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Research on SOC Estimation Based on Second-order RC Model

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Abstract

The estimation accuracy of batteries' State of Charge (SOC) plays an important role in the development of hybrid electric vehicle (HEV). Accurate estimation of SOC can prevent battery from overly charging and discharging, so the lifetime of batteries will be increased. Although Kalman filter algorithm has better estimation accuracy for HEV application in which the current changes fast, Kalman filter algorithm deeply relies on the battery model. In other words, the accuracy of batteries' SOC estimation needs precise batteries models. Besides, when the HEV is running, the statistical characteristics of noise produced in the course of the battery management system collecting data are unknown. This can cause estimated performance of Kalman filter algorithm to decrease even diffuse. To solve the problem, adaptive Kalman filter algorithm is adopted to estimate battery SOC based on the second order RC battery model in this paper. Through MATLAB simulation analysis, the estimation accuracy of battery SOC is improved to some extent.

Keywords *: SOC estimation; second -order RC model; adaptive Kalman filter*

1. Introduction

Along with the problems of environment and energy are more and more serious. Because of a lot of advantages in energy saving and environmental protection, the Hybrid Electric Vehicle (HEV) achieves great development in recent years. As energy storage power source of driving the HEV, batteries are the key to the development HEV. What's more, Battery requires high specific energy, high specific power and high hyperactivity discharge efficiency. The battery SOC indicates how many energy storage in the cell, which is one of the important parameters of showing battery status. The battery SOC needs to maintain within appropriate scope. The accurate estimated value of battery SOC is the guarantee to safe use and optimized control of charging and discharging characteristics.

2. Traditional SOC Estimation Methods

In the traditional SOC estimation methods, the most common method is Ah counting [1], which estimates the SOC by accumulating the electric quantity of battery charging or discharge. Ah counting is not only easy to realize but also not limited by battery itself. But there is a weakness: actually, Ah counting is a kind of prediction of open loop. Because of imprecise current measurements, it will cause SOC estimation error. In fact, Ah counting is usually improved for getting good precision [2]. According to the relatively fixed function relation between OCV and SOC to estimate SOC [3], [4], the open circuit voltage (OCV) method is implemented easily and has high accuracy. But it needs battery to stand for long time in order to achieve the voltage stability. This causes difficult to measure, besides how to determine the standing time also is a problem. Recently, domestic and foreign experts and scholars put forward neural network and Kalman filtering method. Neural network method can be applied to all kinds of batteries. It can rely on training a large number of sample data to get very good accuracy based on the premise network model [5]. But the neural network method needs a large number of reference data for training, and estimate error is greatly affected by training data and training way.

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The core idea of Kalman filter is to make Optimal Estimation of minimum variance sense for power system's state. So it is applied to both linear system and nonlinear system [6], [7]. Kalman filtering algorithm, which has very strong correction function to the initial value error and has strong inhibition to noise also, can keep very good accuracy in counting process . Therefore, it is particularly suitable for the HEV which current changes fast. In the papers that using Kalman filter algorithm to estimate SOC, either matter equivalent circuit or mathematical experience formula are use to describe the batteries' model , two utilization ways are adopted : one way is that the capacitor's voltages in model are used for a state of system. After the voltages are estimated by Kalman filter, SOC will be estimated by using the relationship between SOC and electromotive force (or OCV)[8] which is solved through mathematical relation in battery model. Another way is that Ah counting formula is taken as one of state equations in system, then SOC is directly estimated by Kalman filter[9][10][11]. But the main problems of using Kalman filter algorithm to estimate battery SOC are as follows. It deeply depends on the battery model, so only establishing accurate battery model can get accurate SOC value. What's more, the statistical characteristics of noise produced in the course of the battery management system collecting data are unknown in the period of HEV running. This can cause estimated performance of Kalman filter algorithm to descend even diffuse. So, adaptive Kalman filtering algorithm is adopted to decrease the influence from measurement noise which causes estimated result error.

3. Estabishment of Batteries Model and Parameter Identification

When the battery is charging and discharging, it will show some characteristics of capacitance and resistance at external characteristics. According to these characteristics, circuit model is used for simulating the dynamic characteristics of battery [12]. The equivalent circuit model is such kind of battery model. The purpose of the researching battery model is to make clear the quantitative relationship between the battery external electrical characteristics and internal state. After mathematical model was established, the internal states such us SOC, SOH, internal resistance, electrodynamic force and so on, could be calculated based on mathematical model analytic expression, the battery voltage, current, temperature and external variables. When equivalent circuit model was taken, the following factors need be considered. On the one hand because battery management system need estimate SOC, then the variable SOC should be taken into account. In order to improve the accuracy of model, model should well reflect the dynamic performance of the battery. On the other hand, finally the battery model is transformed into codes to inset into the battery management system. So in order to reduce the calculation amount of calculation processor, the model structure should not be too complex and should be easy to engineering realization.

