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Enhanced Equivalent Circuit Modeling for Li-ion Battery Using Recursive Parameter Correction

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Abstract – This paper presents an improved method to determine the internal parameters for improving accuracy of a lithium ion battery equivalent circuit model. Conventional methods for the parameter estimation directly using the curve fitting results generate the phenomenon to be incorrect due to the influence of the internal capacitive impedance. To solve this phenomenon, simple correction procedure with transient state analysis is proposed and added to the parameter estimation method. Furthermore, conventional dynamic equation for correction is enhanced with advanced RC impedance dynamic equation so that the proposed modeling results describe the battery dynamic characteristics more exactly. The improved accuracy of the battery model by the proposed modeling method is verified by single cell experiments compared to the other type of models.

Keywords: Li-ion battery, Battery modeling, 2nd RC ladder model, Offline parameterization.

1. Introduction

Recently, while environmental problems caused by fossil fuels became worse, regulation of greenhouse gas emissions has been strengthened. For this reason, interest to find the energy source to replace the fossil fuels is concentrated [1, 2]. With such the background, lithium-ion battery has attracted an attention as a next generation energy source because of its high energy density, low self-discharge, and long lifetime [3-9]. In order to use the lithium-ion battery safely and efficiently, the high reliable state estimation of the battery such as state-of-charge (SOC), state-of-health (SOH), and state-of-power (SOP) should be ensured [10-12]. Li-ion battery operation, which is determined by complex chemical reactions inside the battery, has strongly nonlinear dynamic characteristics [13-17]. Thus, it is necessary to analyze the nonlinearity of the battery dynamics so that battery models have been continuously studied to understand battery dynamics [25]. Especially in case of model-based battery state estimation algorithm, the model accuracy determines the overall performance.

Battery models are typically classified into electrochemical model, the mathematical model and the equivalent circuit model. Electrochemical model is based on the information of the electrochemical reactions occurring at the electrode and the electrolyte with very high accuracy. However, the high model complexity by the equations of complex chemical reactions is regarded as the serious disadvantage [18-21]. The mathematical model consists of equations that can effectively describe the nonlinear response of the battery. By selecting suitable mathematical expressions for the battery dynamics, it is possible to ensure high accuracy of mathematical model with low model complexity in comparison with the electrochemical model. However, merely to mathematically analyze the battery dynamic characteristics, it is impossible to represent the electrochemical sense of the battery [22]. Equivalent circuit model (ECM) can intuitively describe the chemical elements of the battery by using the electrical circuit components so that the model can be easily compatible with target system circuits [23-25]. In addition, the ECM is preferred by the model based state estimation algorithm because of its easiness for estimating the variation of parameters due to aging of the battery. However, it has the disadvantage of low accuracy as compared with other types of models because of difference between electrochemical reactions and circuit elements. In order to overcome the problem, many researches to increase the accuracy of the ECM have been developed [23-26, 30, 31].

Li-ion battery can be modeled as connections of resistors and capacitors by analyzing the output characteristics of the current versus voltage. The parameters of the ECMs are widely extracted by electrochemical impedance spectroscopy (EIS) method which measures the impedance in response of frequency and applying pulse waveform method which analyzes voltage in response of pulse shape current such as hybrid pulse power characterization (HPPC) [24, 27]. Especially in case of modeling method using a pulse waveform, it has an advantage to extract the parameters at aimed SOC point through charging or discharging battery until the target SOC point with constant current. This modeling method calculates the parameters based on voltage data while current is not applied to the battery, so it is important to get accurate fitting results from

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rest period voltage curve and extract parameters from the fitting results for accurate modeling.

The existing parameter extraction method using rest period voltage curve assumes that internal capacitors of the battery model are saturated just before starting rest so the voltage values of fitting results are directly divided by the terminal current to calculate the resistance values [25, 28, 29]. However, modeled RC impedance with the relatively large time constant value describing the long-term reaction of the battery does not reach a steady state during charging and discharging period so an error occurs in the extraction of the internal resistance value. To solve these problems, several correcting methods for the parameter extraction with estimating the transient state of the RC impedance were studied [26, 30-32]. The conventional correction method complements the parameter extraction by calculating the current flowing through the capacitor at transient state of RC impedance. However, the conventional RC impedance dynamic equation used for estimating transient state does not consider the additional electrical charge of internal capacitor caused by capacitance variation during SOC changing, so that the battery dynamic characteristics are not effectively expressed by the conventional dynamic equations.

