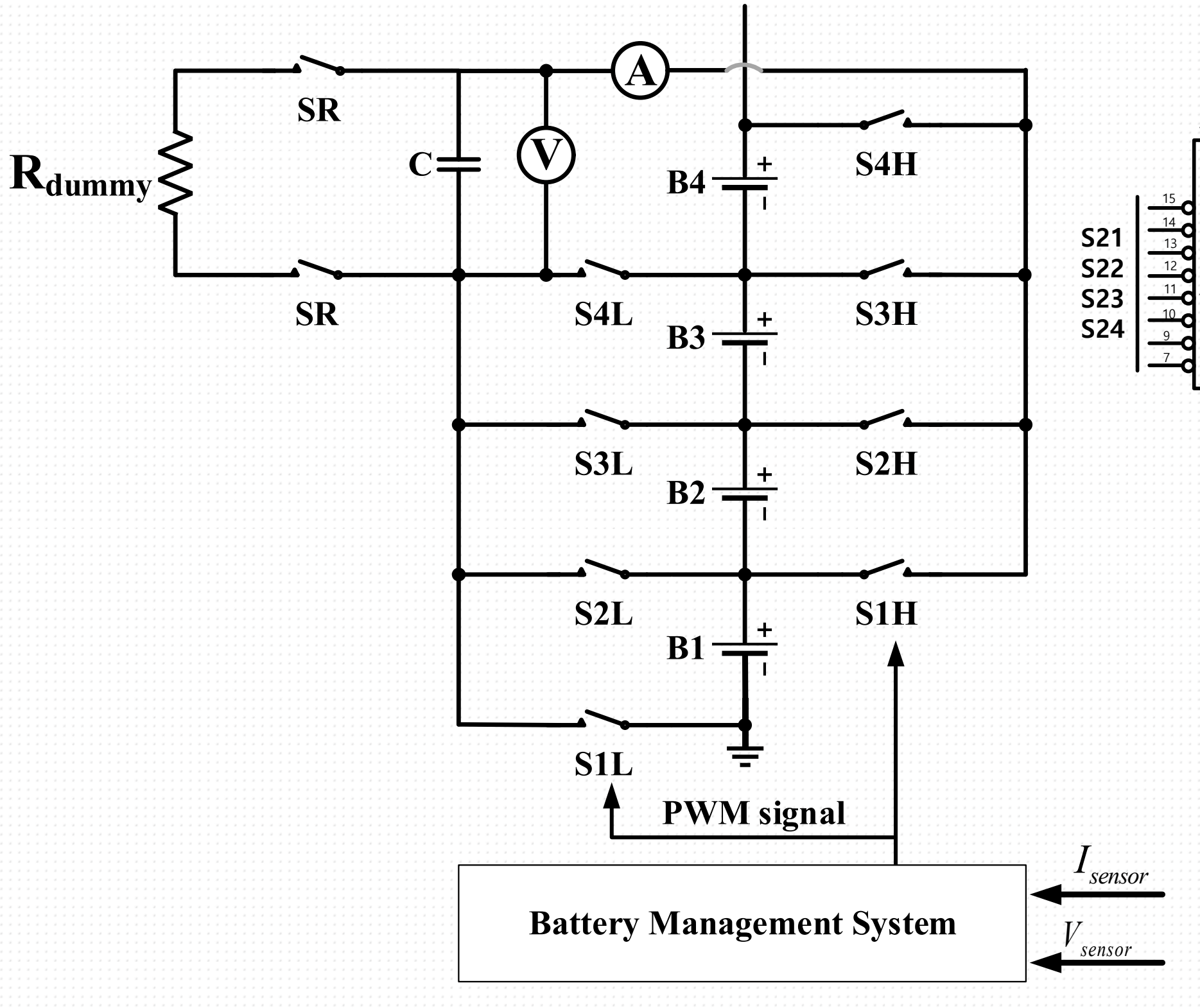
Table I: Actual and Estimated Value of DCIR