The typical Thevenin model can well reflect the battery dynamic and static characteristic. This model could relatively accurately simulate the battery charging and discharging behavior under the circumstance of considering temperature, current and difference between charging and discharging status. It has been widely used in power battery modeling because its structure is simple [13-15]. Although Thevenin model could already well reflect the battery dynamic and static characteristic, it is just a structure of the simple one order system, while the battery itself is a very complicated nonlinear system. For the purpose of getting more accurate simulation of battery characteristics, the order number of battery model must be improved.

In order to satisfy the precision requirement of the battery model and get a relatively simple battery model, simplified Massimv Cetanln model is chosen: one resistor and two RC networks, meanwhile removing the parasitic branch. It is also called a second-order RC model and shown in Figure 2. In the figure, E indicates electrodynamic force, which has a fixed function relationship with battery SOC. R3 stands for ohm resistance. R2, C2 are used to simulate short time constant shown in dynamic characteristics of the battery, which is the process of discharging voltage rising fast. R1, C1 are used to simulate long time constant shown in dynamic characteristics of the battery, which is the process of discharging voltage slow stability. The sum of R1, R2 is considered as the battery polarization resistance.

According to the second order RC circuit model in Figure 2, mathematical relationship is got as follow:

$$V = E - IR_3 - IR_2(1-e^{-t/\tau_2}) - IR_1(1-e^{-t/\tau_1}) \quad (1)$$

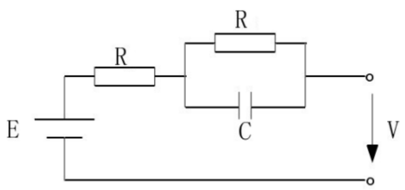

Figure 1. Thevenin model

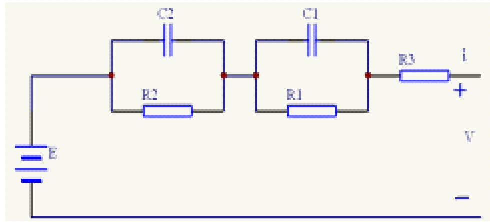

Figure 2. Second order RC battery model

In the formula, τ_2 indicates short time constant ($\tau_2 = R_2C_2$) and τ_1 indicates long time constant ($\tau_1 = R_1C_1$). The adopted expressions of index fitting function as follow:

$$V = A_0 + A_1e^{-\lambda_1 t} + A_2e^{-\lambda_2 t} \quad (2)$$

Comparing with the formula (1), the following equations can be acquired:

$$R_2 = A_2 / I \quad (3)$$

$$R_1 = A_1 / I \quad (4)$$

$$C_2 = 1/(\lambda_2 R_2) \quad (5)$$

$$C_1 = 1/(\lambda_1 R_1) \quad (6)$$

R3 respects ohm internal resistance and could be calculated by the following method. Pulse discharging is used to discharge the battery. At the end of discharging, the battery voltage will emerge a momentary rise. While at the end of charging, the battery voltage will emerge a momentary drop. Both all reflect the characteristics of the battery internal resistance. Taking use of this battery character, the value of ohm resistance R3 could be calculated by using the value of instantaneous change voltage to divide the value of current.

4. SOC Algorithm Research

Mathematical relation could be obtained based on this model.

$$\dot{U}_1(k) = (-\frac{1}{R_1C_1})U_1(k) + \frac{1}{C_1}i(k) \quad (7)$$

$$\dot{U}_2(k) = (-\frac{1}{R_2C_2})U_2(k) + \frac{1}{C_2}i(k) \quad (8)$$

$$V(k) = E(SOC,k) - U_1(k) - U_2(k) - R_3i(k) + v(k) \quad (9)$$

Among them, the E(SOC,k) indicates that there is one-to-one relationship between electromotive force (EMF) E and SOC. U1 and U2 respectively indicate the voltage estimated value of R1 and R2 at sampling instant k. V(k) and i(k) respectively indicate the working voltage and the working current at sampling instant k. v(k) indicates the measurement noise of terminal voltage.

