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Estimation of Power Lithium–ion Battery SOC Based on Fuzzy Optimal Decision

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Abstract. In order to improve vehicle performance and safety, need to accurately estimate the power lithium battery state of charge (SOC), analyzing the common SOC estimation methods, according to the characteristics open circuit voltage and Kalman filter algorithm, using T–S fuzzy model, established a lithium battery SOC estimation method based on the fuzzy optimal decision. Simulation results show that the battery model accuracy can be improved.

Key words: power lithium–ion battery; T–S fuzzy model; Optimal Decision; SOC.

INTRODUCTION

It is very important for electric vehicle and vehicle power battery whether the estimation of the charge state SOC (State of Charge) of the power lithium battery is accurate or not. A scientific and reasonable SOC estimation method for lithium battery has become one of the key technologies to improve the efficiency of power lithium battery and improve the overall performance of electric vehicle [1].

At present, Estimation methods of SOC for power cell are ampere hour measurement, neural network method and Kalman algorithm etc. And the merits and demerits of various methods are detailed in Table 1.

Studies have shown that only one method cannot accurately estimate the SOC of lithium battery, and many methods need to be combined to improve the estimation method. KIM K H [3] proposed adaptive fading extended Kalman filter to solve the problem of state estimation when the information part of a stochastic nonlinear system is known. In which a forgetting factor is used to modify the filter gain matrix, so that a better effect of state estimation is obtained. JWO D J [4] proposed adaptive fuzzy strong tracking Kalman filter to solve the problem of state estimation when the system model cannot be obtained accurately. In which a fuzzy logic inference system is constructed by using T–S model. And the inference system can dynamically adjust the softening factor according to the divergence degree, thus modifying the filter gain matrix and improving the performance of the state estimation algorithm.

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TABLE 1. The performance table of SOC estimation methods

Methods	Advantages	Disadvantages
discharge test method	Accurate estimation	Can't be used in an electric car
Open circuit voltage method	Simple, suitable for estimating the initialization of SOC	It takes a long time to wait for the battery to stay still. Unable to apply dynamic working conditions
Ampere hour method	It can be measured online, and the method is simple	There is a cumulative error, which is difficult to eliminate
Neural network method	Suitable for all kinds of SOC estimation of batteries	Based on Simulation and theoretical analysis, the practical application is difficult.
Fuzzy logic method	Suitable for all kinds of SOC estimation of batteries	Based on Simulation and theoretical analysis, the practical application is difficult.
Electrochemical method	Accurate	It is difficult in on–line measurement
Internal resistance method	There is no need to consider the state of the battery	The internal resistance value is very small, and it is difficult to measure.
Kalman filter method	Online measurement can be achieved	The precision of the battery model is high and the noise statistics are inaccurate

In this paper, in the estimation of the Kalman filter algorithm, the open circuit voltage is taken, and by looking for the data in the table of the open circuit voltage, the SOC value of the open circuit voltage method is obtained. Combining the SOC value of the open circuit voltage method and the SOC value in the Kalman filter algorithm, the optimal value of SOC is obtained by applying the T–S fuzzy model to optimize the decision. The operation process is shown in Figure 1.

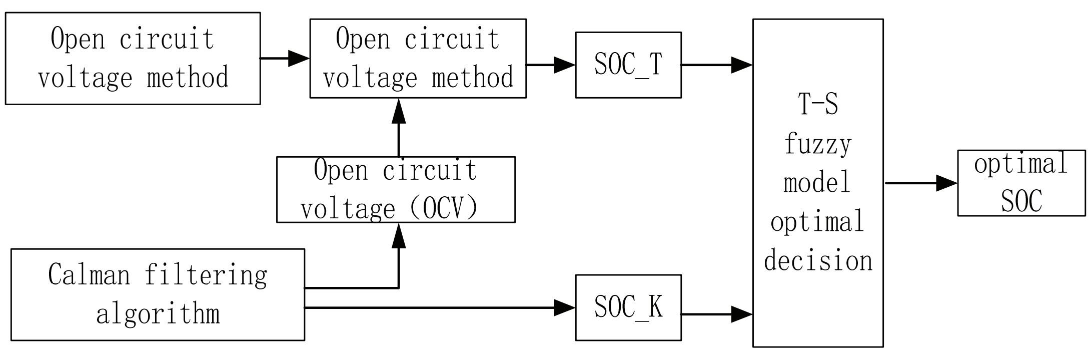

FIGURE 1. Diagram of optimal decision system based on T–S fuzzy model

OPEN CIRCUIT VOLTAGE METHOD AND ACQUISITION OF OPEN CIRCUIT VOLTAGE

The open circuit voltage method is based on the relationship between the residual charge of the battery and the open circuit voltage. When the method is used, the open circuit voltage of the battery is measured, and the estimated SOC value is obtained by the look–up table method. The shortcoming of the open circuit voltage method is batteries need to be placed for a long time to achieve steady state and take several hours or even more than ten hours, which causes difficulties for SOC estimation. And how to determine the static time is also a problem, so this method is only suitable for the parking condition of electric vehicles. The open circuit voltage is the voltage that tends to be stable when the battery is open, and the continuous charging and discharging of driving battery cannot satisfy the open circuit voltage condition. So the open circuit voltage method cannot be used for the driving electric vehicle.

