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Use Kalman Filter to Estimate the State Of Change of Lithium-Ion Battery

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ABSTRACT: Currently, lithium-ion batteries are widely applied in many fields, requiring a large capacity, stable, flexible and safe battery supply. To meet these requirements, a lithium-ion battery pack is often connected from many cells, including series to increase voltage and parallel to increase capacity. However, due to the different charging/discharging processes and working temperatures of the lithium-ion battery cells, the State of change imbalance between the cells in series leads to the State of change imbalance. This paper presents a method for estimating the State of change of a lithium-ion battery using an extended kalman filter. First, an ESC model of a lithium-ion battery was built to describe the charge/discharge dynamics of a lithium-ion battery. Based on the equations of state will determine the parameters of the enhanced self – correcting model, then use a kalman filter to observe the State of change of lithium-ion battery.

KEYWORDS: Lithium-ion battery, Mathematical model, ESC model, SoC estimation.

I. INTRODUCTION

Battery management system (BMS) is one of the most important parts of an electric vehicle. As the core of BMS, state of charge (SoC) estimation has an extremely considerable effect on safety, dynamic and economy of the electric vehicles. If an accurate SoC can be obtained, the SoC range can be used of batteries could be extended [1]. The precision of SoC estimation rely on the accuracy of the battery model[1]. Several authors have studied State of change estimation to improve the charging efficiency of lithium-ion batteries. some robust SoC observer have been built to reduce the negative impacts, such as sliding mode observer and, proportional integral observer.

[2] Research has shown that errors of a battery model will dramatically enlarge as the internal parameters of a battery varying. To reduce the systematic errors, a parameter adaptive battery model is proposed. Based on it, sliding mode algorithm is adopted to estimate the SoC of a battery.

[3] This paper presents a state of charge estimation method based on fractional order sliding mode observer (SMO) for lithium-ion batteries. A fractional order RC equivalent circuit model (FORCECM) is firstly constructed to describe the charging and discharging dynamic characteristics of the battery. Then, based on the differential equations of the FORCECM, fractional order SMOs for SoC, polarization voltage and terminal voltage estimation are designed. After that, convergence of the proposed observers is analyzed by Lyapunov's stability theory method.

[4] In this paper, a new state of charge estimation method for lithium battery has been presented. Contrary to the conventional methods which use complicated battery modeling, a simple resistor–capacitor battery model was used in order to reduce calculation time and system resource. Modeling errors caused by the simple model are compensated by the sliding mode observer. The structure of the proposed system is simple, but it shows robust control property against modeling errors and uncertainties. The state equation for battery model and the systematic design approach for sliding mode observer also have been presented.

[5] BMS requires an accurate prediction of state of charge of electric vehicles (EVs). In this paper, a first-order RC network equivalent circuit battery model with the hysteresis characteristic of Lithium-ion battery is built up. The parameters of battery equivalent circuit model is identified. And then, we design a SMO to estimate SoC of batteries in EVs.

This paper presents a method for estimating the State of change of a lithium-ion battery using an extended kalman filter. First, an ESC model of a lithium-ion battery was built to describe the charge/discharge dynamics of a lithium-ion battery. Based on the equations of state will determine the parameters of the enhanced self –

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correcting model, then use a kalman filter to observe the State of change of lithium-ion battery.

II. STATE OF CHANGE (SOC)

In order for the user to know how long the battery will continue to work before it needs to be recharged, it is necessary to determine the amount of energy remaining in the battery compared to the energy that the battery has when fully charged. This is a measure of the remaining power of the battery.

SoC is defined as the available power expressed as a percentage. Electrochemically, the SoC is a parameter related to the average ion density of Lithium on the cathode. The stoichiometry of the current lithium battery's ion density is expressed between 0% and 100%, which is the ratio of the remaining ion density to the fully charged ion density on the cathode.

$$\theta = \frac{c_{s,avg}}{c_{s,max}} \quad (1)$$

The SoC is defined as follows:

$$Z = \frac{\theta - \theta_{0\%}}{\theta_{100\%} - \theta_{0\%}} \quad (2)$$

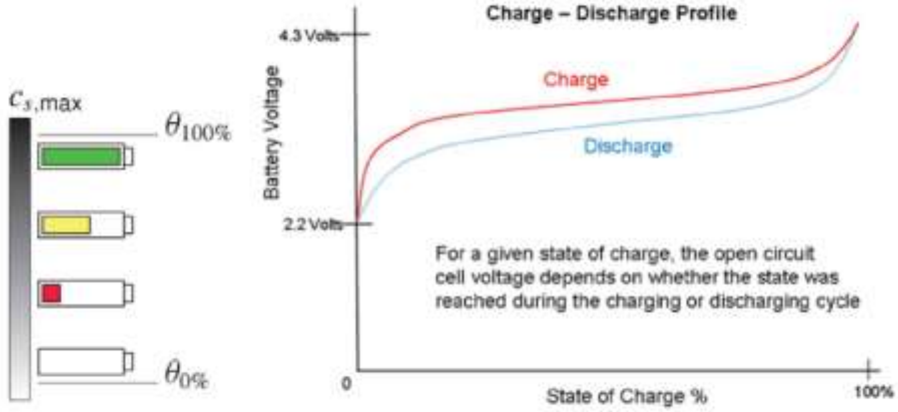

Figure 1. SoC illustration and graph illustrating the change of SoC and open circuit voltage during charging and discharging

III. ENHANCED SELF- CORRECTING OF LITHIUM-ION BATTERY

The ESC model considers hysteresis, the voltage of the model converges to the Open Circuit Voltage (OCV) hysteresis voltage. In addition, the model can also use more than one pair of parallel RCs to represent the kinetics of the battery. The ESC model is illustrated as shown in Figure 2.

