Study on the State of Health Detection of Li-ion Power Batteries Based on Adaptive Unscented Kalman Filters

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ABSTRACT: It is essential to estimate the state of charge (SOC) and state of health (SOH) of the monomer battery in the electric vehicle li-ion power battery accurately for extending the li-ion power battery life. Based on the battery Thevenin equivalent circuit model, the paper uses adaptive unscented Kalman filter (AUKF) to estimate the inner ohmic resistance and the state of charge in real time, according to the function between the inner ohmic resistance and the state of health, the state of health can be estimated in real time. The battery charged and discharged experiments were done under two different conditions to verify the feasibility and accuracy of this method.

1. Introduction
With the development of new energy electric vehicle, li-ion power battery as the only energy storage part of the electric vehicle, the study of its performance and state of health attracts attention increasingly. Due to the factors such as the inconsistency of the monomer battery in the electric vehicle li-ion power battery pack, the service life of the power battery pack is much shorter than the rated service life of the monomer battery. Therefore, the real-time evaluation of the battery state of monomer battery in the li-ion power battery pack is of great significance to prolong the service life of the power pack and reduce the cost of electric vehicles.

Based on the battery second order Thevenin equivalent circuit model, the adaptive unscented Kalman filter (AUKF) algorithm is used to estimate the state of battery in real time.

2. The space model of battery state

2.1 The establishment of the space model of battery state
In this paper, the second order Thevenin equivalent circuit model[3] is used to establish the state space equation of the battery. The model is composed of voltage source, inner ohmic resistance and two RC parallel circuit in series, the circuit form is shown in Figure 1. $U_{oc}$ represents the battery open circuit voltage related to the SOC of battery, $R_0$ represents inner ohmic resistance of the battery; $RC$ parallel circuit describes the polarization characteristics of the battery, $R_1C_1$ circuit represents the process of electrochemical polarization[3], $R_2C_2$ circuit represents the process of concentration polarization[4]; $U_t$ is terminal voltage of the battery.
Fig.1 The Second order Thevenin equivalent circuit model of Li-ion battery

The electromotive force is numerically equal to the battery open-circuit voltage $U_{oc}$, which is related to the SOC of battery, the function relationship is $U_{oc} = f(t(SOC))$. The relationship curve of OCV-SOC can be obtained by the fast method.

The state equation and the output equation of the battery second order equivalent circuit model are shown as follows:

$$
\begin{align*}
\frac{d\text{SOC}(t)}{dt} &= \frac{i(t)}{C} \\
\frac{dU_{p1}(t)}{dt} &= \frac{U_{p1}(t) + i(t)}{R_i C_1} \\
\frac{dU_{p2}(t)}{dt} &= \frac{U_{p2}(t) + i(t)}{R_2 C_2} \\
U(t) &= U_{oc}(\text{SOC}(t)) - U_{p1}(t) - U_{p2}(t) - R_i i(t)
\end{align*}
$$

(1)

2.2 Parameter identification of battery model

1) Parameter identification of the inner ohmic resistance $R_0$[7]

In the voltage response curve, the instantaneous change in the battery terminal voltage at the beginning and the end of the current pulse is caused by the inner ohmic resistance. The inner ohmic resistance is calculated as follows:

$$
R_0 = \frac{\Delta V_1 + \Delta V_2}{2I}
$$

(3)

2) Parameter identification of polarization capacitance

After the pulse discharge, the terminal voltage response will first generate an instantaneous voltage rise, and then the voltage starts to rise slowly and tends to be stable, the terminal voltage is shown as follows.

$$
U(t) = U_{oc}(t_0) - U_{p1}(t_0) e^{\frac{t-t_0}{\tau_i}} - U_{p2}(t_0) e^{\frac{t-t_0}{\tau_f}}
$$

(4)

The time constant and the open circuit voltage of the two RC networks can be obtained by fitting the terminal voltage response by matlab least squares method after the end of the pulse. The time constant obtained is substituted into the formula (5) to obtain the $R$ value and $C$ value of the two RC networks respectively.

$$
U(t) = U_{oc} - IR_0 - IR_1 (1 - e^{\frac{t-t_0}{\tau_i}}) - IR_2 (1 - e^{\frac{t-t_0}{\tau_f}})
$$

(5)

