State-of-charge estimation of lithium-ion batteries based on multiple filters method

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Abstract

Energy crises and environmental issues have promoted research into development of various types of electric vehicles (EVs). Since the control strategy of EVs is essentially dependent on the state-of-charge (SOC) estimation of the batteries, one of the most critical issues of battery management system (BMS) is to accurately estimate the SOC in real-time. This paper proposes a multiple filters method for SOC estimation by combining extended Kalman filter (EKF) and particle filter (PF) method. Compared with EKF and PF method, this approach has higher SOC estimation accuracy. In the new method, each particle has its own filter, thus provides better tracking and prediction of SOC. Validation experiments are carried out based on IFP1865140-type batteries developed by Hefei Guoxuan High-Tech Power Energy CO. LTD. of China. Experiments under dynamic current condition are performed to verify the robustness of the proposed method. The experimental results have indicated that accurate and robust SOC estimation results can be obtained by the proposed method.

Keywords: Electric vehicles; Lithium-ion battery; State-of-charge estimation; Battery model; Multiple filters method.

1. Introduction

The traction battery system of electric vehicles (EVs) usually consists of hundreds or thousands of single cells, thus the battery management system (BMS) plays an important role to manage such numbers of cells. Since the control strategy is essentially dependent on the state-of-charge (SOC) estimation of the batteries, one of the most critical issues of BMS is to accurately estimate the SOC in real-time. Since the SOC is not directly measurable by any sensors, it needs to be inferred, commonly from open-circuit voltage method [1] or coulomb counting method [2]. These lead to big estimation errors, since the non-linear behavior of the battery voltage at operation is not regarded and the current offsets are accumulated. Compared with the voltage measurement method or current integral method, model based filter algorithms...
which can effectively avoid the problems from noise or accumulated errors are attracting more attentions.

Many model based methods have been proposed in literatures to obtain an accurate SOC estimation such as the extended Kalman filter (EKF) [3-6], unscented Kalman filter (UKF) [7] or particle filter (PF) [8-11, 13]. Plett [3-5] applied the EKF method for SOC estimation and believed that high-fidelity cell models are required to estimate accurate SOC. Wang [6] et al. proposed a multi-model switching method for SOC estimation based on EKF. It indicated that accurate SOC estimation results and reasonable estimation time can be obtained by the proposed method. Tian [7] et al. proposed a modified model based SOC estimation method by using UKF. The experimental results showed that the proposed method can reduce the computation cost and improve the SOC estimation accuracy simultaneously. He [8] et al. proposed a new working model that takes the drift current as a state variable to eliminate the effects of drift noise in SOC estimation. The unscented PF was employed in the SOC estimation. It indicated that accurate SOC estimation results can be obtained by this method. Zhong [9] et al. analyzed the relationship between the pack SOC and the in-pack cells under different equalization conditions and proposed a method for battery pack SOC estimation. Liu [10] et al. developed a temperature-compensated battery model and employed a dual particle filter for SOC estimation. A joint estimation method of SOC and state-of-energy (SOE) of LiFePO\textsubscript{4} batteries in EVs was proposed by Wang [11] et al. The experiment results under dynamic current and temperature have verified that accurate and robust SOC and SOE estimation results can be obtained by the proposed method. Currently the integrated methods include sliding mode observer, fuzzy logic based method, artificial neuronal networks (ANN) method and support vector machines (SVM) have been proposed and applied in SOC estimation [12]. In this paper, we propose a multiple filters method by combining EKF and PF method which provides high accuracy for SOC estimation. Compared with PF method, this approach has higher SOC estimation accuracy. In the new method, each particle has its own filter, thus provides better tracking and prediction of SOC.

This paper is organized as follows: In Section 2, the definition of SOC and the model of lithium-ion batteries are introduced. In Section 3, The EKF-PF based multiple filters method is introduced. In Section 4, validation experiments are carried out based on IFP1865140-type batteries developed by Hefei Guoxuan High-Tech Power Energy CO. LTD. Experiments under dynamic current condition are performed to verify the robustness of the proposed method. The experimental results have indicated that accurate and robust SOC estimation results can be obtained by the proposed method.

2. Model description

2.1. Definitions of SOC

The SOC reflects the residual capacity of a battery, and is defined as the ratio of the remaining capacity to the nominal capacity. The SOC can be expressed by Eq.(1):

$$SOC(t) = SOC(t_0) + \frac{\eta_C \int_{t_0}^{t} i(\tau) d\tau}{C_N}$$  \hspace{1cm} (1)

where $SOC(t)$ is the SOC value at time $t$, $SOC(t_0)$ is the SOC value at initial time $t_0$, $C_N$ represents the nominal capacity, $i(\tau)$ represents the current at time $\tau$, $\eta_C$ represents the coulombic efficiency ($\eta_C \approx 1$).

2.2. Battery model

The most commonly used battery models for SOC estimation are the equivalent circuit model and the electrochemical model. Based on the dynamic characteristics and working principles of the battery, the
equivalent circuit model is developed by using resistors, capacitors, and voltage sources to form a circuit network. The electrochemical model based on the electrochemical mechanism of the battery can accurately reflect the characteristics of the battery. With the SOC available as part of the model state based on the electrochemical model, the open-circuit voltage can be expressed by Eq.(2) according to the combined model in reference [4]:

\[
V_{OCV}(t) = V_1^0(t) + i(t)R = f(SOC(t))
\]

\[
= V_{OCV,0} - k_0SOC(t) - k_1 / SOC(t) + k_2 \ln(SOC(t)) + k_3 \ln(1 - SOC(t))
\]

where \(V_{OCV}(t)\) represents the open-circuit voltage at time \(t\), \(V_1^1(t)\) represents the terminal voltage at time \(t\), \(R\) represents the internal resistance, \(i(t)\) represents the current at time \(t\), \(V_{OCV,0}\) represents the initial open-circuit voltage and \(k_i (i = 0, 1, 2, 3)\) are model coefficients which can be obtained by the least-squares method.