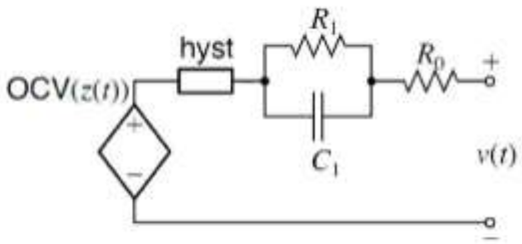

Figure 2. ESC model of Lithium - Ion battery

The equation for the current in the general case when more than one RC pair is connected in parallel in the model is:

$$i_{R_1}(k+1) = \begin{bmatrix} e^{\left[-\frac{\Delta t}{R_1 C_1}\right]} & 0 & \cdots \\ \cdots & e^{\left[-\frac{\Delta t}{R_1 C_1}\right]} & \cdots \\ \vdots & \cdots & \ddots \end{bmatrix} i_{R_1}(k)$$

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$$+\begin{bmatrix}\left[1-e^{\left[-\frac{\Delta t}{R_1C_1}\right]i_{R_1}(k)}\right]\\ \left[1-e^{\left[-\frac{\Delta t}{R_1C_1}\right]i_{R_1}(k)}\right]\\ \vdots\end{bmatrix} i(k) \quad (3)$$

Set $A_H(k) = e^{\left[-\left|\frac{\eta(k)i(k)\gamma\Delta t}{Q}\right|\right]}$, set the state vector as SoC, battery current and hysteresis voltage as follows:

$$X = \begin{bmatrix} z(k) \\ i_R(k) \\ h(k) \end{bmatrix} \quad (4)$$

Then the kinematic equation describing the state of the Lithium Ion battery in the discrete domain with sampling period Δt is:

$$X(k+1) = \begin{bmatrix} z(k+1) \\ i_R(k+1) \\ h(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & A_{RC} & 0 \\ 0 & 0 & A_H(k) \end{bmatrix} \begin{bmatrix} z(k) \\ i_R(k) \\ h(k) \end{bmatrix} + \begin{bmatrix} -\frac{\eta(k)\Delta t}{Q} & 0 \\ B_{RC} & 0 \\ 0 & A_H(k)-1 \end{bmatrix} \begin{bmatrix} i(k) \\ sgn(i(k)) \end{bmatrix} \quad (5)$$

The equation for the output voltage across the battery terminals is written as:

$$v(k) = OCV\big(z(k), T(k)\big) + M_0 s(k) + Mh(k) - \textstyle\sum_j R_j i_{R_j}(k) - R_0 i(k) \quad (6)$$

So the equation of state for the ESC model of a Lithium battery is:

$$\begin{cases} X(k+1) = \begin{bmatrix} z(k+1) \\ i_R(k+1) \\ h(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & A_{RC} & 0 \\ 0 & 0 & A_H(k) \end{bmatrix} \begin{bmatrix} z(k) \\ i_R(k) \\ h(k) \end{bmatrix} + \begin{bmatrix} -\frac{\eta(k)\Delta t}{Q} & 0 \\ B_{RC} & 0 \\ 0 & A_H(k)-1 \end{bmatrix} \begin{bmatrix} i(k) \\ sgn(i(k)) \end{bmatrix} \\ v(k) = OCV\big(z(k), T(k)\big) + M_0 s(k) + Mh(k) - \sum_j R_j i_{R_j}(k) - R_0 i(k) \end{cases} \quad (7)$$

In this model all parameters are non-negative. Parameters Q, η, γ, M, M_0, R_0, R_jC_j, R_j are determined through experimental data, this data is collected based on different experimental scenarios for battery.

IV. DETERMINE THE PARAMETERS OF THE ESC MODEL

To determine the parameters in the ESC model, we need to go through two steps as follows:
Step 1: Collect experimental data, known as OCV experimental data, and then rely on this data to determine the relationship between OCV and SoC by temperature.
Step 2: Collect kinetic data, this kinetic data along with the relationship between OCV and SoC found in step 1 to determine the parameters of the ESC model.

Determine The Relationship Between OCV AND SOC

To determine the relationship between the OCV and the SoC of a battery cell, we need to discharge the battery very slowly, then charge it slowly, respectively, under the same temperature conditions, the charging and discharging process is slow for the purpose. eliminate heat generation.
During that process, the following parameters should be measured:
+ Measurement time point (s)
+ Current (A)
+ Battery terminal voltage (V)
+ Charging capacity (Ah)
+ Discharge capacity (Ah)
+ Charge energy (Ah)
+ Discharge energy (Ah)
+ Rate of change of voltage (dV/dt)
The above parameters are collected as shown in Table 1. The table of data to be collected for the four stages is as follows:

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Table 1. Experimental data sheet to determine the relationship between OCV and SoC for lithium ion batteries

Data – Point	Test_Time (s)	Current (A)	Voltage (V)	Charge_Capacity (Ah)	Discharge_Capacity (Ah)	Charge_Energy (Wh)	Discharge_Energy (Wh)	dV/dt(V/s)
1	60.0076	0	3.599443197	0	0	0	0	-3.2568E-05
2	120.0219	0	3.599606037	0	0	0	0	0
3	180.0364	0	3.599769115	0	0	0	0	-3.2568E-05
4	240.051	0	3.599931955	0	0	0	0	3.2568E-05
5	300.0669	0	3.600095034	0	0	0	0	3.26157E-05
….								
121	7210.065	-0.076687	3.590806961	0	0.000213308	0	0.000766669	-0.00048885
122	7220.081	-0.076687	3.585429668	0	0.000426616	0	0.001532013	-0.00045629
123	7230.096	-0.07665194	3.580704212	0	0.00063993	0	0.002296304	-0.00035849
124	7240.112	-0.07665194	3.576467752	0	0.000853264	0	0.003059696	-0.00032587
125	7250.127	-0.076687	3.572068214	0	0.001066582	0	0.003822147	-0.00032587
126	7260.142	-0.07665194	3.568646193	0	0.001279904	0	0.004583784	-0.00026073
127	7270.158	-0.076687	3.565061569	0	0.001493239	0	0.00534468	-0.00022812
128	7280.173	-0.07661688	3.561802626	0	0.00170657	0	0.006104824	-0.0001955
129	7290.189	-0.076687	3.558217764	0	0.001919909	0	0.00686429	-0.0002933
...								

