International Journal of Hybrid Information Technology
Vol.8, No.7 (2015), pp.199-206
http://dx.doi.org/10.14257/ijhit.2015.8.7.18

Study on SOC Estimation of Power Battery Based on Kalman Filter Optimization Algorithm

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Abstract

Power battery's remaining capacity is affected by many interior and exterior uncertainties during use. To achieve estimate of current remaining measurable battery power by using battery measurable parameter data, which has always been the core issue of electric vehicle battery management system and the technical difficulties need to be resolved. In this paper, Kalman filtering theory is introduced in estimation algorithm, and then combined with open circuit voltage method and ampere measurement method, the SOC estimation according with the requirements of the electric car is achieved.

Keywords*: electric car; power battery; SOC estimation; Kalman filtering algorithm*

1. Introduction

With the oil energy shortages and the increasing air pollution, energy saving electric car has become a major trend in today's automotive industry development. Power battery as a power source and an energy carrier of electric car, in order to ensure that the battery can work safely and efficiently, specific battery management system for controlling and managing the states of the power battery pack should be configured. As the battery remaining capacity is affected by many interior and exterior uncertainties, battery remaining capacity estimation has been the core of battery management system, it is a reflection of the battery status of the main parameters and technical difficulties need to be resolved. Currently, the SOC (State of Charge) is widely used to indicate the battery's remaining charge at home and abroad.

In the electric vehicle, the battery pack shows a high degree of nonlinearity. SOC is influenced by discharge rate, battery temperature, discharge rates, cycle times, and many factors, which has brought great difficulties for giving an accurate estimate of SOC. Currently, Many different methods and techniques about power battery SOC estimation have been proposed and successful applications have been made in some fields, such as discharge test, open circuit voltage, ampere measurement method, the resistance measurement, load voltage, neural networks and Kalman filtering method.

From a practical point of view, the SOC estimation methods cannot reach attaining precise estimates of battery pack SOC for electric vehicle online in real time. Comparing advantages and disadvantages of various methods used to estimate SOC, analyzing vehicle power battery operating conditions, and considering carefully the influence of charge-discharge rate, temperature and other influence factors affecting on SOC, this paper presents a kind of extended Kalman filtering algorithm as the main method, and the counting method and the open circuit voltage method as helper methods.

ISSN: 1738-9968 IJHIT

2. Extended Kalman Filtering Algorithm

2.1 Kalman Filter Algorithm

Kalman filtering algorithm based on time-domain state space theory was proposed by Kalman in 1960. And another recursive Kalman filter algorithm facilitating the realization on computer was further developed, which is widely used in precision-guided, data communications, global positioning, target tracking and other fields.

By analyzing of the long-term experimental data, it shows that Kalman filtering algorithm can provide an effective solution for the estimation of the battery SOC states of electric vehicle. As common methods of dynamic system state estimation, Kalman filter can estimate the value of the previous state of the moment combined with the input value of the current system, using an iterative cycle approach to achieve the minimum variance estimation. Kalman filter introduces a concept of state variables and use it instead of all the inputs used in the system, make the current system of calculating the output of the process is simplified, only current input variables and state variables can be achieved.

Kalman filter algorithm is mainly applied in linear dynamic systems, which has better estimation effect for the system state variables. State space model is as follows:

State equation:

$$x_{k+1} = A_k x_k + B_k u_k + w_k \tag{1}$$

Output equation:

$$y_k = C_k x_k + D_k u_k + v_k \tag{2}$$

Where x_k is the system state variable; u_k is input; y_k is output; w_k represents the process noise variable; v_k represents the process noise variables; A_k , B_k , C_k , D_k denote the coefficients of the dynamics equation. Here, we assume that the process noise w_k and the measurement noise v_k are assumed white Caussian distributed with zero mean. The expression of the state space model is shows in Fig.1.