Using the above parameter identification method, the lowest monomer battery 3-9 monomer as an example to be identified parameters as follows.
Table 1 Parameter identification of the second order Thevenin equivalent circuit model

| SOC/%  | R0/mΩ  | Uoc/V  | R1/mΩ  | R2/mΩ  | C1/kF  | C2/kF  | τ1/s  | τ2/s  |
|--------|--------|--------|--------|--------|--------|--------|-------|-------|
| 99.99  | -      | 3.348  | 0      | -      | -      | -      | -     | -     |
| 90.03  | 16.00  | 3.303  | 3.700  | 0.371  | 7.955  | 4      | 3.430 | 29.434 1.272 7 |
| 79.24  | 16.14  | 3.290  | 3.490  | 0.165  | 9.101  | 1      | 3.492 | 32.663 0.888 5 |
| 68.29  | 15.21  | 3.280  | 3.300  | 1.157  | 10.250 | 9      | 5.146 | 64.085 5.813 1 |
| 57.20  | 15.79  | 3.272  | 3.657  | 0.399  | 8.931  | 8      | 2.223 | 32.663 0.888 5 |
| 46.47  | 15.21  | 3.268  | 4.457  | 1.129  | 15.269 | 9      | 5.146 | 64.085 5.813 1 |
| 31.69  | 16.00  | 3.239  | 4.867  | 0.916  | 13.300 | 8      | 4.462 | 64.745 4.087 7 |
| 23.00  | 15.57  | 3.207  | 5.086  | 1.283  | 8.546  | 6      | 3.361 | 43.465 4.319 0 |
| 13.40  | 15.14  | 3.161  | 8.571  | 1.966  | 8.010  | 1      | 2.012 | 68.654 3.956 9 |
| 4.24   | 15.50  | 2.976  | 10.080 | 2.067  | 4.059  | 9      | 1.013 | 40.927 2.094 0 |
| 0.035  | 17.14  | 2.821  | 14.556 | 2.546  | 3.188  | 3      | 0.836 | 46.410 2.130 1 |

In order to reduce the estimation error, the Gregory L. Plett’s "composite model"\[8\] can be used to describe the relationship between the open circuit voltage $Uoc$ and SOC of the battery:

$$Uoc = f_{Uoc}(SOC) = K_0 - \frac{K_1}{SOC} - K_2 SOC + K_3 \ln(SOC) + K_4 \ln(1 - SOC) \quad (6)$$

3. Adaptive unscented Kalman filtering algorithm for estimating battery state

Adaptive unscented Kalman filter (AUKF) is used to combine the unrecognized Kalman filter estimating state with the extended Kalman filter estimating inner ohmic resistance of the battery and establish the cyclic iterative relationship. The model parameters known are used to estimate the battery state, and then the battery state is used as the known parameter to identify the model parameters, the recursive operation is carried out, which has a good adaptive feature.

3.1 AUKF estimate SOC and inner ohmic resistance of battery

The method of estimating the battery state using the adaptive unscented Kalman filter algorithm is as follows:

1) Initialize the state variables and their covariance:

$$
\begin{align*}
    k &= 0; \hat{x}_0^k = E(X_0^k); R_0^k = E(R_0^k) \\
    P_{x_0}^k &= E\left[ (X_0^k - \hat{x}_0^k)(X_0^k - \hat{x}_0^k)^T \right] \\
    P_{R_0}^k &= E\left[ (R_0 - \hat{R}_0^k)(R_0 - \hat{R}_0^k)^T \right] 
\end{align*}
$$

(7)

2) The UT transform is used to construct the Sigma point set associated with the state variables and the corresponding weight $\alpha$. The selection method\[9\] of Sigma point set is shown as follows.

$$
\begin{align*}
    X_{k-1,0} &= \hat{X}_{k-1} \\
    X_{k-1,i} &= \hat{X}_{k-1} + (\sqrt{(n+\lambda)P_{X,k-1}^k})_i, i = 1, ..., n \\
    X_{k-1,i} &= \hat{X}_{k-1} - (\sqrt{(n+\lambda)P_{X,k-1}^k})_i, i = n+1, ..., 2n 
\end{align*}
$$

(8)

3) Calculate state updates and covariance updates of battery...
The measurement of the state variable $R_0$ is updated as follows by using AUKF iterative algorithm

$$
\begin{aligned}
\hat{R}_{0,k} &= \hat{R}_{0,k-1} \\
P_{R_0,k}^- &= P_{R_0,k-1}^- + D_t \\
P_{R_0,k}^+ = P_{R_0,k}^- (C_{R_0}^*)\hat{P}_{R_0,k}^- (C_{R_0}^*)^T + D_t \\
K_{R_0,k} &= P_{R_0,k}^- (C_{R_0}^*) \left[ C_{R_0}^* P_{R_0,k}^- (C_{R_0}^*)^T + D_t \right]^{-1}
\end{aligned}
$$

5) The estimation of AUKF state variable and variance

$$
\begin{aligned}
\hat{x}_{k} &= \hat{x}_{k-1} + K_k (y_k - \hat{y}_k) \\
P_{x,k}^- &= P_{x,k-1}^- - K_k P_{y,y,k} K_k^T \\
\hat{R}_{0,k} &= \hat{R}_{0,k}^- + L_k (y_k - \hat{y}_k) \\
P_{R_0,k}^+ = (I - L_k C_{R_0}^*) P_{R_0,k}/k^{-1}
\end{aligned}
$$

Combining the state space model and the state space model with regarding the inner ohmic resistance as the state variable, the corresponding amount of computation in the state space expression is substituted into the AUKF algorithm. The cyclic iteration is used to estimate the SOC and the inner ohmic resistance of the battery in real time.