3. EKF-PF estimation algorithm

The EKF method has been proposed and applied for SOC. However, there are some essential defects in the methods of EKF [8]. First, the method can be difficult to tune and often give unreliable estimation if the nonlinearity of the battery models are severe. Second, the system noise and observation noise must satisfy the Gaussian distribution, and the system parameters must be accurate. Otherwise, the filter performance will decrease or even diverge. In contrast to the EKF, the PF is a completely nonlinear state estimator based on the probability and can be a good candidate for SOC estimation [11]. Because the PF uses a statistical approach, the method can yield better performance and works particularly well for nonlinear and robust problems that are difficult for EKF. In this paper, we propose a multiple filters method for SOC estimation by combining EKF and PF. In the new approach, each particle has its own filter based on EKF before the PF works. The diagram of filter of each particle is shown in Fig.1.

Fig.1 Diagram of filter of each particle based on EKF

4. Experiments and result analysis

4.1. Battery test bench

In order to acquire experimental data such as current, voltage and accumulated ampere-hour (Ah), a battery test bench which composes of a host computer, a battery test system NEWARE BTS-4000 and a programmable temperature chamber has been established for the validation experiment. The configuration of the battery test bench is shown in Fig. 2. The host computer is used for on-line experiment control and
data recording. The NEWARE BTS-4000 is used to load the battery with dynamic current and the programmable temperature chamber is used to provide manageable temperatures for the batteries. The temperature is set as constant 25 °C.

![Battery test bench](image)

**Fig.2. Battery test bench**

4.2. Parameter identification and validation

The parameters of the battery model were determined by the recursive least-squares method from the experimental data of an IFP1865140-type battery developed by Hefei Guoxuan High-Tech Power Energy CO. LTD. of China. The resulting values of the parameters are listed in Table 1. Fig.3 (a) shows the testing current condition. The tested battery is both charged and discharged. The estimated values from the battery model and the measured values are compared in Fig.3 (b). As shown in the figure, the general shape of the model output and that of the measured value are almost the same.

![Battery testing](image)

**Fig.3. (a) Testing current condition. (b) Comparison of terminal voltage of combined model and measured voltage.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OCV,0}$</td>
<td>3.6196V</td>
<td>$R$</td>
<td>0.0157Ω</td>
</tr>
<tr>
<td>$k_0$</td>
<td>0.3102V</td>
<td>$k_1$</td>
<td>$-7.6576 \times 10^{-4}$V</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.2302V</td>
<td>$k_3$</td>
<td>-0.0151V</td>
</tr>
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4.3. Experiments

In order to verify the applicability of the proposed method, validation experiments under dynamic current condition are carried out based on IFP1865140-type batteries developed by Hefei Guoxuan High-Tech Power Energy CO. LTD.

The current profile of the dynamic condition is shown in Fig.4. Fig.5 (a) shows the comparison of SOC estimate results based on different estimation algorithms. Fig.5 (b) shows the comparison of SOC estimate error based on different estimation algorithms. The numerical results of root-mean square error (RMSE) and maximum absolute error (MAE) of SOC based on different estimation algorithms are calculated and listed in Table 2. As can be seen from the results, the EKF-PF method has shown better accuracy and robustness than EKF and PF method.

![Fig.4. Dynamic current condition.](image)

![Fig.5. (a) Comparison of SOC estimate results based on different estimation algorithms. (b) Comparison of SOC estimate error based on different estimation algorithms.](image)

Table 2. Comparison of RMSE and MAE of different estimation algorithms

<table>
<thead>
<tr>
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<th>EKF</th>
<th>PF</th>
<th>EKF-PF</th>
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<tr>
<td>RMSE$^a$</td>
<td>0.849%</td>
<td>0.432%</td>
<td>0.363%</td>
</tr>
<tr>
<td>MAE$^b$</td>
<td>1.336%</td>
<td>0.414%</td>
<td>0.390%</td>
</tr>
</tbody>
</table>

$^a$ root-mean square error, $^b$ maximum absolute error.

5. Conclusions

The SOC of traction batteries is a critical index in BMS. In this paper, we propose a multiple filters method for SOC estimation by combining EKF and PF. In the new approach, each particle has its own filter based on EKF before the PF works. Compared with EKF and PF method, this approach provides better tracking and prediction of SOC. Validation experiments under dynamic current condition are
carried out to verify the applicability of the proposed method. The results have indicated that accurate and robust SOC estimated results can be obtained by the proposed method.

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References


Zonghai Chen received his BS and MS degrees from University of Science and Technology of China (USTC) in 1988 and 1991 respectively. He has served on the faculty of USTC from 1991. Since 1998, he has been a professor of USTC. He was assigned assistant to the president of USTC from 2000 to 2003, in charge of the technology industry. He is an expert that enjoys the special government allowances of the State Council of People's Republic of China. He has more than 300 refereed publications. His research is focused on the modeling, simulation and control of complex systems, information acquisition and control, robotics and intelligent systems. He has 12 provincial and ministerial progress prizes in scientific and collective technology.