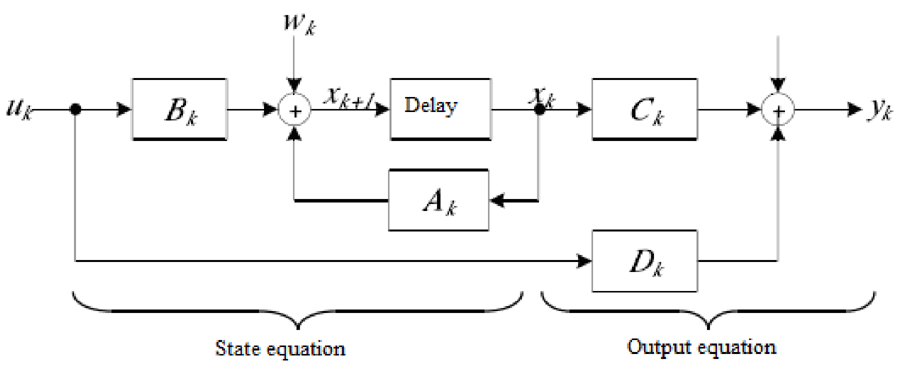

Figure 1. Linear Discrete-time State Space Model

Standard Kalman filter is needed to make two different estimates for the state variable x_k and mean squared error P_k in each sampling interval. Now, take the state x_k as an example, the first estimate x_k^- is achieved by using state equation backward recursive on the basis of the previous state estimate value x_{k-1}^+ . Before the end of measuring for the observation data Y_k , the forward prediction estimation is given, with "-" as a superscript. Then the second-best estimate x_k^+ can only be calculated until after the observation data from the measurement, with "+" as a superscript. After obtaining the value of the Y_k , the final estimate x_k^+ , P_k^+ of the system is given by correcting the estimation of the forecast results x_k^- and P_k^- .

2.2 Extended Kalman Filter Algorithm

For linear dynamic systems, the Kalman filter is the best method for state estimation. But the electric vehicle battery pack itself is a nonlinear dynamic system, the battery state of charge and the charge-discharge rate, battery voltage and ambient temperature change is a nonlinear relationship, so it should use the extended Kalman filter method to achieve the battery pack SOC online estimates.

Compared with Kalman filtering, EKF is linearized model based on the battery nonlinear state space model. Then Using Kalman filter algorithm to estimate the state of variables. State space model is as follows:

State equation:

$$x_{k+1} = f(x_k, u_k) + w_k \tag{3}$$

Output equation:

$$y_k = g(x_k, u_k) + v_k \tag{4}$$

Where: $f(x_k, u_k)$ is nonlinear transfer function, $g(x_k, u_k)$ is nonlinear measurement function. Fig.2 shows block diagram of the nonlinear discrete-time state space models.

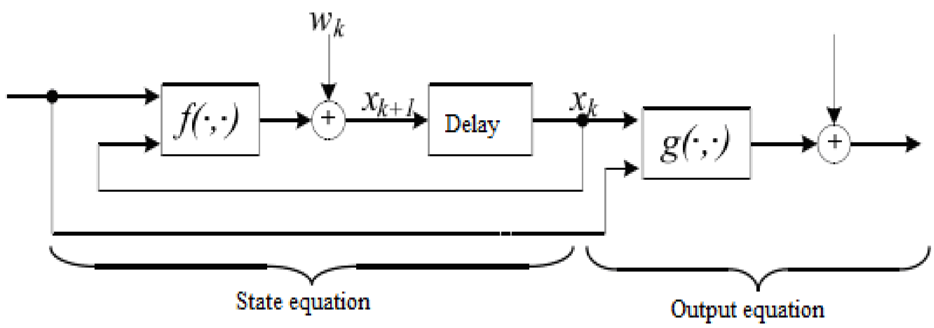

Figure 2. Block Diagram of the Nonlinear Discrete-Time State Space Models

In addition to selecting a different state space model, the extended Kalman filter and the standard Kalman filter have its similarity in nature, both of which are composed by the initialization, forecasting estimate, optimal estimation. Extended Kalman filter using a nonlinear model to achieve the estimate of state variables, using $f(x_{k-1}^+, u_{k-1})$ replaces the standard Kalman filter estimate of $A_{k-1}x_{K-1}^+ + B_{k-1}u_{k-1}$ in the forecast, and in the best estimate is used $g(x_k^-, u_k)$ instead of $C_k x_k + D_k u_k$.

3. Realization Of Kalman Filtering Algorithm

According to the special requirements of electric cars on the SOC estimation algorithm, this paper presents a Kalman filter optimization algorithm, which combined organically the extended Kalman filter algorithm and time measurement method with open circuit voltage method. Depending on the different states of the battery, to select a appropriate method of SOC estimation.

On the basis of the conventional current accumulation method, time measurement method can improved the SOC estimation accuracy by using charge-discharge rate SOC model and temperature SOC model to quantify the external factors. Time measurement method can be showed as:

$$SOC_{k+1} = SOC_k - \frac{1}{Q_n}\int_k^{k+1} \frac{\eta_i}{\eta_T} i dt \tag{5}$$

Where SOC_k represents battery remaining power at time k, i is positive when the battery discharges, On the contrary i is negative, η_i denotes charge-discharge rate coefficient, and temperature coefficient η_r can be obtained by calculation.