Make model state variables X(k)=[U1(k) U2(k) SOC(k)]T, input of the system U(k)=I(k). Supposing that U(k) is constant at each sampling time, adaptive Kalman filter algorithm is used to measure battery SOC. The discretization equivalent equations are as follows:

$$X(k+1) = A(k)X(k) + B(k)U(k) + \Gamma w(k)$$
$$Y(k) = C(k)X(k) + v(k) \quad (10)$$

X(k) is the system state at moment k. Y(k) is the working voltage through battery model calculating. A(k),B(k) and C(k) respectively are system matrix, control input matrix and measure matrix. U(k) is system controlled variable. w(k) and v(k) respectively are system noise and measurement noise. Γ is interference matrix. E[w(k)]=q(k), E[v(k)]=r(k), E[w(k)w(j)T]=Q(k), E[v(k)v(j)T]=R(k).

$$X(k|k-1) = A(k-1)X(k-1) + B(k-1)U(k-1) + \Gamma q(k-1)$$
$$P(k|k-1) = A(k)P(k\text{-}1)A^T + \Gamma Q(k-1)\Gamma^T$$
$$K(k) = P(k|k-1)C^T(k)[C(k)P(k|k-1)C^T(k) + R(k-1)]^{-1}$$
$$X(k) = X(k|k-1) + K(k)Y$$
$$P(k) = [I - K(k)C(k)]P(k|k-1)$$
$$Y = Y(k) - C(k)X(k|k-1) - r(k-1) \tag{11}$$

$X(k|k-1)$ and $X(k)$ respectively are prior estimate and the best estimate of state at moment k. $P(k|k-1)$ and $P(k)$ respectively are prior estimate and the best estimate of state error covariance at moment k. K(k) is Kalman gain matrix. Its adaptability reflects in the updates of q(k), Q(k), r(k) and R(k).

$$q(k) = (1-d(k-1))q(k-1) + d(k-1)G(X - A(k-1)X(k-1) - B(k-1)U(k-1))$$
$$Q(k) = (1-d(k-1))Q(k-1) + d(k-1)G(K(k)YY^T K(k)^T + P(k) - AP_{k|k-1}A^T)G^T$$
$$r(k) = (1-d(k-1))r(k-1) + d(r-1)(Y(k) - C(k)X(k|k-1))$$
$$R(k) = (1-d(k-1))R(k-1) + d(k-1)(YY^T - C(k)P(k|k-1)C(k)^T) \tag{12}$$

In these, $G = (\Gamma^T\Gamma)\Gamma^T$, $d(k-1) = (1-b)/(1-b^k)$, b (0<b<1) is forgetting factor. In this take b = 0.96, $\Gamma = [0.01 \quad 0.01 \quad 0.01]^T$. This increases the computation of system, which influences the convergence rate to actual state. In addition, when suddenly a huge current pulse emerges in battery charging and discharging, the tracking forecast of also can appear the corresponding lag because of the lag of observation voltage. So as current mutations come, we increase the elements value of gain matrices and increase adjustments to make the system quickly converge to actual state. When current mutations steady, we reduce the gain adjustments. These will enhance the rate of tracking the real value of SOC. K' is improved value.

$$K'(k) = r(1+0.5^{t_k - t_0})P(k|k-1)C^T(k)(C(k)P(k|k-1)C^T(k) + R(k-1))^{-1} \tag{13}$$

In this, when batteries are on standing, r=0.1; when batteries discharge and charge, r=1.3. t0 is the moment when current mutations start. tk is the moment k after current mutations start. Complete battery state space model is as follows.

$$\begin{bmatrix} U_1(k+1) \\ U_2(k+1) \\ SOC(k+1) \end{bmatrix} = \begin{bmatrix} 1-\frac{\Delta t}{R_1C_1} & 0 & 0 \\ 0 & 1-\frac{\Delta t}{R_2C_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} U_1(k) \\ U_2(k) \\ SOC(k) \end{bmatrix} + \begin{bmatrix} \frac{\Delta t}{C_1} \\ \frac{\Delta t}{C_2} \\ \frac{k_1 k_T \Delta t}{k_I Q_0} \end{bmatrix} i(k) + w(k) \tag{14}$$

$$V(k) = \begin{bmatrix} -1 & -1 & \frac{\partial E(SOC)}{\partial SOC} \end{bmatrix} \begin{bmatrix} U_1(k) \\ U_2(k) \\ SOC(k) \end{bmatrix} + v(k) \tag{15}$$

In this, ki , kT and kl respectively are coefficients relating to current, temperature and life. Δt is sampling period. Besides, V(k) and i(k) are all direct measurement quantity. While there is a corresponding function relation between E(k) and SOC. Then as long as given the initial value of X(k), every stroke X(k) could be deduced based on above formula to recursively calculate. Thus, based on basic Kalman filter algorithm, the adaptive Kalman filter algorithm can enhance the SOC estimation precision through online real-time estimating q(k), Q(k), r(k) and R(k) to continuously revise the estimated value of state variable SOC.