In this paper, a series of methods for improving the accuracy of the ECM of the Li-ion battery is proposed. Configuration method of the modeling profile leading to the accurate fitting results is analyzed based on the secondary RC ladder model. Furthermore, effective parameter extraction method using the fitting results is proposed. Model parameters are calculated firstly based on the results of the fitting, and corrected by considering the transient state of RC impedance networks based on proposing differential equations of RC impedance dynamics.

2. Conventional Modeling Method

ECM of Li-ion battery is widely represented by second RC ladder model and it consists of a series resistor, two resistance-capacitance impedance networks and voltage source as shown in Fig. 1. The internal voltage source represents open circuit voltage (OCV) which appears to terminals of the battery when the terminals are opened with a long time. The series resistor represents the internal conductive resistance component of the battery and it shows the voltage characteristics in response to the instantaneous change of current. The two RC impedance components represent both diffusion and polarization reaction of the battery and each of them shows short-term reaction and long-term voltage reactions in response to the current change. Voltage responses resulted from the model elements are prominently displayed at the rest period curve of the battery.

As shown in Fig. 2, each instantaneous, short-term and long-term reaction appears successively responding to constant input current at the rest period voltage curve of the battery. Finally, OCV value is displayed on the terminal

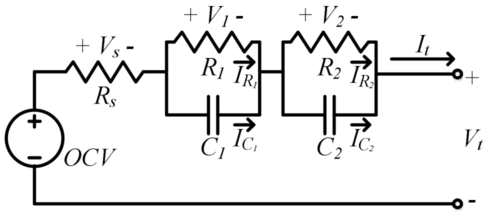


Fig. 1. The second RC ladder battery model

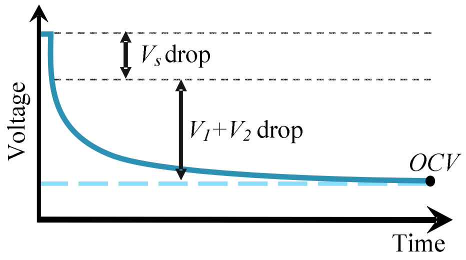
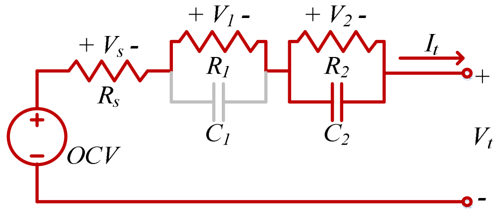
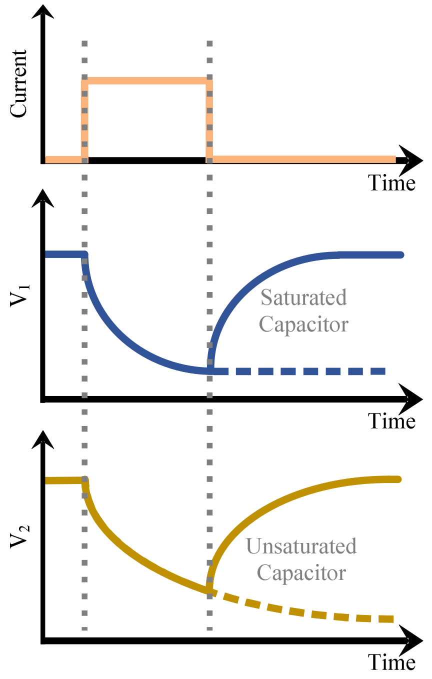


Fig. 2. Components of rest period voltage curve



(a) Practical current flow in battery just before rest period.



(b) Impedance voltage during charge and discharge.