STAGE 1, AT WORKING TEMPERATURE (Figure 3)

Step 1: The battery is fully charged and remains fully charged for 2 hours to ensure uniform temperature throughout the battery.

Step 2: Discharge the battery with a constant current and equal to C/30 until the remaining voltage is equal to the minimum voltage (vmin) according to the manufacturer's specifications.

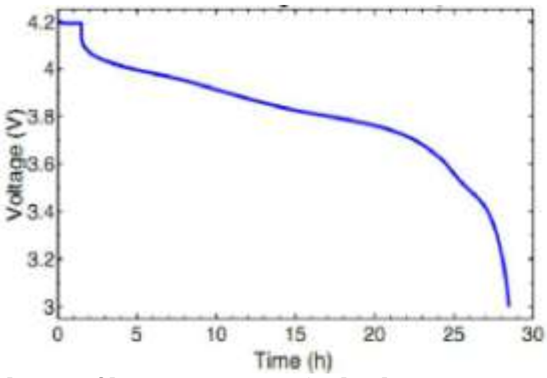

Figure 3. Change of battery two-terminal voltage 1st stage

STAGE 2, AT 250C

Step 3: Leave the battery in a room with a temperature of 250C for at least 2 hours so that the battery has a uniform temperature of 250C throughout the battery.

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Step 4: If the voltage of the battery is less than vmin, charge it with a charging current of C/30 until the voltage is equal to vmin. If the voltage is greater than vmin, discharge with a current of C/30 until the voltage is equal to vmin. The same process repeats.

STAGE 3, AT WORKING TEMPERATURE (Figure 4)

Step 5: Leave the battery in a room that is at the operating temperature of the battery specified by the manufacturer for 2 hours.

Step 6: Charge the battery with the C/30 line until the voltage reaches vmin as specified by the manufacturer.

STAGE 4, AT 250C

Step 7: Leave the battery in a room with a temperature of 250C for at least 2 hours so that the battery has a uniform temperature of 250C throughout the battery.

Step 8: If the voltage is lower than vmax, then charge it with the C/30 line until the voltage is equal to vmax. If the voltage is greater than vmax, discharge with current C/30 until the voltage is equal to vmax, the same process repeats.

From the above data, we can determine: Coulomb efficiency and the relationship between OCV and SoC.

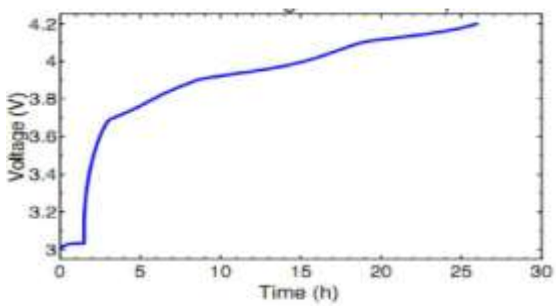

Figure 4. Change of battery two-terminal voltage 3rd stage

Determine Coulomb's Efficiency

Taking the temperature of 250C as the standard, first determine the Coulomb efficiency at 250C as the ratio of the total discharge capacity $\sum_{i=1}^{md} CC_i^{dischage}$ and the total charge capacity $\sum_{j=1}^{mc} CC_j^{chage}$ according to the following formula, where md is the number of data points corresponding to the discharge and mc is the number of data points corresponding to the loading:

$$\eta(25^0C) = \frac{\sum_{i=1}^{md} CC_i^{disc\ hage}}{\sum_{j=1}^{mc} CC_j^{chage}} \quad (8)$$

Then the Coulomb performance at any temperature is determined by the formula

$$\eta(T) = \frac{\sum_{p=1} CC_i^{disc\ hage}}{\sum_{q=1} CC_j^{chage\_T}} - \eta(25^0C) = \frac{\sum_i CC_i^{chage\_25}}{\sum_j CC_j^{chage\_T}}$$

(9)Where: $\sum_{p=1} CC_i^{dischage}$ is the total discharge, $\sum_{q=1} CC_j^{chage\_T}$ is the total charge at temperature T, $\sum_i CC_i^{chage\_25}$ is the total charge of 250C, $\sum_j CC_j^{chage\_T}$ is the total charge at temperature T. The following figure 5 illustrates the Coulomb deviation for 6 different types of lithium-ion battery cells.

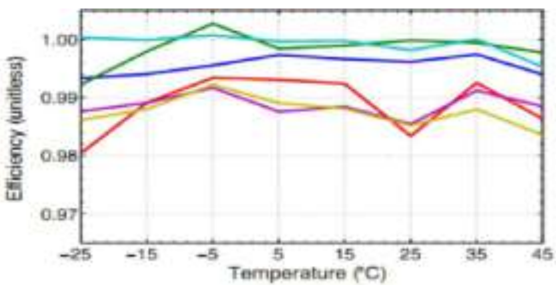

Figure 5. Coulomb deviation for 6 different types of Lithium Ion battery cells

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Determine the relationship between OCV and SoC

Determine the DoD (the depth of discharge), which is a parameter that measures how much discharge a battery has. When the battery is fully discharged, DoD = 100%).