Open circuit voltage method refers to access the battery open circuit voltage value, by using of OCV in open circuit voltage SOC models and linear relationship of SOC to complete SOC estimation, its main role is to give time measurement method and extended Kalman filter method to provides a relatively accurate initial value of SOC.

Extended Kalman filter has a strong correction capability, which can improve estimation results using open circuit voltage and time measurement method. And it solved initial values inaccurate problem of the open circuit voltage and current cumulative error problem of time measurement method of SOC.

Extended Kalman filter specific algorithm as follows:

(1)Model selection

$$x_{k+1} = x_k - (\frac{\eta_i \Delta t}{\eta_T Q_n}) i_k \tag{6}$$

$$y_k = K_0 - Ri_k - K_1 / x_k - K_2 x_k + K_3 \ln(x_k) + K_4 \ln(1 - x_k) \tag{7}$$

(2)System parameters

By calculation, you can determine the system parameters A_{k-1}, C_k

$$A_{k-1} = \left.\frac{\partial f(x_{k-1}, u_{k-1})}{\partial x_{k-1}}\right|_{x_{k-1}=x_{k-1}^+} = 1 \tag{8}$$

$$C_k = \left.\frac{\partial y_k}{\partial x_k}\right|_{x_k = x_k^-} = K_1 / (x_k^-)^2 - K_2 + K_3 / x_k^- - K_4 / (1 - x_k^-) \tag{9}$$

(3)Algorithm class

$$x_0^+ = SOC_0, P_0^+ = \text{var}(x_0) \tag{10}$$

(4)Extended Kalman filter recursive calculations

$$\begin{cases} x_k^- = x_{k-1}^+ - (\dfrac{\eta_i \Delta t}{\eta_T Q_n}) i_{k-1} \\ y_k = K_0 - Ri_k - K_1 / x_k^- - K_2 x_k^- + K_3 \ln(x_k^-) + K_4 \ln(1 - x_k^-) \\ P_k^- = A_{k-1} P_{K-1}^+ A_{k-1}^T + D_w \\ L_k = \dfrac{P_k^- C_k^T}{C_k P_k^- C_k^T + D_v} \\ x_k^+ = x_k^- + L_k (Y_k - y_k) \\ P_k^+ = (1 - L_k C_k) P_k^- \\ k = 1, 2, 3 \ldots \end{cases} \quad (11)$$

State initial values SOC0 can be calculated based on the previous battery remaining capacity and current open circuit voltage values, during initial value P_0^+ of mean square estimation error, process noise error of D_w, observation noise error D_v is closely related to the battery type performance, data acquisition systems, whereas the data sample period is generally decided by the charge and discharge rate and battery operation condition.

Kalman filter algorithm has certain advantages over the other, because of combining open circuit voltage and time measurement method with extended Kalman filtering method. Firstly, using open circuit voltage for the battery pack to provide a relatively accurate SOC initial value, and then the cycle of alternating the use of time measurement method and extended Kalman filter, using the extended Kalman filter for the open circuit voltage and time measurement method estimates value correction, it will ensure the battery SOC line estimation accuracy and feasibility, but also greatly reduces the overall cost of the battery management system, so that the final estimate of SOC becomes more effective and reliable.

4. SOC Algorithm Test

This paper takes Urban Dynamometer Driving Schedule (UDDS) as simulation background, and regards lithium iron phosphate battery pack with fully charged as test objects.

SOC initial values are calculated by using open-circuit voltage method before starting of the experiment of discharge battery, and minimum value is compared to previous SOC value which stored in E2PROM ,averaging the minimum value and previous SOC as SOC0 of the entire battery pack. The battery open circuit voltage measured as：SOC of E2PROM values is 68.8%. Then the battery open circuit voltage of SOC0 is equal to 65.2%. The entire discharge duration 4980s, it is divided into 5 cycles, the experimental end of battery pack SOC is 0. Maximum output power of Battery pack is 192.9W, maximum estimation error of SOC is 7.8%, and average estimated error rate is 3.11%. Battery test result under UDDS cycle test conditions are shown below. Among them, the fig.3 denotes 1th battery voltage curve under UDDS and Fig. 4 represents battery SOC change curve under UDDS.