Fig. 3. Parameter extraction problems caused by capacitors in transient state

voltage.

The rest period curve is represented as (1) based on the 2nd RC ladder model. Model parameter values of aimed SOC point are estimated through fitting results of the rest period curve at the particular SOC point. If there is sufficient charge and discharge time compared to the time constant of RC impedance, the RC impedance networks reach a steady state so that the model capacitors are saturated and there is no current flowing through the model capacitors. Therefore terminal current of the battery flows only through model resistors and the model parameters can be calculated by (2) using the fitting results [24].

$$V_t(t) = OCV + V_s\left(1-u(t)\right) + V_1 e^{-\frac{t}{\tau_1}} + V_2 e^{-\frac{t}{\tau_2}} \qquad (1)$$

$$R_1 = \frac{V_1}{I_{R_1}},\ C_1 = \frac{\tau_1}{R_1}\ \left(where, I_{R_1} \approx I_t\right) \qquad (2)$$

However, as shown in Fig. 3, RC impedance indicating long-term delay effect stays in the transient state by a large time constant value while other RC impedance indicating short-term delay effect is able to reach the steady state by a small time constant value, so that current flowing through RC impedance with large time constant is separately flowed through the model resistor and capacitor. RC parameters should be calculated by current flowing through the resistor and thus, correction procedure with transient state analysis of the RC impedance networks should be added to the parameter estimation method.

2. Proposed Parameter Extraction Method

2.1 Correction mechanism of parameter extraction

In order to correct the error due to the parameter calculation with unsaturated RC impedance, parameter correction method is proposed as shown in Fig. 4.

Step 1. Generating model output before correction - First, 2nd RC ladder model is primarily constituted by the parameter values $R_{1,before}$, $C_{1,before}$ which are directly obtained from curve fitting results. Same current profile used in modeling experiment is entered to obtain the voltage output of the primary model.

Step 2. Calculating voltage difference – By comparing the RC impedance voltage values of model output $V_{1,model}$ just after charging or discharging period with RC impedance voltage values of actual fitting result $V_{1,model}$, the voltage difference just before rest period is calculate ($\Delta V_1 = V_{1,model} - V_{1,fitting}$).

Step 3. Recalculating resistance value - By using the calculated voltage difference (ΔV1), the predetermined ratio of the voltage difference is multiplied to uncorrected resistance at 'SOC = a+b' point ($R_{1,after} = R_{1,before} \cdot \alpha_1 \cdot \Delta V_1$). Rising of the resistance value at the point 'SOC = a + b' leads to increase of the model output voltage.

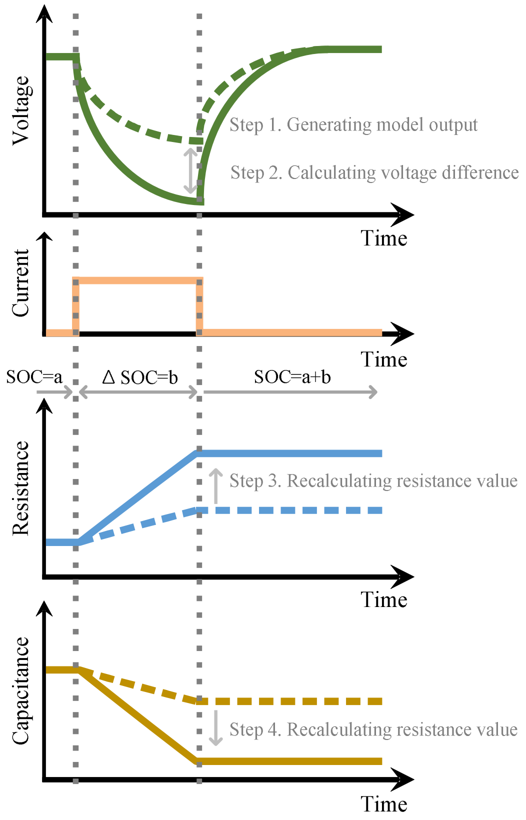
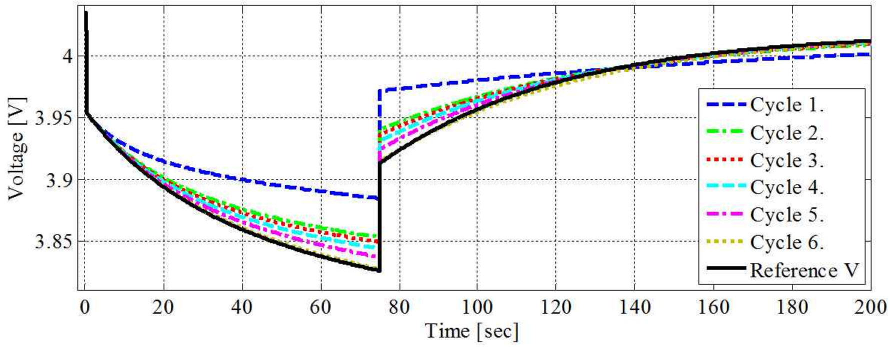