DoD at time t, at temperature T, is determined by the formula

$$DoD(t) = S_{dis}(t) - \eta(25^0\text{C})xS_{char}^{25}(t) - \eta(T)xS_{char}^{T}(t) \quad (10)$$

Where: $S_{dis}(t)$is the total discharge at time t, $S_{char}^{25}(t)$is the total charge at 250C up to time t, $S_{char}^{T}(t)$is the total charge at temperature T calculated to time t.

Using the metric system, the Q capacity of the battery (measured at temperature T) is equivalent to the DoD of the battery at the end of step 4.

Likewise, the SoC at time t corresponds to the collected data

$$SoC(t) = 1 - \frac{DoD(t)}{Q} \quad (11)$$

To check we can see that the SoC at the end of step 4 must be 0%, and the SoC at the end of step 8 must be 100%. The figure 6 illustrates the relationship line between OCV and SoC corresponding to step 2 and step 6, in which the lowest line is the relationship between OCV and SoC corresponding to the loading process in step 6, the top line is the important line The relationship between OCV and SoC corresponds to the discharge process corresponding to step 2, the dashed line in the middle is an approximation of the relationship between OCV and SoC.

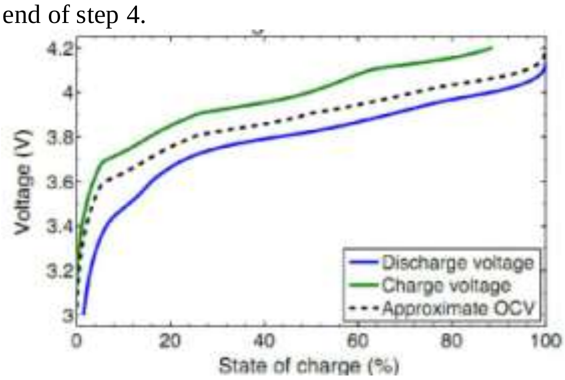

Figure 6. Relationship between OCV and SoC corresponding to the charging and discharging process in step 2

Also, the resistance R can be determined at the time SoC = 50% by assuming the voltage varies between the discharge curve and the charge curve at the 50% point of the SOC. We then assume that the resistance varies linearly from SoC = 0% to SoC = 50%, and linearly between SoC = 50% and SoC = 100%.

Combining OCV relations by temperature, we can establish the relationship between SoC and OCV by temperature as follows:

OCV (z (t),T (t)) = OCV0 (z (t)) + T(t)OCVrel (z (t)) (12)

Where: OCV0(z(t)) is the relationship between OCV and SoC at 00C, OCVrel (z(t)) is a linear correction factor for temperature, which is a function of z(t).

Once OCV0(z(t)) and OCVrel (z(t)) are determined, OCV(z(t), T(t)) can be calculated via the following matrix equation, respectively for each value. Value of SoC:

$$\begin{bmatrix} OCV(z,T_1) \\ OCV(z,T_2) \\ \vdots \\ OCV(z,T_n) \end{bmatrix} = \begin{bmatrix} 1 & T_1 \\ 1 & T_2 \\ \vdots & \vdots \\ 1 & T_n \end{bmatrix} \begin{bmatrix} OCV_0(z) \\ OCV_{rel}(z) \end{bmatrix} (13)$$

The following figure illustrates the relationship SoC and OCV determined for 6 different battery cells at 00C (left) and when the temperature changes (right).

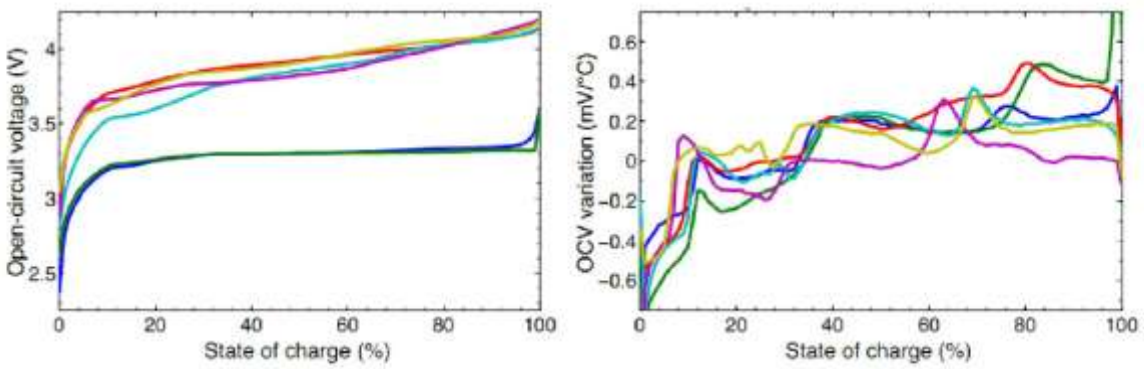

Figure 7. Relationship between OCV and SoC respectively when the temperature is 0^0C (left) and when the temperature changes (right)

Determine the remaining parameters of the ESC model

The remaining parameters of the ESC model that need to be determined are: Q, η, γ, M, M_0, R_0, R_jC_j, R_j. To determine these parameters we need to collect kinetic data of the lithium-ion battery through the experiments shown in Table 2. The data includes:

+ Measurement time point (s)
+ Current (A)
+ Battery terminal voltage (V)
+ Charging capacity (Ah)
+ Discharge capacity (Ah)
+ Charge energy (Ah)
+ Discharge energy (Ah)
+ Rate of change of voltage (dV/dt)
+ Temperature (T)

