Comparison of Different Current Sampling Strategies for an Online Battery Model Identification using Switched-Capacitor Equalizer

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ABSTRACT

Online state estimations require an accurate EIS model to reduce the estimation error. To evaluate the inconsistency of battery characteristics and aging, an online EIS-integrated equalizer circuit for individual-cell has been presented in [1]. By virtue of switch-matrix structure, every cell can be connected to the equalizing capacitor directly, and the equalizer series as an EIS model identifier. However, the model accuracy is heavily dependent on the current sampling strategy. This paper studies various current sampling schemes required for analyzing the exponential current waveforms to further enhance the accuracy. The strategies are assessed by a real-time test system and are compared with the EIS model from a commercial EIS analyzer. The results show that the start and end time-point strategy can achieve good accuracy, but it is difficult to determine optimal sampling instant. On the other hand, the multiple time-points strategy can accurately estimate the model parameters and overcome the disadvantages of the start and end time-point strategy.

Keywords: Online EIS model identification, switch-matrix structure, current measurement scheme.

1. INTRODUCTION

In recent years, the applications of lithium-ion batteries have been strongly developed. Along with the development of battery applications, the research on battery management systems is also focused on. Even if the cells have identical characteristics in the beginning, the inconsistency of the battery cell during operation is unavoidable [2]. The SOC deviation is known as one of the reasons for over-charging and over-discharging. Among various SOC estimation methods [3], model-based approaches are widely adopted.

On the contrary, the EIS model can be identified based on the correlation between the battery voltage and battery current [4]. The sinusoidal injection method is the most popular, but its execution-time is long and it requires extra signal generation circuits. Thus, it is hard to be applied to online estimation applications.

This paper compares different current measurement schemes for EIS-integrated equalizer that has been presented in [1]in terms of accuracy and simplicity. The strategies are assessed by a real-time test system and are compared with the EIS model from a commercial EIS analyzer. A brief review of the online estimation scheme is shown in section 2. The strategies are shown in section 3, section 4 is the verification results and section 5 is the conclusion.

2. REVIEW OF ONLINE MODEL IDENTIFICATION

The online measuring scheme is embedded into a switch matrix single-capacitor equalizer as Fig. 1. Simple additional circuit consisting of resistor, switch and voltage sensor are utilized to constitute the system. By virtue of the switch-matrix structure, the individual EIS-model of the cells can be identified one by one. The impedance measurement process is divided into two phases: charge transfer in phase A ($t_0 \sim t_1$) and capacitor recalibration in phase B ($t_2 \sim t_3$). The EIS-model identification is executed in phase A, when the battery cell is connected to the capacitor, C. The capacitor is fully discharged by R_{dummy} in phase B.

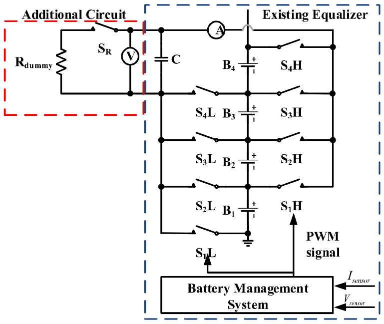

Fig. 1. EIS-integrated equalizer in [1]

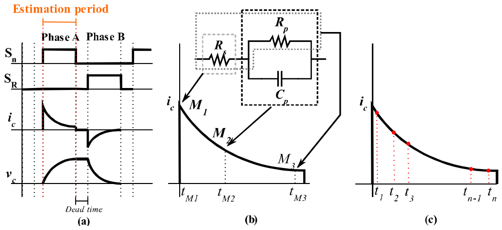

Fig. 2. Theoretical waveforms (a) current and voltage of the measuring capacitor; (b) start and end point strategy; (c) multiple time-points strategy

The single R-C Thévenin model is chosen to balance the trade-off between the accuracy and the calculation complexity. The current flow through the loop and the voltage of the capacitor are expressed by

$$i_C(t) \;=\; \frac{\Delta V}{R_n + R_p}\left(1 + \frac{R_p}{R_n} e^{\frac{-(R_n+R_p)t}{R_n R_p C_p}}\right) \qquad (1)$$

$$\Delta V \;=\; OCV \;-\; v_C(t) \qquad (2)$$

where OCV is the open-circuit voltage of the battery, which is measured in the initial process. $v_C(t)$, $i_C(t)$ are the measured voltage and current of the capacitor at t, respectively; R_n is the sum of the model's serial resistance, R_s, and the circuit R_{loop} resistance (including ESR of the capacitor, on-resistance of switches, and resistance of the sensor circuit).