Fig. 4. Parameter correction process for matching voltage curve

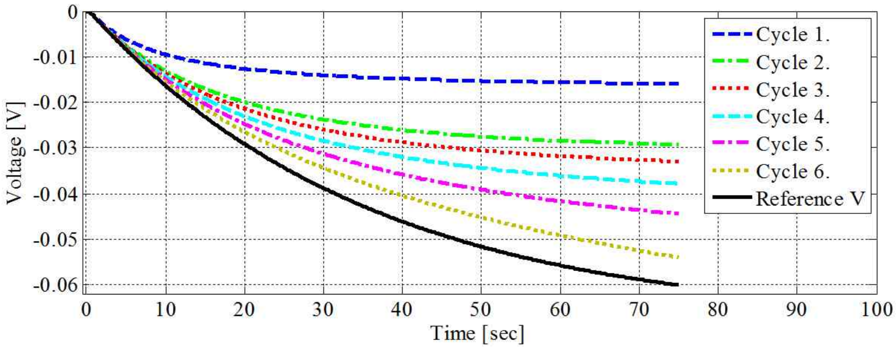
Step 4. Recalculating capacitance value – By using Recalculated resistance value ($R_{1,after}$) capacitance value is recalculated by the time constant value T1,fitting obtained by fitting of rest period voltage curve ($C_{1,after}=T_{1,fitting}/R_{1,after}$).

The processes of Step 1~4 are performed recursively with the recalculated parameter value $R_{1,after}$ and $C_{1,after}$ by correction. This parameter correction procedures are repeated until the voltage difference between cell data and model output (ΔV_1) is satisfied with the acceptable error rate to calculate the final target R_1, C_1 parameters. Same correction procedure is applied to the other RC impedance independently then R_2, C_2 parameters also can be recalculated. After finishing the correction at 'SOC=a+b' point, parameter correction of next SOC point (SOC=a+2b) is carried out. In case of modeling for battery charging, b value is positive so the SOC point of correction is gradually increased while SOC point is decreased in case of discharging because of negative value of b. The correction ratio α, so the value is greater, so the voltage difference is largely reflected to recalculated resistance to quickly reach the target value. However, large α value is possible to diverge correction results so the appropriate α value should be selected.

Fig. 5 shows matching procedure of the model output voltage with the actual battery voltage through the



(a) Terminal voltage with parameter correction process.



(b) Impedance voltage with parameter correction process.

Fig. 5. Matching voltage curve by recursive parameter correction

recursive parameter correction. Voltage curve based on parameters before correction is represented as curve of cycle 1. Because of transient state of RC impedance, model output before correction is larger than the cell voltage value just after discharge period. The resistance value calculated to be less by the current through the capacitance is increased to the original value by correction so that the amplitude of RC impedance voltage just before the rest period is increased and model output becomes more consistent with the actual battery voltage. This method is able to estimate the model parameters without particular parameter estimation algorithm.