5. The Simulation Result

In order to validate the accuracy of adaptive Kalman filter algorithm estimating SOC, MATLAB was used for simulation according to formula (9)(10)(11)(15) to establish mathematical model of SOC. In the simulation experiment, environmental temperature should be controlled between the 20-30 .The rated capacity of lithium ion battery pack was 18Ah.The rated voltage was 25V. Figure 3 and Figure 4 show the comparison between the measured value of the battery terminal voltage and the model value. Then we could see that the second order RC model had better dynamic performance. Figure 5 shows comparison of convergence time. It can be seen that the system which adopts improved gain coefficient K' can more quickly converge to actual state.

Figure 7 shows the error of adopting adaptive Kalman filter estimate algorithm, and its extent of error reduced observably comparing with Figure6. We can see that the improved method had better inhibitory ability for noise.

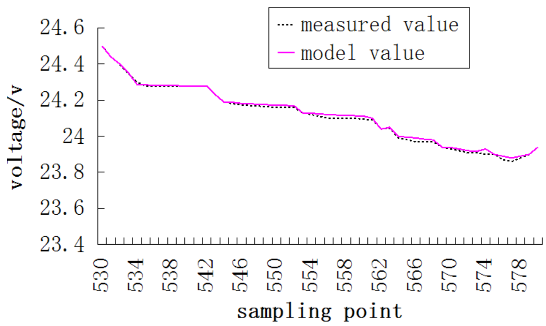

Figure 3. The comparison of Thevenin model terminal voltage

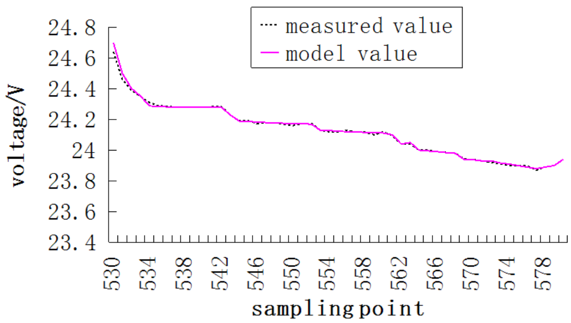

Figure 4. The comparison of second order RC model terminal voltage

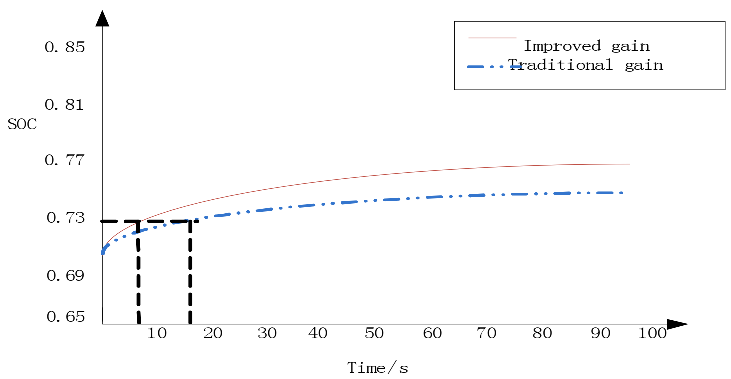

Figure 5. Comparison of convergence time

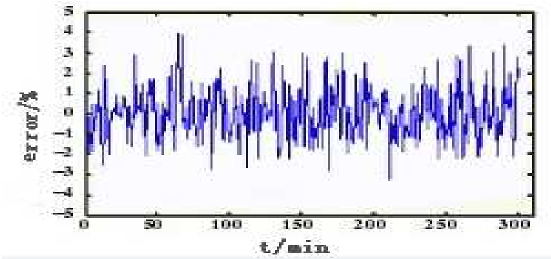

Figure 6. Regular Kalman filter estimate error

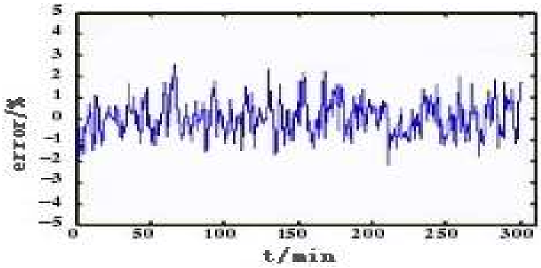

Figure 7. Adaptive Kalman filter estimate error

6. Conclusion

In this paper, in order to obtain more accurate estimated value of SOC, adaptive Kalman filter algorithm was taken based on second -order RC model. It can effectively reduce the influence of SOC estimate due to unknown noise. But the real-time accurate estimates of noise still need be further researched.

Aknowledgement

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