3. COMPARATIVE STUDY

Based on the measured current and voltage of the balancing capacitor, the battery model parameters can be determined. Because the capacitor current, i_C, is an exponential form as Fig.2(a), the model parameters can be identified by appropriately choosing the measurement points. In this paper, two promising sampling schemes in Fig.2(b) and Fig.2(c) are compared.

3.1 Start and end time-point strategy (S-ETPS)

In the technique, since equation (1) has 3 parameters, they can be solved by measuring at 3 points during phase A.

***Table 1**. Model parameter identification results*

			Cell #1			Cell #2			Cell #3		
			R_n (mΩ)	R_p (mΩ)	C_p (F)	R_n (mΩ)	R_p (mΩ)	C_p (F)	R_n (mΩ)	R_p (mΩ)	C_p (F)
Commercial EIS analyzer			49.617	3.258	1.117	40.104	3.631	0.916	40.504	4.136	0.799
EIS-integrated equalizer	**S-ETPS**	**Avg.**	49.525	3.314	1.129	40.175	3.678	0.928	40.391	4.282	0.816
		Error (%)	**0.185**	**1.719**	**1.074**	**0.177**	**1.294**	**1.288**	**0.279**	**3.530**	**2.114**
	MTPS	**Avg.**	49.646	3.294	1.159	40.022	3.545	0.845	40.529	4.115	0.825
		Error (%)	**0.058**	**1.102**	**3.747**	**0.205**	**2.363**	**7.82**	**0.062**	**0.503**	**3.189**

Additionally, (1) is also the exponential function. By assuming $t_{M1} \approx 0$, $t_{M3} \rightarrow \infty$, and t_{M2} as a mid-point between t_{M1} and t_{M3}, the computational effort can be reduced as follow.

At $t_{M1} \approx 0$, R_n can be obtained by

$$R_n = \frac{OCV - v_C(t_{M1})}{i_C(t_{M1})} \tag{3}$$

Meanwhile, the battery impedance becomes a sum of R_n and R_p at t_{M3}. Thus, R_p is determined by

$$R_p = \frac{OCV - v_C(t_{M3})}{i_C(t_{M3})} - R_n \tag{4}$$

At t_{M2}, C_p is calculated by

$$C_p = \frac{(R_n + R_p)t_{M2}}{R_n R_p ln(1/K)} \tag{5}$$

where K is denoted by

$$K = \left(\frac{i_C(t_{M2})(R_n + R_p)}{OCV - v_C(t_{M2})} - 1\right)\frac{R_n}{R_p} \tag{6}$$

3.2 Multiple time-points strategy (MTPS)

In this strategy, equation (1) is transformed to

$$\frac{i_C(t)}{\Delta V} = \frac{1}{R_n + R_p} + \frac{R_p}{R_n(R_n + R_p)} e^{\frac{-(R_n+R_p)t}{R_n R_p C_p}} \tag{7}$$

By using the exponential curve fitting method, the EIS model of the battery cell is identified. In this paper, the current and the voltage of the equalization capacitor are measured at multiple time-points during phase A to identify the model.

4. VERIFICATION TESTS

To assess the performances, both measuring strategies are implemented for a 3S1P battery string, which consists of three 18650 cells (3.6V/2.85Ah). The switching frequency of the equalizer is 1Hz and the equalization capacitance is 2000μF. The individual EIS-model of the cells is examined by EIS measurement equipment (Zive SP10) as a reference. The reference parameters of the battery model are programmed into a real-time simulator to eliminate the influence of the environment change. For each battery cell, the measurement schemes are repeated 4 times, and the average value is calculated to reduce the measuring noise.