The proposed correction method calculates parameters at ‘SOC = a + b’ point through fitting result at ‘SOC = a + b’ point and the parameters before constant charging or discharging (SOC = a). Therefore, selecting the parameters at the first point of the SOC which cannot be extracted theoretically by modeling method using pulse current profile is one of the most important issue of the proposed correction method. For analyzing influence of parameters at the first point of the SOC, parameter correction results in other SOC regions according to different parameter values at initial SOC is compared. As a result, only parameter values at next step from initial SOC are influenced and parameter values at gradually proceeding step of SOC are hardly changed. In conclusion, the parameter values in the total SOC region have same correction result regardless of the parameter values at first SOC point. In this paper, the parameter values at the first SOC are determined by using extrapolation and the parameter correction was performed.

2.2 Enhancing RC impedance dynamics

The amount of electrical charges in the capacitor is determined by the capacitor voltage as well as the capacitance. The current flowing through capacitor which means the rate of changing capacitor charge is affected by the change of the voltage as well as the changes of the capacitance and resistance. Therefore, RC impedance dynamics should reflect the capacitor current change according to the changes of resistance and capacitance during the charging or discharging periods as (3) for the accurate parameter correction. Differential equation of the RC impedance dynamics considering parameter variation is expressed as (3)-(5). By solving the differential equation, (6) is derived. For exact parameter extraction, the correction procedure is conducted by proposed RC impedance dynamics.

$$I_{C_1} = \frac{dQ_1}{dt} = \frac{d(C_1 \cdot V_1)}{dt} \tag{3}$$

$$I_t = I_{C_1} + I_{R_1} \tag{4}$$

$$\frac{d}{dt} I_t = \frac{d}{dt} I_{C_1} + \left(V_1 \frac{d(1/R_1)}{dt} - \frac{V_1}{R_1 \cdot C_1} \cdot \frac{dC_1}{dt} + \frac{I_{C_1}}{R_1 \cdot C_1} \right) \tag{5}$$

$$I_{C_1,k} = \left\{ \frac{\left(\exp\left(\alpha_{1,k}-\gamma_{1,k}\right)-1\right)\cdot\left(1-\alpha_{1,k}\right)}{\alpha_{1,k}-\gamma_{1,k}} \right\} \times I_{t,k} - \left\{ \frac{\exp\left(\alpha_{1,k}-\gamma_{1,k}\right)-1}{\alpha_{1,k}-\gamma_{1,k}} \right\} \times I_{t,k-1} + \exp\left(\alpha_{1,k}-\gamma_{1,k}\right) \times I_{C_1,k-1}$$
$$\left(where, \gamma_{1,k} = \frac{\Delta t}{R_{1,k}\cdot C_{1,k}},\ \alpha_{1,k} = R_{1,k}\left(\frac{1}{R_{1,k}} - \frac{1}{R_{1,k-1}}\right) - \frac{1}{C_{1,k}}\left(C_{1,k}-C_{1,k-1}\right) \right) \quad (6)$$

Table 1. Error results of the equivalent circuit modeling

	Pre-correction	Conventional correction method	Proposed correction method
RMSE [mV]	3.7990	1.6310	1.5882
Mean error rate [%]	0.0618	0.0257	0.0252