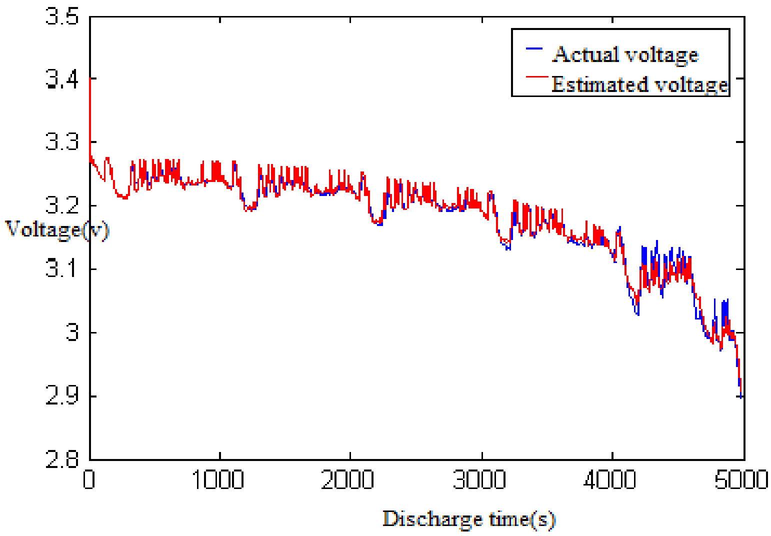

Figure 3. 1th Battery Voltage Curve under UDDS

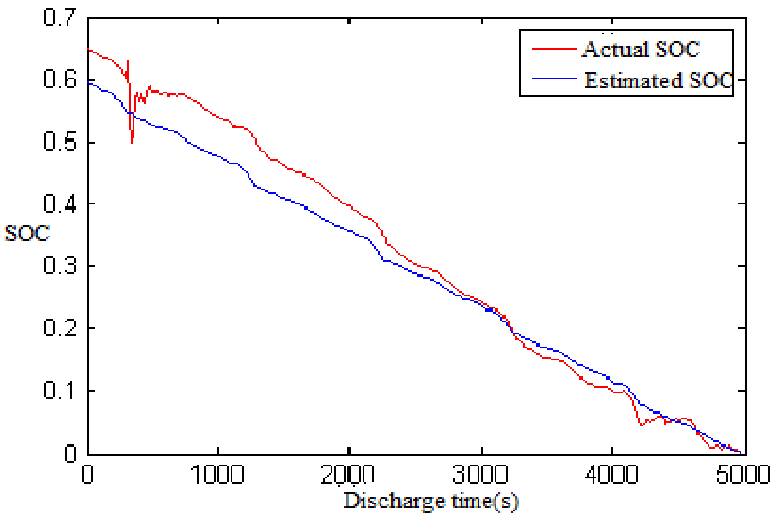

Figure 4. Battery SOC Change Curve under UDDS

From battery pack SOC change curve, we can see:

1) In advance of the discharge, the battery pack can get a more accurate charge remaining of initial values by using OCV method and SOC stored in E2PROM value.
2) Within 200 seconds before their discharge, the battery pack removes the hysteresis effect on battery model to estimate performance by using an econometric method successfully, which provided a good foundation for the effective implementation of extended Kalman filter algorithm.
3) The Kalman filter has more and more correction capability of SOC estimation values in the beginning of the extended Kalman filter algorithm. The SOC errors between the estimated value and the true value are getting smaller with the development of discharge.
4) Kalman filtering algorithm alternate between the time measurement method and extend Kalman filter method, which not only ensures the accuracy of final estimate SOC, but also reduces the overall cost of battery pack SOC on-line estimates system.

In UDDS car cycle test conditions, the above experimental test battery results clearly reflect the accuracy of extended Kalman filter dynamic model, charging and discharging

SOC model, temperature model and the open circuit voltage SOC model. On the basis of data collection using MATLAB software, comparing the SOC estimation of Kalman filter algorithm with real value and battery SOC values, the maximum error and the average error of SOC are achieved during simulation conditions. In the experiment, SOC estimation error lowers than the State for vehicle design requirements of battery charge remaining the largest estimated error 10%.

5. Concluding Remarks

The discharge of battery is a very complex process of electrochemical reaction in the electric vehicle. Discharge rate, temperature, battery internal resistance, self-discharge rate and the other factors also affect the battery SOC estimate value, but these factors will change as the recycling times increased, in turn, increasing the difficulty of the battery model and SOC estimation. Judging from the experimental data, the proposed method can estimate for the SOC, which fully meets the requirements of algorithms of SOC for electric vehicles.

Acknowledgements

Class of 2014-Heilongjiang provincial science and technology and talents project (12541148).

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