	Cell 1	Cell 2	Cell 3	Cell 4
ACTUAL (mΩ)	34	40	42	50
ESTIMATION (mΩ)	33	38	41	52
ERROR (%)	2.9	5.0	2.4	4.0

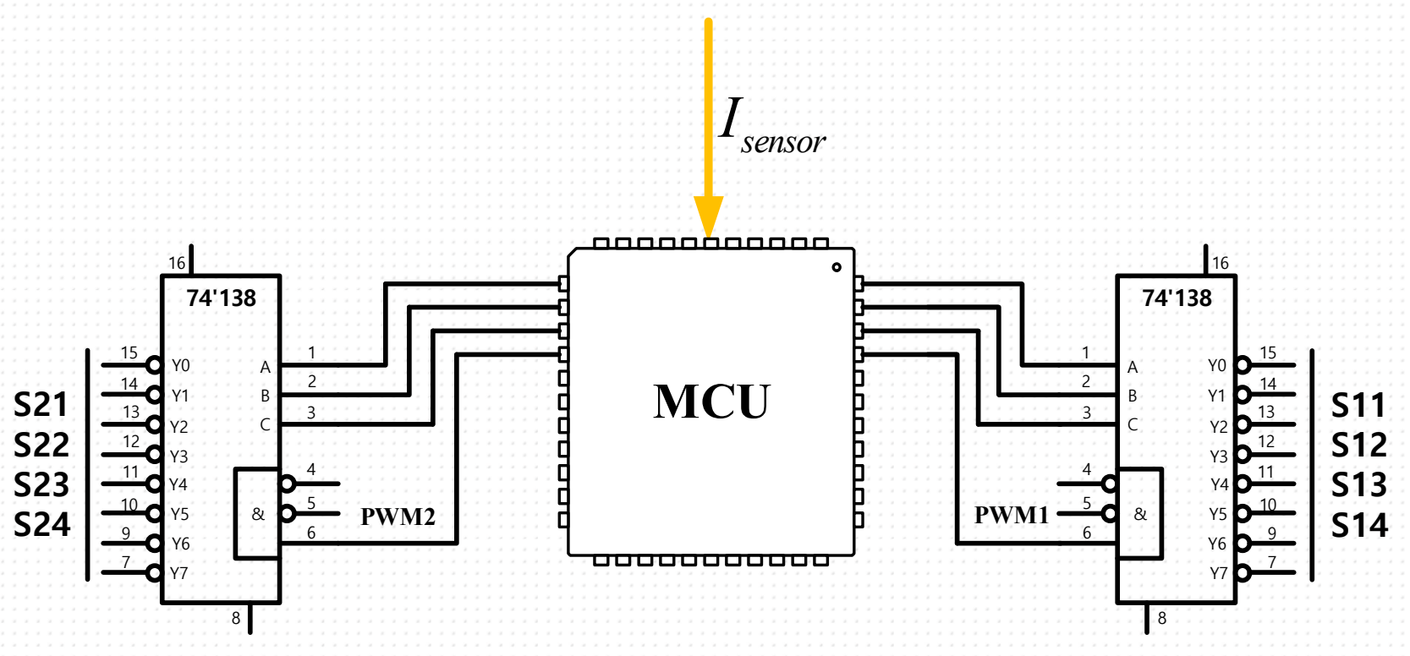
- Hardware-in-the-loop tests for 4 series-connected 18650 battery cells (3.7V/2.6Ah) are implemented.
- All cells are fully charged but the impedances are different as Table I.
- Initial tests setup:
    - $C = 6800uF$;
    - Sum of $R_{d,on}$ and ESR is $100m\Omega$;
    - $R_{dummy}=20m\Omega$;
    - $f_s = 1kHz$.
- Proposed method can estimate the individual DCIR of battery cells in series string within 5.5% error.