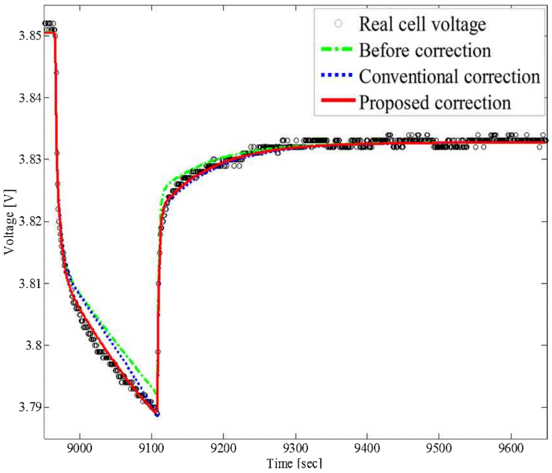


Fig. 6. Parameter correcting results based on different dynamic equation

Fig. 6 shows the modeling results with the proposed RC impedance dynamics equation. Since parameters are corrected to be matched with rest period data such as OCV, V_S, V_1, T_1, V_2 and T_2 value, both conventional correcting equation and proposed correcting equation have the same graph during rest period. However, despite the same curve during rest period, model output during conductive period is different according to RC impedance dynamic equations and that model output with proposed correcting equation describe the reference voltage more exactly. Table 1 shows the accuracy of the models by each modeling method. Through the proposed RC impedance dynamics, root mean square error (RMSE) and mean error rate is respectively decreased by 58.2% and 59.2% as compared to the pre-correction model, decreased by 2.6% and 1.9% as compared to the model with conventional correcting equation.

3. Single Cell Experimental Evaluation

3.1 Experimental conditions and Pre-modeling

(a) (b)

Fig. 7. Experiment condition for single cell test. : (a) Battery cell. (b) Experimental equipment for single cell test

In order to verify the improving ECM accuracy of the Li-ion battery through the suggested modeling method, the enhanced self-correcting (ESC) model which is typically used in the mathematical model of the Li-ion battery [22] was compared with the proposed modeling result. As shown in Fig. 7, Kokam SLPB 75175280PS which is the NCM type and has current capacity 27Ah, nominal voltage of 3.7V was used for model validation. The equivalent circuit modeling was conducted from SOC 10 % to 90% every SOC 2%. Modeling was performed with current profile consisting of each 0.5, 1.0, and 1.5 C-rate of constant current and 60 minutes rest time based on the analysis of chapter 2.

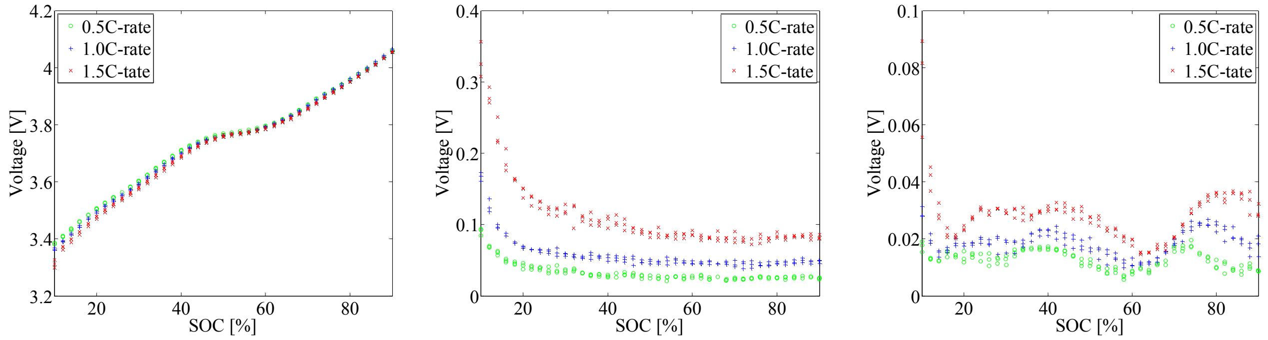
Fig. 8 shows the curve fitting result of rest period curve based on the 2nd RC model. Using the results of Fig. 8, the parameter correction was respectively carried out by the conventional and proposed method. The correction results are shown in Fig. 9. Each parameter value was changed in the form of mathematic equation which is useful for BMS, and the selection of R_2 in fitting accuracy [24]. The model was completed with the ninth order polynomial function instead of look-up table.