In the S-ETPS, the measuring accuracy of C_p is dependent on t_{M2} while R_s and R_p are calculated at two fixed time point, t_{M1} and t_{M3}, respectively. To analyze the impact of t_{M2}, the estimation error of the model paramters in three battery cells are illustrated in Fig. 3. The results show a large estimation error of C_p when t_{M2} is closed to t_{M1} and t_{M3}. Besides, the optimal t_{M2} point of three battery cells are different, which raise a big challenge to fix a t_{M2} point for all estimations.

To assess the impact of the sampling on the estimation error, the MTPS is implemented by multiple measurement points (from 3 to 100). The estimation error is calculated and illustrated in Fig. 4, which shows a concave error trend. With the initial setup in this paper, the error becomes the smallest with 50 time-points during phase A.

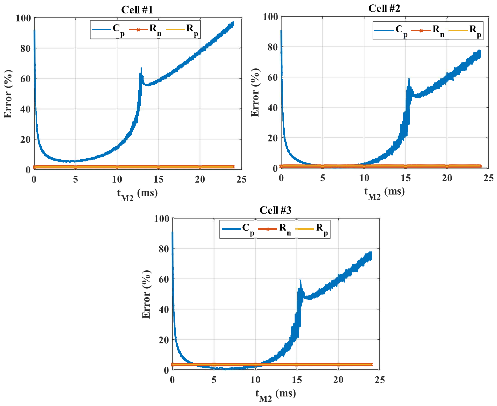

***Fig. 3**. The error dependency on t_{M2} in S-ETPS*

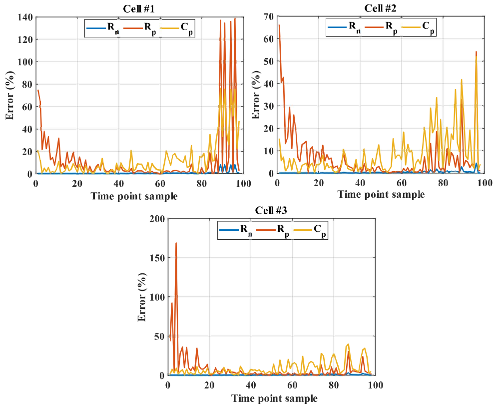

***Fig. 4**. The error dependency on number of time point in the MTPS*

Table 1 shows the estimated model-parameters. The errors of the S-ETPS are within 4% for all model-parameters. For the MTPS, the estimation error is good more accurate for R_s and R_p. However, the error becomes up to 8% for C_p. Therefore, it is found that the MTPS can partially improve the model accuracy, but the number of time-point should be optimized for all three parameters.

5. CONCLUSION

This paper assesses two estimation strategies for online EIS-model identification for EIS-integrated equalizers. The test results indicate that the MTPS has more advantages than S-ETPS in terms of practical implementation. While the S-ETPS is sensitive to the characteristics mismatching of the cells, the MTPS can estimate the model parameters just by some arbitrary estimation point.