Proposed Online DCIR Estimation

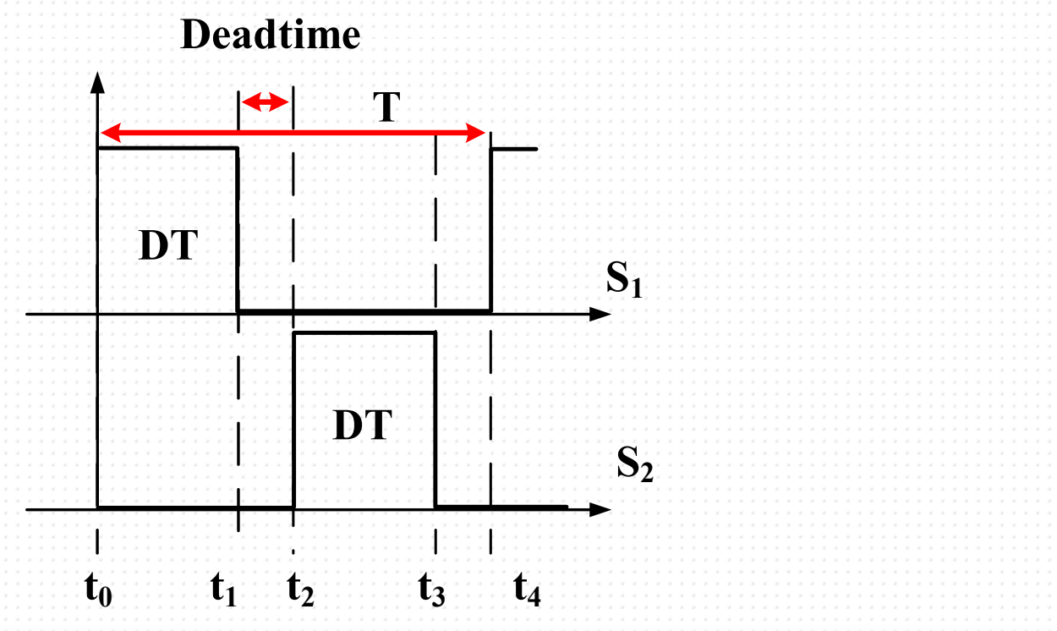
❖Measurement Circuit



Measuring circuit based on the switch-matrix equalizer



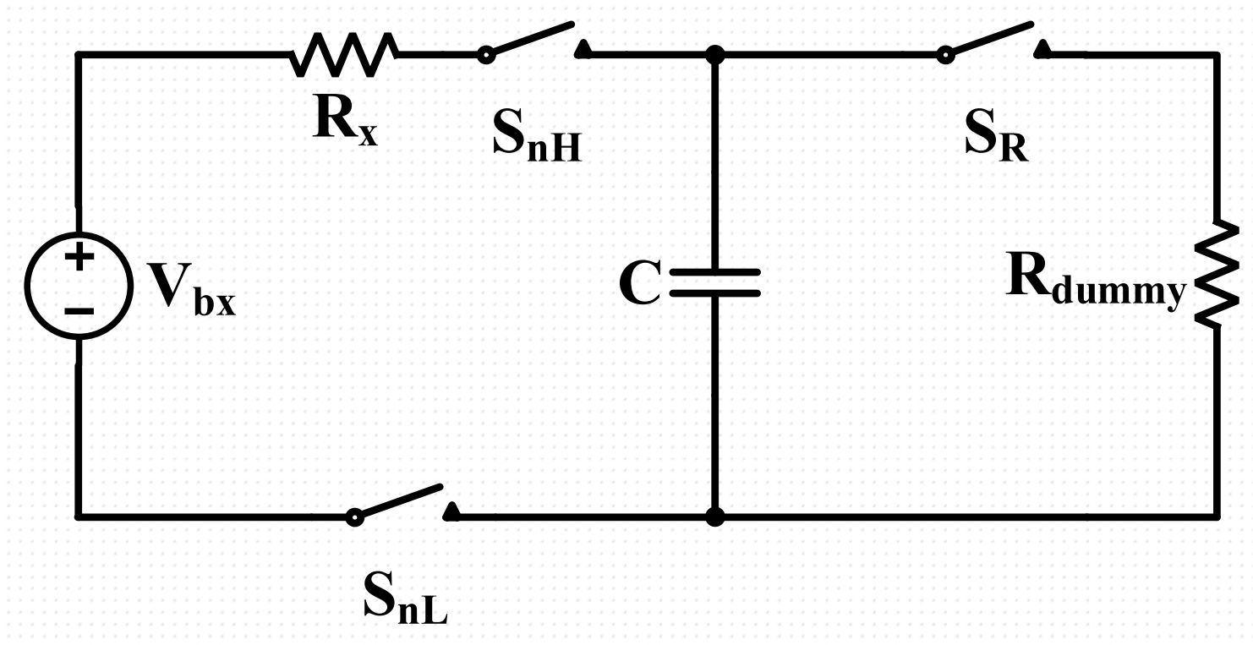
Example of Switching decision making



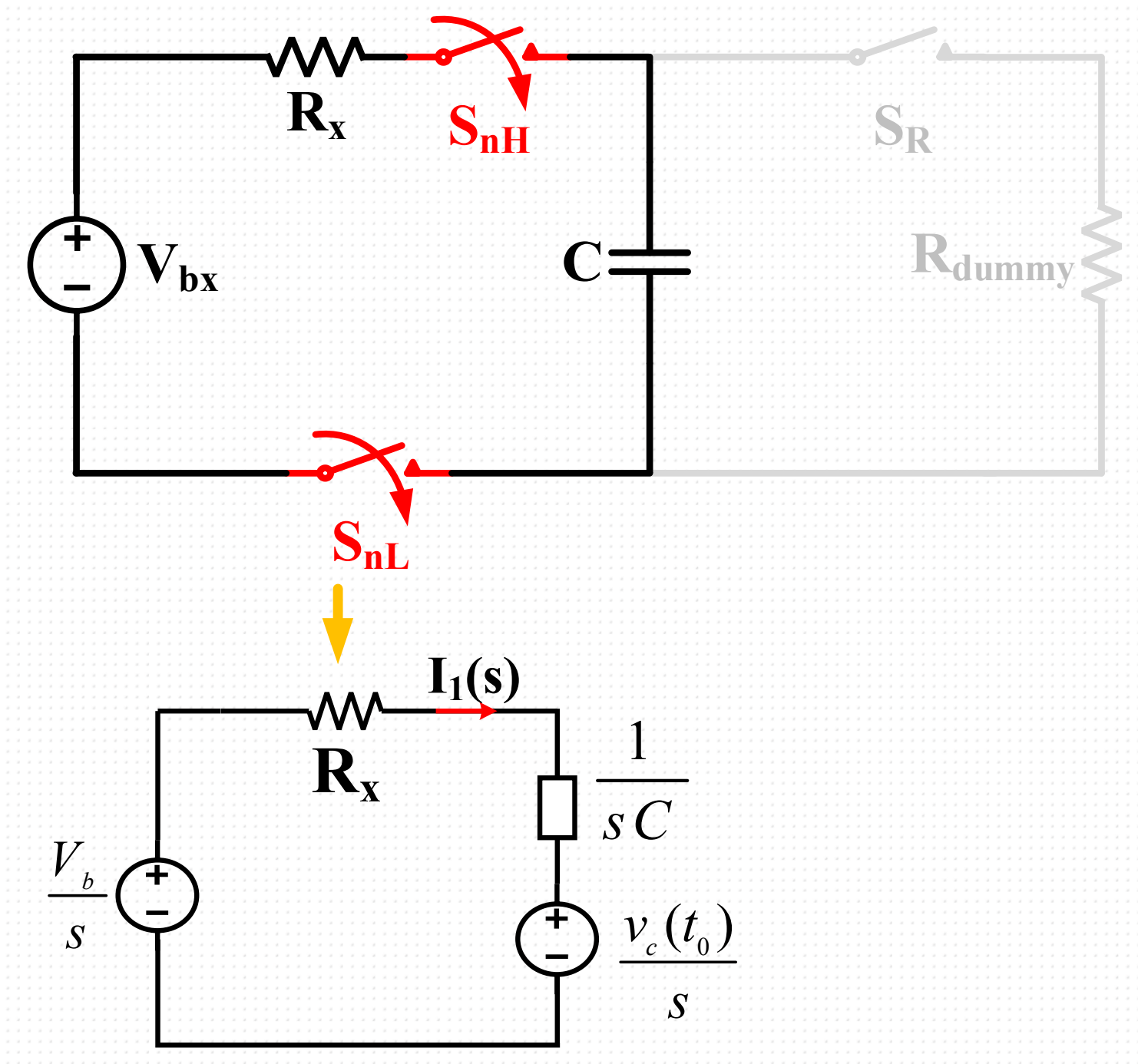
Control pattern of the proposed method

- Reuse of the existing switch-matrix flying capacitor equalizer.
- Only one pair of current-voltage sensors are required additionally.
- Discharging network for the equalization capacitor is required.
- The individual battery impedance is estimated one by one.