3.2 Inner resistance method to estimate the SOH of battery

The definition of SOH of monomer battery is evaluated by the inner ohmic resistance proposed in the literature.

$$
SOH = \frac{R_{EOL} - R_{now}}{R_{EOL} - R_N} \times 100\%
$$

$R_{EOL}$ is the inner ohmic resistance value when the actual capacity is 80% of the rated capacity at the end of the battery life, $R_N$ is the ohmic resistance value of the battery, and $R_{now}$ is the inner ohmic resistance value of the current state of the battery.

4. Experimental verification and analysis

4.1 Intermittent constant current discharge condition

The experiment was carried out at room temperature, 0.3 C current intermittent constant current discharge. Current conditions are shown in Fig.5. The parameters are substituted into matlab algorithm to obtain the terminal voltage and real-time estimates of inner ohmic resistance and the SOC of monomer battery.
The SOC of battery initial estimated value is set to 90%, Fig.3 shows that when the battery SOC initial value have a larger error, The SOC of battery can still quickly converge to the real value, and the estimated error is between ± 2%; Fig.5 shows that when the inner ohmic resistance is estimated using this algorithm, the estimated value of inner ohmic resistance can converge rapidly and become stable.

4.2 variable current conditions

Variable current conditions is shown in Fig.7, the test is conducted at room temperature.

The SOC evaluation error curves of the monomer battery

Fig.4 SOC evaluation error curves of the monomer battery

Fig.5 Inner resistance evaluation of the monomer battery

Fig.6 SOH evaluation curves of the monomer battery

Fig.8 SOC evaluation curves of the monomer battery

Fig.9 SOC evaluation error curves of the monomer battery
By comparing the estimation results of the battery state in two conditions above, the self-adaptive Kalman filter algorithm is almost immune to the battery condition and is not affected by the initial value of the state variables. It can track the real value and converge quickly with the small error. Because of the fast running algorithm, the on-line estimation of li-ion power battery state can be obtained in real time.

5. Conclusion
1) In this paper, the self-adaptive Kalman filter algorithm is used to identify the inner ohmic resistance of the time-varying battery system, and the SOH of the battery is estimated by using the function of inner resistance and the SOH of battery. The algorithm is fast, accurate and practical.
2) On the basis of the battery model, the on-line estimation of the polarization characteristics of the battery model in real time can be realized by establishing the state space model for different parameters.

References
[1] Meissner E, Richter G. The challenge to the automotive battery industry: the battery has to become an increasingly integrated component within the vehicle electric power system[J]. Journal of Power Sources, 2005, 144(2): 438-460.
[2] KONG SN, MOO CS, CHEN YP, et al. Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries[J]. Applied Energy, 2009, 86(9): 1506-1511.
[3] Remmlinger J, Buchholz M, Meiler M, et al. State-of-health monitoring of lithium-ion batteries in electric vehicles by on-board internal resistance estimation [J]. Journal of Power Sources, 2001, 196(12): 5357-5363.
[4] Marchildon J, Doumbia ML, Agbossou K. SOC and SOH characterisation of lead acid batteries[J]. Conference of the IEEE Industrial Electronics Society, 2015: 001442-001446.
[5] Aylor J H, Thieme A, Johnson B W. A battery state of charge indicator for electric wheelchairs[J]. IEEE Transactions on Industrial Electronics, 1992, 39(5): 398-409.
[6] Sharkh S A, Doerffel D. Rapid test and non-linear model characterization of solid-state lithium-ion batteries[J]. Journal of Power Sources, 2004, 130(1): 266-274.
[7] WEI Kexin, CHEN Qiaoyan. Electric vehicle battery SOC estimation based on multiple-model adaptive Kalman filter[J]. Proceedings of the CSEE, 2012, 32(31): 19-26.
[8] Gregory L. Plett. Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs Part 2. Modeling and identification [J]. Journal of Power Sources, 2004, 134: 262-276.
[9] HUANG Xiaoping, WANG Yan. Principle and Application of Kalman Filter: MATLAB Simulation[M]. 1rd ed. Beijing, China: Publishing House of Electronics Industry, 2015: 104-107.
[10] CHEN Qiaoyan. Study on states estimation and equalization management of electric vehicle battery[D]. Tianjin, China: Tianjin University, 2013: 72-75.