ACKNOWLEDGEMENTS

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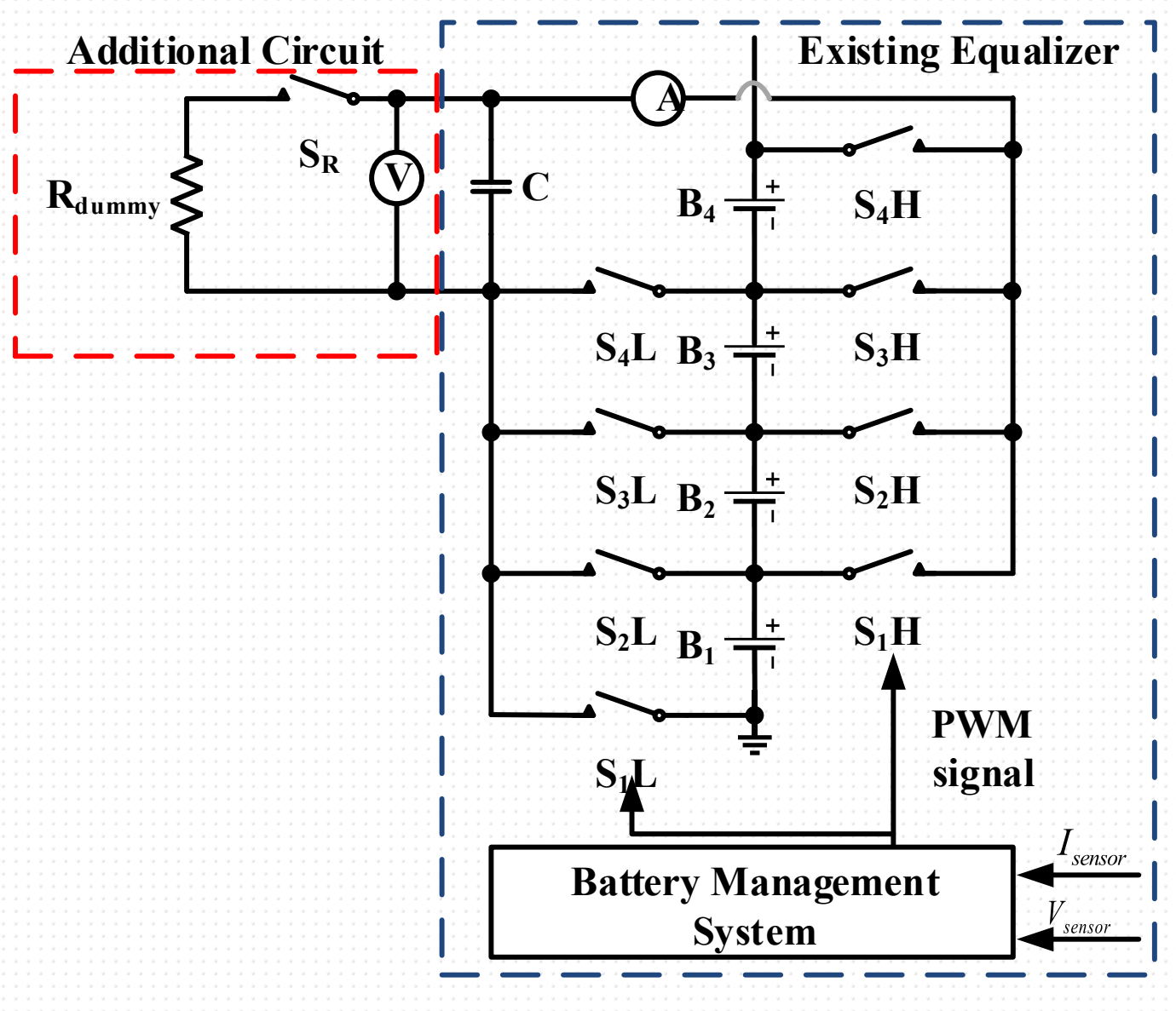
Summary

- **Online state estimations** require an **accurate EIS model** to reduce the estimation error, frequency-swept method require a long processing time.
- By virtue of **switch-matrix structure, an EIS model** of every cell can be identified but it is heavily dependent on **the current sampling strategy**.
- By assessed **current sampling strategies**, the **start and end time-point strategy** can achieve **good accuracy**, but it is **difficult to determine optimal sampling instant**.
- The **multiple time-points strategy** can **accurately estimate** the model parameters and **overcome the disadvantages** of the **start and end time-point strategy**.