❖Theoretical analysis of the proposed methods:



Equivalent Circuit of The Proposed Method



Operation principle during phase A

- Battery cell is modeled by a voltage source, V_b and a resistor R_b.
- Charging time constant:

$$\tau_1 = R_x C \quad (1)$$

$$R_x = R_{bx} + R_{d,on} + ESR \quad (2)$$

- Current flowing into the capacitor in s-domain of the circuit during phase A:

$$I_{1s}=\frac{\Delta V}{R_x}\frac{1}{s+\frac{1}{\tau_1}} \quad (3)$$

$$\Delta V = V_b - v_c(t_0) \quad (4)$$

- The charging current in time-domain and the increased charge during phase A:

$$i_1(t)=\frac{\Delta V}{R_x}e^{\frac{-t}{\tau_1}} \quad (5)$$

$$Q_{in}(t_1)=\int_{t_0}^{t_1} i_1(t)dt=\Delta V\left(1-e^{\frac{-t_1}{\tau_1}}\right)C \quad (6)$$

- The capacitor voltage at the end of charging time:

$$v_c(t_1)=\frac{Q_{in}}{C}=\Delta V(1-e^{\frac{-t_1}{\tau_1}})+v_c(t_0) \quad (7)$$

- The DCIR of battery is estimated by applying the Newton-Rasphson numerical algorithm as follow:

$$\frac{i(t_1)}{v_c(t_1)}=\frac{1}{R_x}\frac{e^{\frac{-t_1}{R_xC}}}{\left(1-e^{\frac{-t_1}{R_xC}}\right)} \quad (8)$$