Table 2. The test data sheet determines the remaining parameters of the battery

Data_ Point	Step_ Time (s)	Current (A)	Voltage (V)	Charge_ Capaci ty (Ah)	Dischar ge_ Capacit y (Ah)	Charg e_ Energ y (Wh)	Discharge _Energy (Wh)	dV/dt (V/s)	Temperatur e (C)_1
1	59.95982098	0	3.58686161	0	0	0	0	3.25203E-05	4.998049736
2	119.9723324	0	3.586699009	0	0	0	0	-3.252E-05	0.452442735
3	179.9846793	0	3.58702445	0	0	0	0	0	-3.20088291
4	239.997046	0	3.58702445	0	0	0	0	0	-6.32111645
5	300.0095185	0	3.587187052	0	0	0	0	0	-8.29769516
6	360.0219397	0	3.587187052	0	0	0	0	0	-7.80291891
7	420.0343577	0	3.587349892	0	0	0	0	0	-8.05780697
8	480.0469467	0	3.587349892	0	0	0	0	0	-8.68115139
			3.58767533					6.50883E-	

9	540.0591973	0	3	0	0	0	0	05	- 9.27183342
10	600.0716245	0	3.58767533 3	0	0	0	0	3.25203E- 05	- 9.65630054
11	660.0840131	0	3.58767533 3	0	0	0	0	0	- 10.0359564
12	720.0965426	0	3.58767533 3	0	0	0	0	0	- 10.3931532
13	780.1089171	0	3.58751273 2	0	0	0	0	-3.252E- 05	- 10.7184267
14	840.1213139	0	3.58767533 3	0	0	0	0	0	- 11.0020475
...									

V. OBSERVING THE SOC USING AN EXTENDED KALMAN FILTER

From the ESC tissue equation of the determined Lithium Ion battery (7), we go to determine: $\hat{A}_k$, $\hat{B}_k$, $\hat{C}_k$, $\hat{D}_k$… First, we go to determine the components to calculate the matrix $\hat{A}_k$, $\hat{B}_k$. Assume that the measured current through the noisy battery is $i_k + \omega_k$ but only i_k is measured. For simplicity $\eta_k = 1$

The equation of the SoC is written as:

$$z_{k+1} = z_k - \frac{\Delta t}{Q}(i_k - \omega_k \quad (14)$$

$$\left.\frac{\partial z_{k+1}}{\partial z_k}\right|_{z_k = i_k^+} = 1, \left.\frac{\partial z_{k+1}}{\partial \omega_k}\right|_{\omega_k = \overline{\omega}} = -\frac{\Delta t}{Q} \quad (15)$$

The equation for the current through the resistance of the battery is:

$$i_{R,k+1} = \underbrace{\begin{bmatrix} T_1 & 0 & \cdots \\ 0 & T_2 & \\ \vdots & & \ddots \end{bmatrix}}_{A_{RC}} i_{R,k+1} + \underbrace{\begin{bmatrix} 1 - T_1 \\ 1 - T_2 \\ \vdots \end{bmatrix}}_{B_{RC}} \quad (16)$$

Where: $T_j = e^{-\frac{\Delta t}{R_j C_j}}$, So the partial derivative with respect to the current and the current noise is:

$$\left.\frac{\partial i_{R,k+1}}{\partial i_{R,k}}\right|_{i_{R,k} = i_k^+} = A_{RC}, \left.\frac{\partial i_{R,k+1}}{\partial \omega_k}\right|_{\omega_k = \overline{\omega}} = B_{RC} \quad (17)$$

The voltage delay equation is:

$$h_{k+1} = A_{H,k} h_k + (A_{H,k} - 1) sgn(i_k + \omega_k) \quad (18)$$

Where: $A_{H,k} = e^{-\left|\frac{(i_k + \omega_k)\gamma \Delta t}{Q}\right|}$, So the partial derivatives with respect to voltage delay and noise are:

$$\left.\frac{\partial h_{k+1}}{\partial h_k}\right|_{\substack{h_k = \hat{h}_k^+ \\ \omega_k = \overline{\omega}}} = e^{-\left|\frac{(i_k + \omega_k)\gamma \Delta t}{Q}\right|} = \overline{A}_{H,k} ,$$

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$$\left.\frac{\partial h_{k+1}}{\partial \omega_k}\right|_{\substack{h_k = \hat{h}_k^+ \\ \omega_k = \overline{\omega}}} = -\left|\frac{\gamma \Delta t}{Q}\right| \overline{A}_{H,k}(1 + sgn(i_k + \qquad + \overline{\omega}_k)\hat{h}_k^+ \qquad (19)$$

Next we go to determine the matrix $\hat{C}_k$, $\widehat{D}_k$, The equation for the output voltage of the battery is:

$$y(k) = OCV(z(k) + M_0 s(k) + Mh(k) - \sum_j R_j i_{R_j}(k) - R_0 i(k) \qquad (20)$$

We have the coefficients:

$$\frac{\partial y_k}{\partial s_k} = M_0, \ \frac{\partial y_k}{\partial h_k} = M, \ \frac{\partial y_k}{\partial i_{Rj,k}} = -R_j, \ \frac{\partial y_k}{\partial v_k} = 1,$$

$$\left.\frac{\partial y_k}{\partial z_k}\right|_{z_k = \hat{z}_k^-} = \left.\frac{\partial OCV\,(z_k)}{\partial z_k}\right|_{z_k = \hat{z}_k^-} \qquad (21)$$

Results of observing the data kinematics for the state 1, 2, 3

State 1:

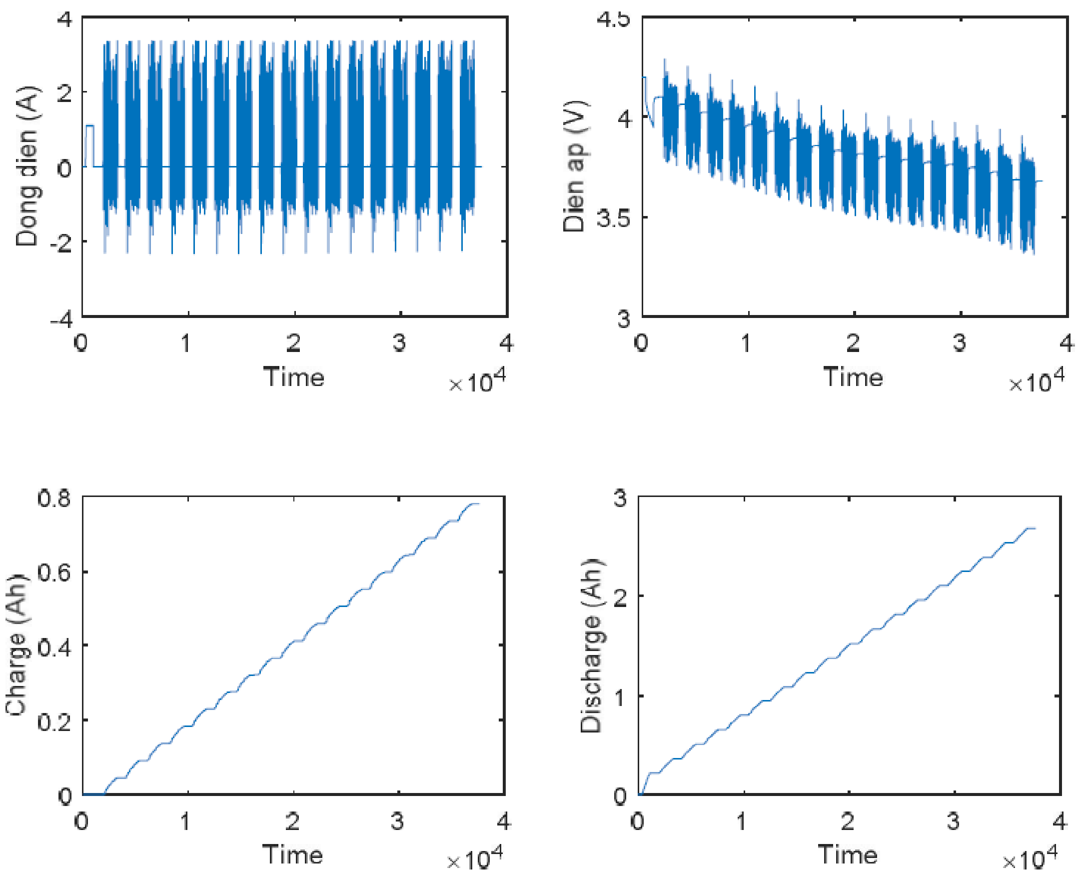

Figure 8. Kinetic data for stage 1

State 2

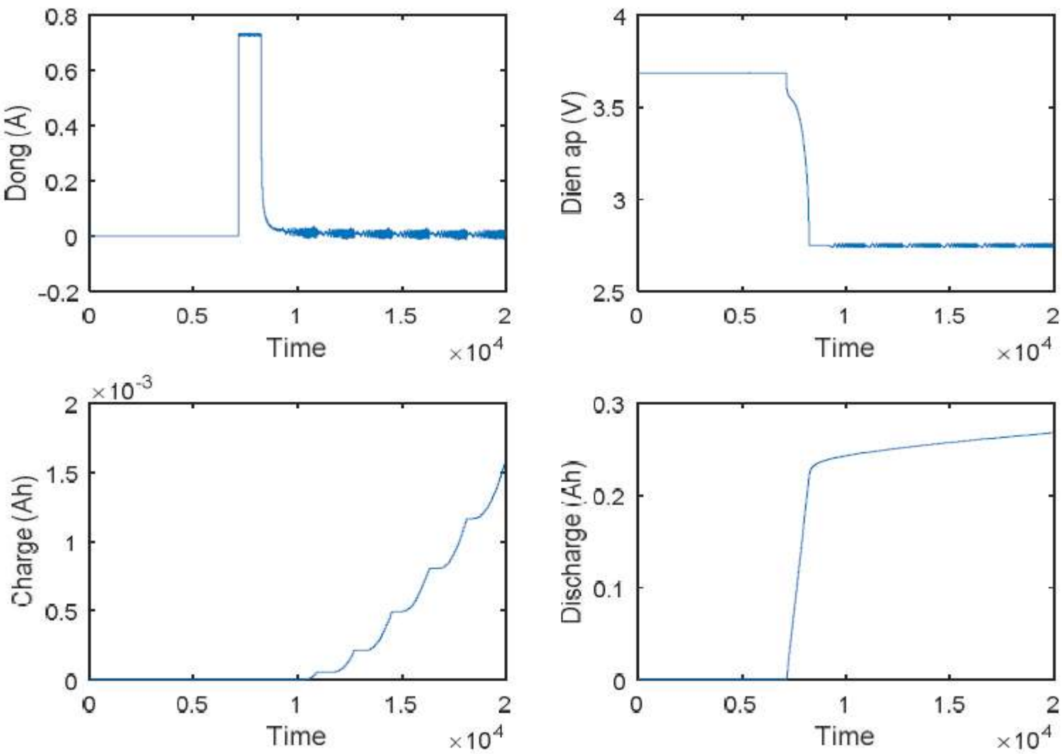

Figure 9. Kinetic data for stage 2

State 3:

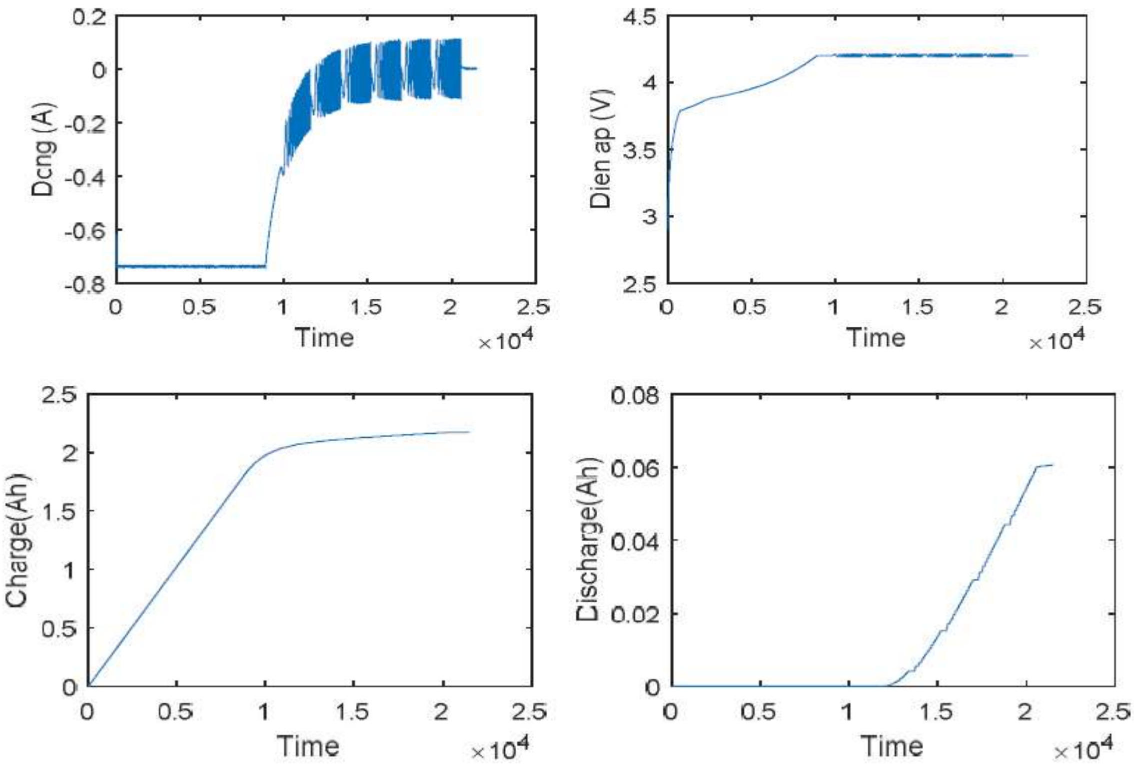

Figure 10. Kinetic data for the stage 3

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Covariance matrices are chosen:

$\hat{x}_0^+ = [0 \quad 0 \quad 0]^T$

$$\Sigma_{\tilde{x},0}^+ = \begin{bmatrix} 1e-3 & 0 & 0 \\ 0 & 1e-3 & 0 \\ 0 & 0 & 1e-3 \end{bmatrix}$$

$\Sigma_{\tilde{v},k} = 2e-1$

$\Sigma_{\tilde{\omega}} = 1$

The observed results for each stage are as follows:

State 1

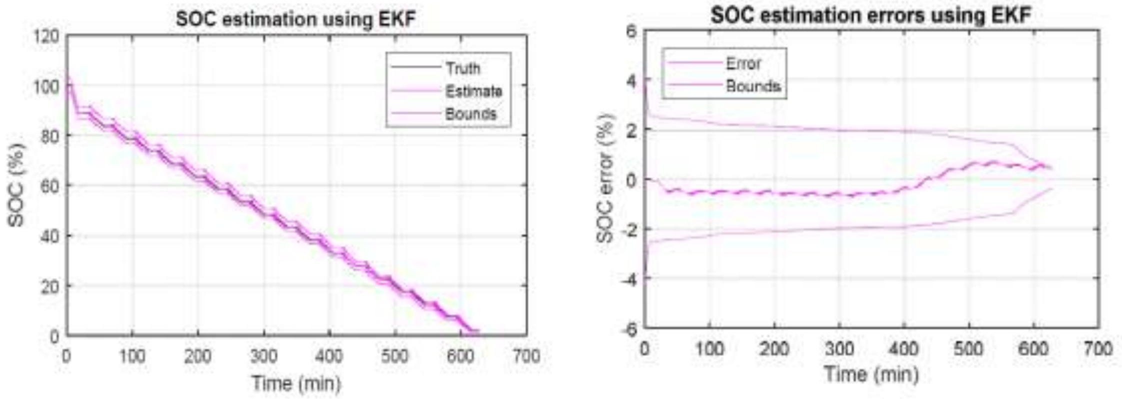

Figure11. SoC observation results and SoC observation deviation for state 1

State 2

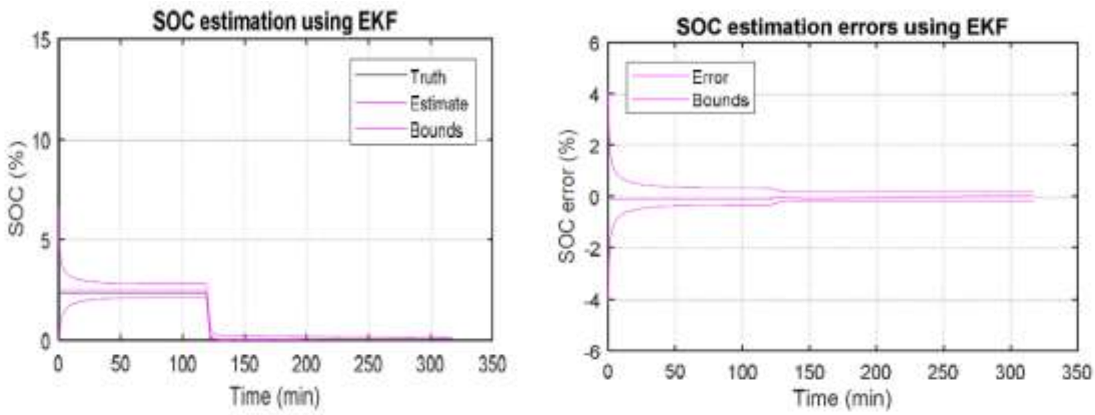

Figure 12. SoC observation results and SoC observation deviation for state 2

State 3

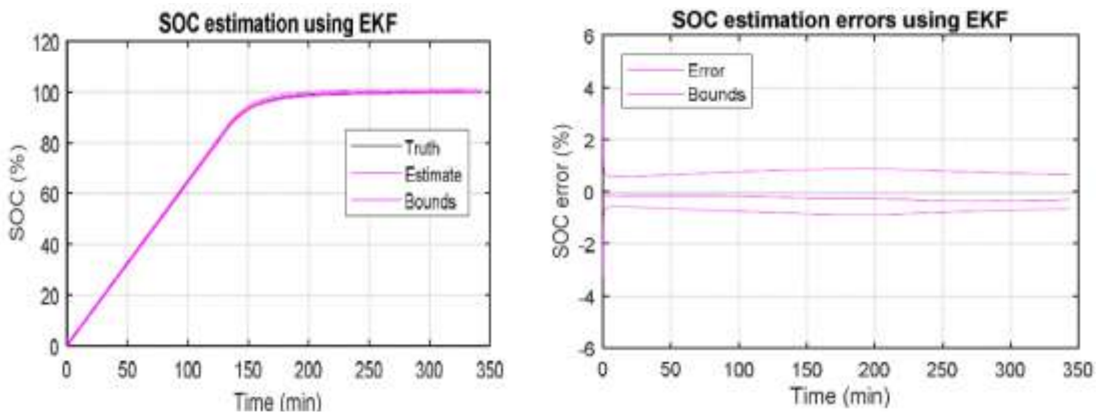

Figure 13. SoC observation results and SoC observation deviation for period 3

COMMENT:

For stage 1: The discharge is more than the charge (shown in Figure 8), the voltage is gradually reduced from 4.2V to 3.5V, the total charge to the battery is 0.8Ah, the total discharge is 2.8Ah. The SoC observation results as shown in Figure 11 show that the SoC decreased from 100% to 5%. The observed line by the ESC model is roughly coincident with the actual SoC curve determined by experimental data. Observation error as depicted in figure 11 has a value in the range of ±1%.

For stage 2: This is the phase of full charge then discharge at a rate of C/30 until the voltage is at min and remains at this level, that is, the SoC is very small as shown in Figure 9. The results of the SoC observation as shown in Figure 12 show that the SoC drops very quickly from 100% to 2.5% and in the period of maintaining the voltage for min, the SoC drops to 0%. The observed line by the ESC model is roughly coincident with the actual SoC curve determined by experimental data. The observed error as depicted in Figure 11 has a value in the range of ±0.1%.

For stage 3: This is a fully charged phase until the voltage is at max and stays at this level, meaning the SoC is very close to 100% as shown in Figure 10. The SoC observation results as shown in Figure 13 show that the SoC increases from 0 to 100%. The observed line by the ESC model is roughly coincident with the actual SoC curve determined by experimental data. Observation error as depicted in figure 11 has a value in the range of ±1%.

VI. CONCLUDE

The article has built an ESC model of a lithium-ion battery, determined the relationship between OCV and SoC open-circuit voltage, and determined the remaining parameters in the model including Q, η, γ, M, M_0, R_0, R_jC_j, R_j are based on experimental data of different discharge/charge processes showing reliable accuracy. From the built-up ESC model, the author used Kalman filter to observe the SoC for Lithium Ion batteries. Observation results show that the SoC of the battery has been determined quite accurately with the required guarantee error of less than 2%.

VII. ACKNOWLEDGEMENTS

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REFERENCES

[1]. Wang JP, Chen QS, Cao BG. Study on the charging and discharging model of Ni/MH battery module for electric vehicle. Journal of Xi'an Jiaotong University 2006,40(1),50-52

[2]. Ning, B.; Xu, J.; Cao, B.; Wang, B.; Xu, G. A sliding mode bbserver SOC estimation method based onparameter adaptive battery model.Energy Procedia 2016, vol. 88, pp. 619–626.

[3]. Zhong, Q.; Zhong, F.; Cheng, J.; Li, H.; Zhong, S. State of charge estimation of lithium-ion batteries using fractional order sliding mode observer.ISA Trans. 2017, vol. 66, pp. 448–459.

[4]. Kim, I.S. The novel state of charge estimation method for lithium battery using sliding mode observer.J. Power Sources 2006, vol.163, pp. 584–590.

[5]. Ma, Y.; Li, B.; Xie, Y.; Chen, H. Estimating the State of Charge of Lithium-ion Battery based on Sliding Mode Observer.IFAC Papers On Line 2016, vol.49, pp. 54–61.