Operation Principle of the Online Identification



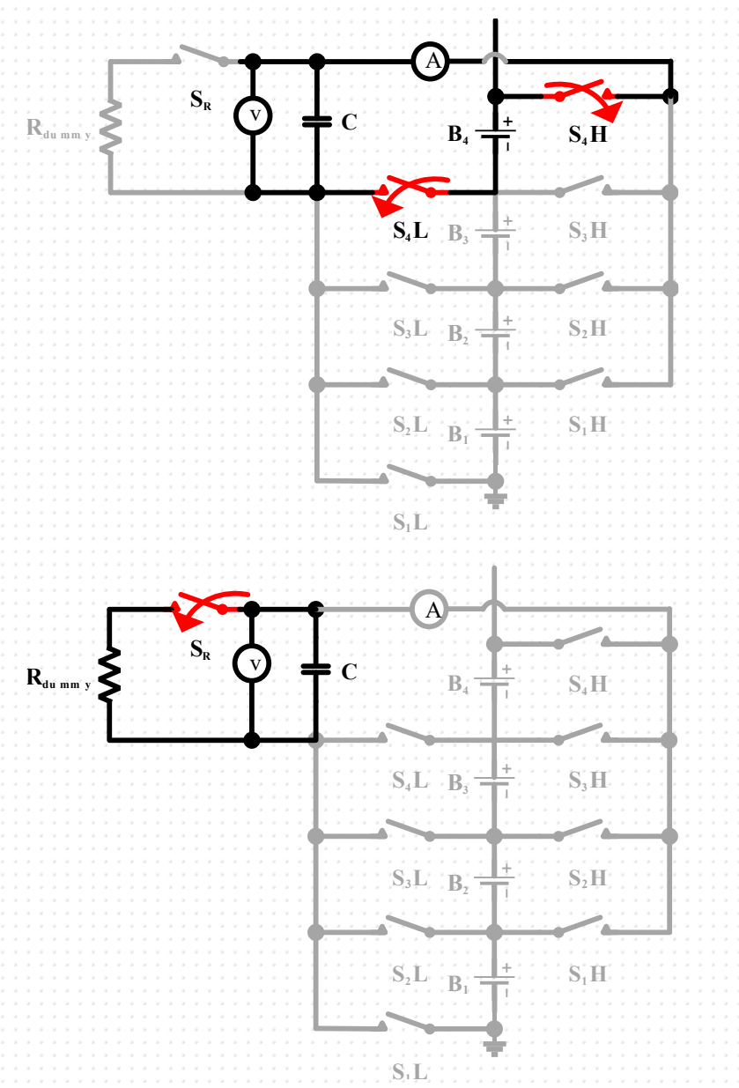
EIS-integrated equalizer

- The **online measuring scheme** is embedded into a **switch matrix single-capacitor equalizer** as Fig. 1.
- The **EIS-model identification** is executed in phase A.
- The **single R-C Thévenin model** is chosen.
- The **current** flow through the loop and the **voltage** of the capacitor are expressed by

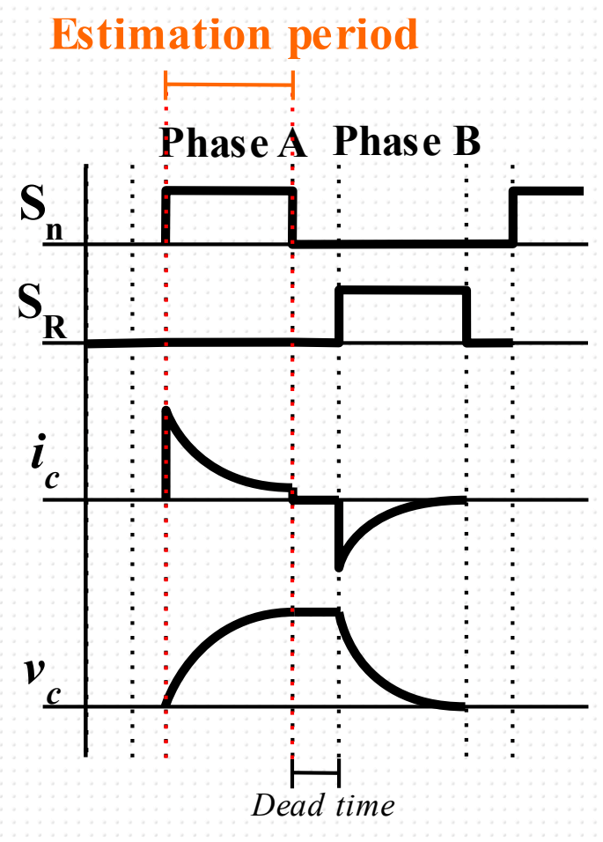
$$i_C(t)=\frac{\Delta V}{R_n+R_p}\left(1+\frac{R_p}{R_n}e^{\frac{-(R_n+R_p)t}{R_nR_pC_p}}\right) \quad (1)$$