$$G_x=\frac{1}{R_x} \quad (9)$$

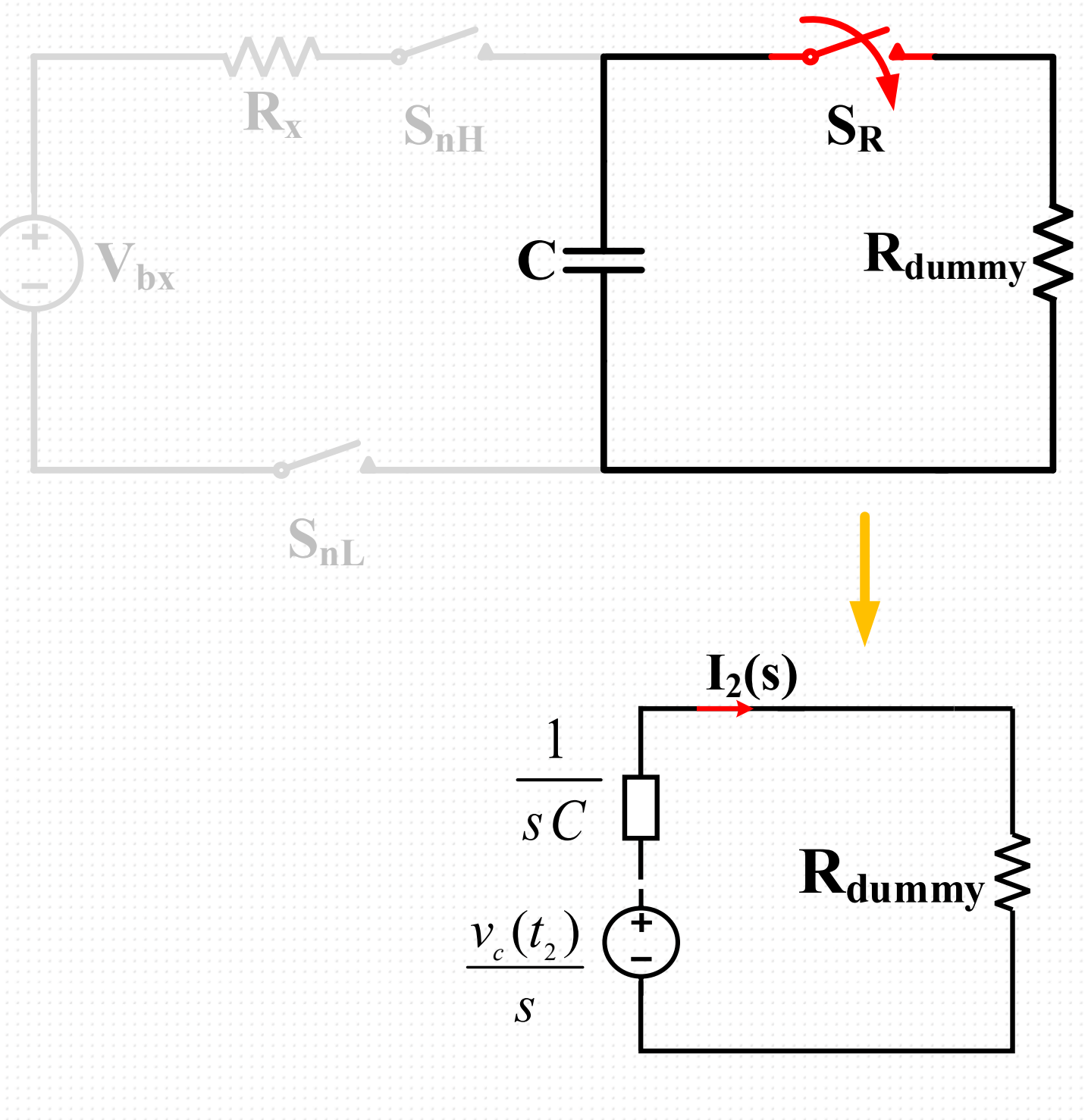
$$f(G_x)=G_x\frac{e^{\frac{-G_xt_1}{C}}}{1-e^{\frac{-G_xt_1}{C}}}-\frac{i(t_1)}{v_c(t_1)} \quad (10)$$

$$G_x(i+1)=G_x(i)-\frac{f(G_x(i))}{f'(G_x(i))} \quad (11)$$

$$\boxed{DCIR=\frac{1}{G_x(i+1)}-R_{d,on}-ESR \quad (12)}$$

- During phase B, capacitor is completely discharged by dummy load:

$$R_{dummy}<\frac{1}{5f_sC} \quad (13)$$



Operation principle during phase B

Conclusions

- An online DCIR estimation method based on the existing switch-matrix flying capacitor equalizer is proposed.
- The individual DCIR of battery cells in series string can be estimated accurately.
- The HIL test results show a high accuracy (The measurement error is within 5.5%).