3.2 Experimental results

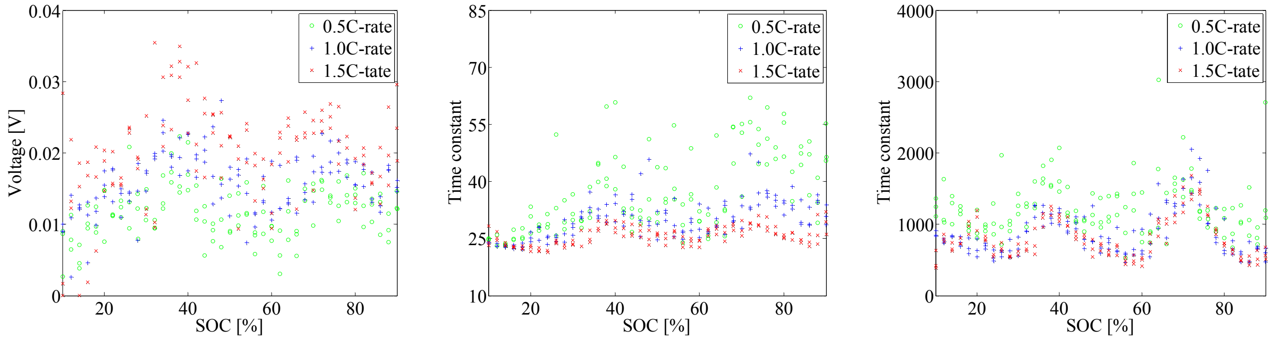
For model validation, ESC (2-stae filter), ESC (4-state filter) model for the mathematical models and pre-correction, the conventional correction and proposed correction model for the ECMs are used to verify the single cell tests. Urban dynamometer driving schedule (UDDS) and highway fuel economy test (HWFET) current profile were used for the single cell verification. Figs. 10(a) and 11(b) show the current profiles for the single cell tests. The results of single cell rests are shown in Table 2 and Figs. 10 and 11. Through proposed modeling method, RMSE and

Table 2. Error results of the single cell tests

		ESC (2-state filter)	ESC (4-state filter)	ECM pre-correction	ECM conventional correction	ECM proposed correction
UDDS profile	RMSE [mV]	6.3323	5.5738	7.4570	5.7429	5.5732
	Mean error rate [%]	0.1279	0.1148	0.1439	0.1102	0.1080
HWFET profile	RMSE [mV]	7.5387	6.7738	7.7699	6.6121	6.2480
	Mean error rate [%]	0.1610	0.1479	0.1769	0.1390	0.1306



(a) OCV fitting result (b) V_1 fitting result (c) V_2 fitting result



(d) V_S fitting result (e) T_1 fitting result (f) T_2 fitting result

Fig. 8. Curve fitting results for cell modeling

the mean error rate are respectively reduced by 25.2% and 26.2%, as compared to the pre-correction ECM and moreover, those values are respectively reduced by 7.7% and 11.7% as compared to ESC (4-state filter) model.

4. Conclusion

In this paper, the method to complement the internal parameter extraction of the Li-ion battery ECM based on second RC ladder model. To solve the occurring parameter estimation error when the parameters are directly extracted by the fitting results, parameter correction procedure analyzing transient state of internal capacitors is added to modeling algorithm. In the process of correction, by using an improved RC impedance dynamic equation considering change in the electrical charges corresponding to the changes in capacitance and resistance, the accuracy of parameter correction is improved than the conventional method. Compared to the existing correction method, RMSE and the mean error rate between cell data for modeling and model output are respectively reduced by 2.6% and 1.9% through the enhanced RC impedance dynamics. In order to verify the accuracy rise of the ECM with proposed modeling method, Single cell tests with enhanced self-correcting model and proposed ECM modeling result are conducted. UDDS and HWFET profiles are used for validation. As a result, RMSE and the mean error rate are respectively decreased by 7.7% and 11.7% through the proposed modeling method.