$$\Delta V = OCV - v_C(t) \quad (2)$$

- **Capacitor voltage** and **current** are measured at ***t*** to calculate **the battery impedance.**



Measuring process of cell #4



Theoretical waveforms current and voltage of the measuring capacitor

Comparative Study of Estimation Strategies

❖Start and end time-point strategy (S-ETPS)

- By assuming $t_{M1} \approx 0$, R_n can be obtained from (1).

$$R_n=\frac{OCV - v_C(t_{M1})}{i_C(t_{M1})} \quad (3)$$

- $t_{M3} \rightarrow \infty$, the battery impedance becomes a sum of R_n and R_p

$$R_p=\frac{OCV - v_C(t_{M3})}{i_C(t_{M3})} - R_n \quad (4)$$

- t_{M2} as a mid-point between t_{M1} and t_{M3}, C_p is calculated by

$$C_p=\frac{(R_n+R_p)t_{M2}}{R_nR_p\ln(\frac{1}{K})} \quad (5)$$

Where **K** is denoted by

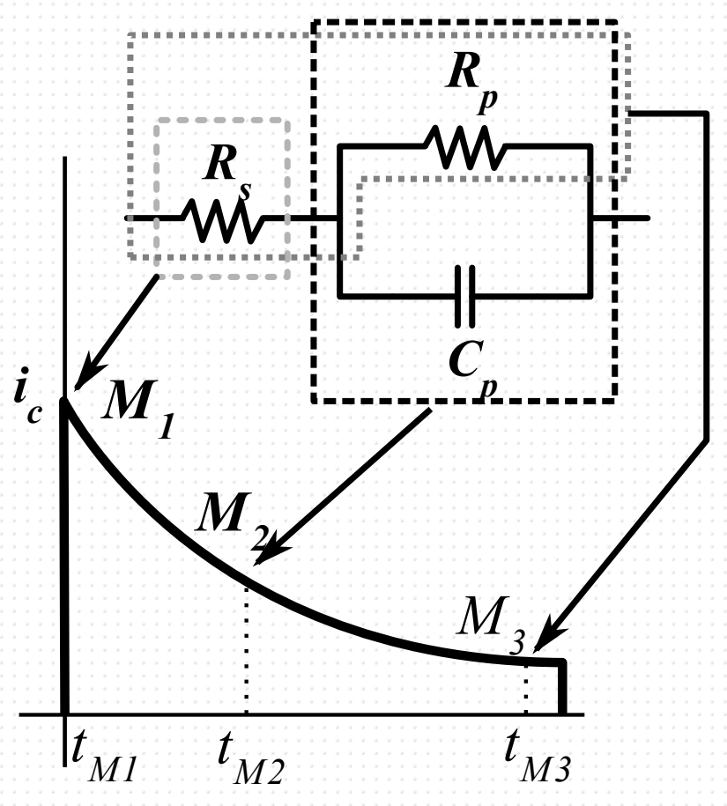
$$K=\left(\frac{i_C(t_{M2})(R_n+R_p)}{OCV - v_C(t_{M2})}-1\right)\frac{R_n}{R_p} \quad (6)$$

❖Multi time-points strategy (MTPS)

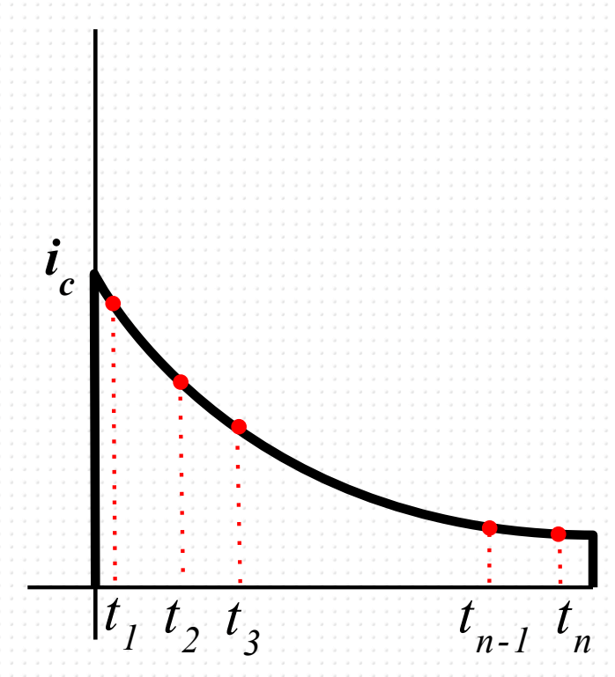
- Equation **(1)** is transformed to

$$\frac{i_C(t)}{\Delta V}=\frac{1}{R_n+R_p}+\frac{R_p}{R_n(R_n+R_p)}e^{\frac{-(R_n+R_p)t}{R_nR_pC_p}} \quad (7)$$

- Using the **exponential curve fitting** method to identify the EIS model of the battery cell.



Theoretical waveforms start and end point strategy



Theoretical waveforms multiple time-points strategy

Performance Verifications

			Cell #1			Cell #2			Cell #3		
			R_n (mΩ)	R_p (mΩ)	C_p (F)	R_n (mΩ)	R_p (mΩ)	C_p (F)	R_n (mΩ)	R_p (mΩ)	C_p (F)
Commercial EIS analyzer			49.617	3.258	1.117	40.104	3.631	0.916	40.504	4.136	0.799
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		Error (%)	**0.185**	**1.719**	**1.074**	**0.177**	**1.294**	**1.288**	**0.279**	**3.530**	**2.114**
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		Error (%)	**0.058**	**1.102**	**3.747**	**0.205**	**2.363**	**7.82**	**0.062**	**0.503**	**3.189**