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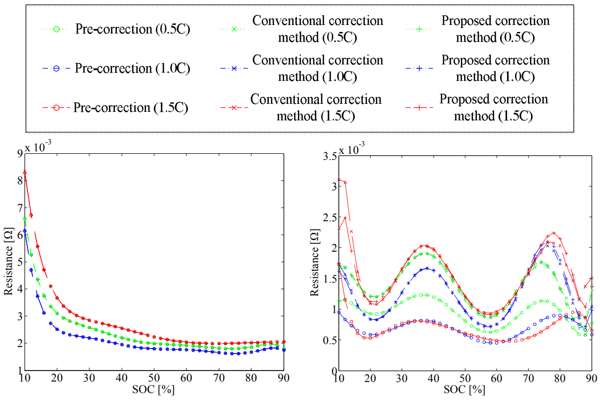
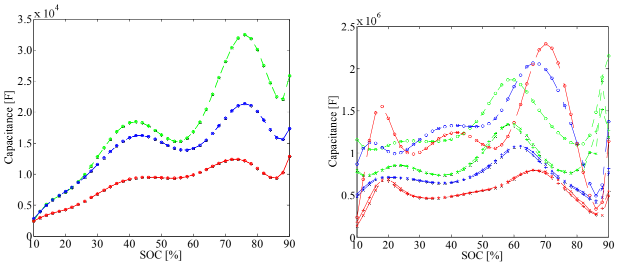
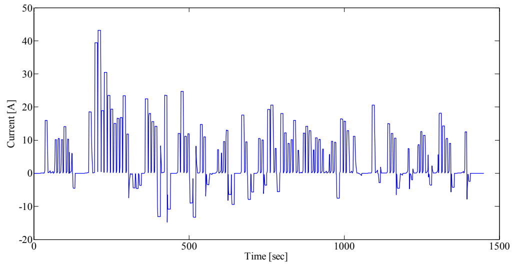


(a) R_1 extraction result (b) R_2 extraction result

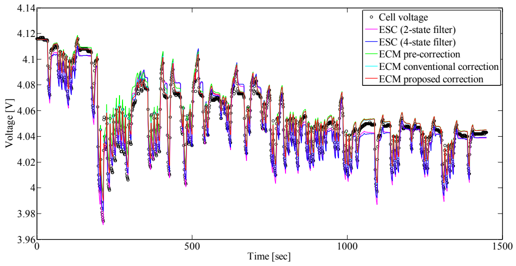


(c) C_1 extraction result (d) C_2 extraction result

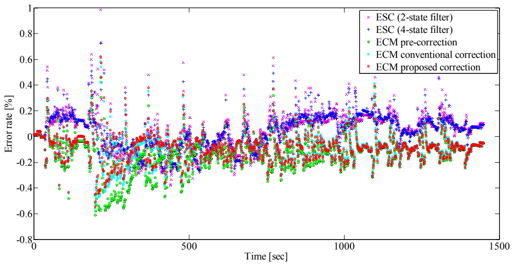
Fig. 9. Parameter extraction results by curve fitting



(a) UDDS profile

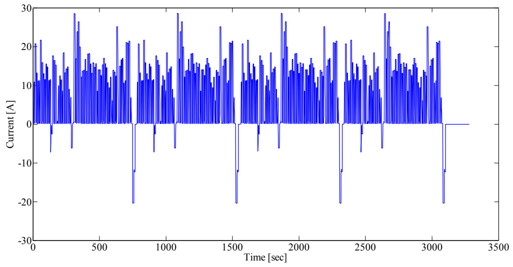


(b) Voltage test result

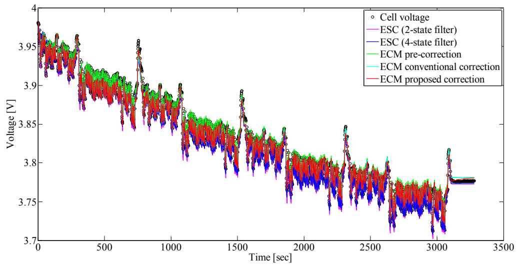


(c) Error rate test result

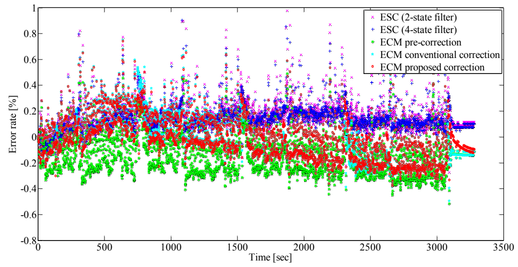
Fig. 10. Single cell test results with UDDS profile



(a) HWFET profile



(b) Voltage test result



(c) Error rate test result

Fig. 11. Single cell test results with HWFET profile

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