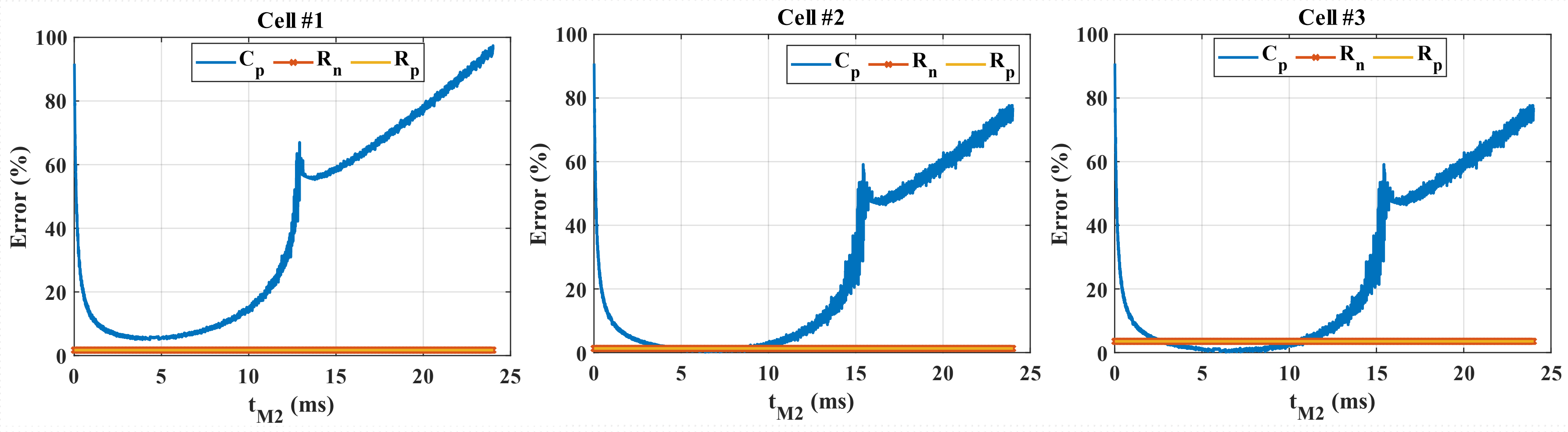

Fig.3. The error dependency on tM2 in S-ETPS

- Error of the **S-ETPS** are within **4%** for all model-parameters.
- Large error of C_p when t_{M2} is **closed to** t_{M1} and t_{M3}.
- The **optimal** t_{M2} **point** of three battery cells are **different.**

➔ Cannot fix a t_{M2} for every cases.

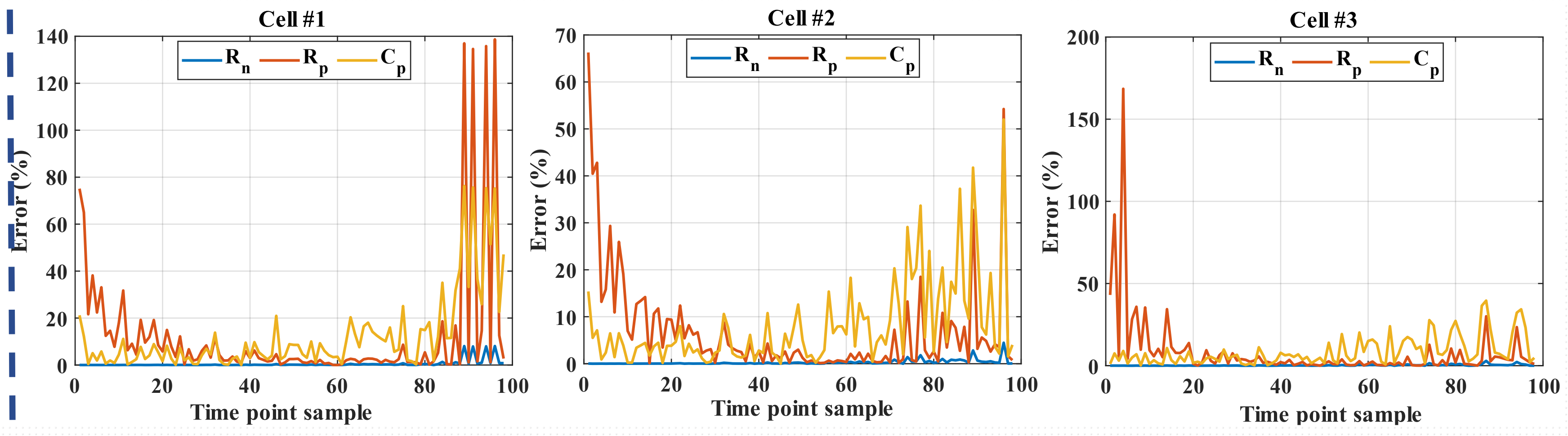

Fig. 4. The error dependency on number of time point in the MTPS

- Error of MTPS is **good more accurate** for R_s and R_p.
- Error of C_p is up to **8%**.
- The **MTPS** is implemented by **multiple measurement points** (from 3 to 100).
- The **error** becomes the **smallest** with **50 time-points**.

➔ Optimizing **the number of time-point** for all three parameters to decrease error.

Conclusions

- This paper assesses **two estimation strategies** for **online EIS-model identification** which is integrated into **existing equalizers**.
- The **MTPS** has more advantages than **S-ETPS** in terms of practical implementation.
- While the **S-ETPS** is **sensitive** to the **characteristics mismatching** of the cells, the **MTPS** can estimate the model parameters just by some arbitrary estimation point.

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