Two methods of obtaining open circuit voltage are introduced in this paper. One is the mean open circuit voltage, that is, the charging and discharging cycle based on the current of 0.3C, and the recorded value of charge voltage and discharge voltage during the charging and discharging process. The average value of them is the mean open circuit voltage. And another way is 10% open circuit voltage, that is, the capacity of the calibration is divided into 10 parts, the interval time is 10 times, the 1C current discharge is used to collect the open circuit voltage before and after the discharge, that is, every 10% open circuit voltage, and the median is equally divided.

Two kinds of open circuit voltage curves are shown in figure 2.

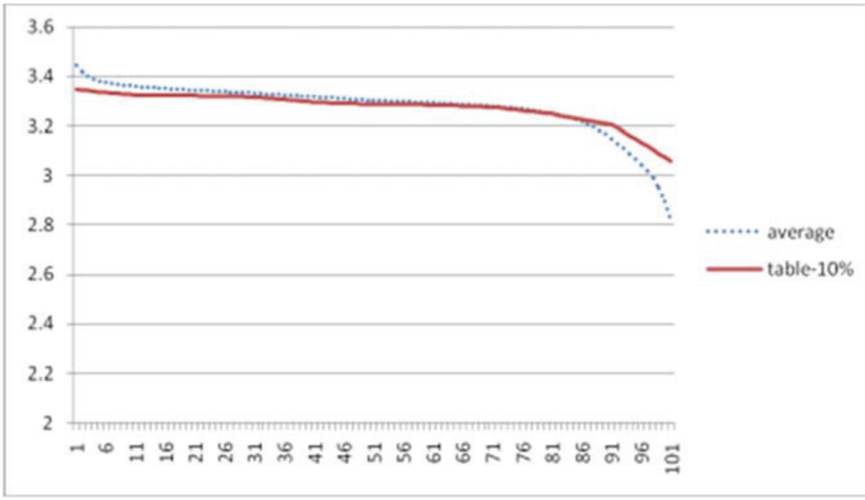

FIGURE 2. Two kinds of open circuit voltage curves

KALMAN FILTERING ALGORITHM

Kalman filter method is an optimal estimation of the state of the system which is made in the sense of minimum variance. It is not only applicable to linear systems but also for nonlinear systems. When the battery SOC is estimated, the Kalman filter regards SOC as an internal state of the battery system, and the minimum variance estimation of SOC is realized by the recursive algorithm. The core of the algorithm is a set of recursive formulas composed of filter and filter gain. The estimated value of SOC is obtained by the filter calculation based on the state of the input. The filter gain is calculated according to the statistical characteristics of the variable, and the filter gain is obtained, and the estimated error is obtained. Kalman filtering can maintain good accuracy in the estimation process, and has a strong correction effect on initialization error, and strongly inhibits the noise.

The Kalman filtering algorithm is more dependent on the battery equivalent circuit model, and the key to the algorithm is to establish an accurate battery model. In this article, the first order RC equivalent circuit model is chosen as the model of the power lithium battery. The model can better reflect the dynamic and static characteristics of the battery. Considering the difference of temperature and current and the difference of internal resistance in charge and discharge, it can accurately simulate the charge and discharge behavior of battery, at the same time its structure is relatively simple, and the amount of computation is small.

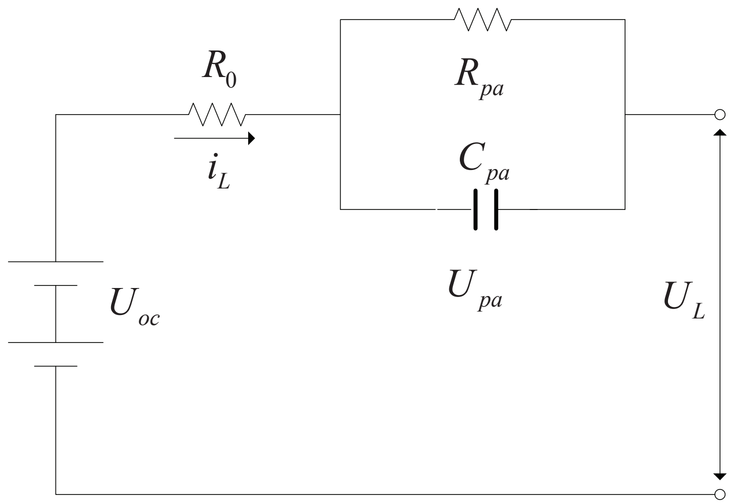

FIGURE 3. RC equivalent model circuit diagram

The mathematical expression of the equivalent circuit can be obtained from Figure 3.

$$U_{pa}^{'} = -\frac{U_{pa}}{R_{pa}C_{pa}} + \frac{i_L}{C_{pa}} \tag{1}$$

$$U_L = U_{oc} - U_{pa} - i_L R_0 \tag{2}$$

In the formula, U_L is the working voltage of the battery; U_{pa} is the voltage estimation of U_{pa} ;U_{pa}' is the derivative of U_{pa} pairs of time; U_{oc} is the open circuit voltage of the battery.;R_0 is the internal resistance of the battery ohm;R_{pa} is the polarization internal resistance of the battery;C_{pa} is the equivalent capacitance;i_L is the charge discharge current

The SOC value estimated by the Kalman filter method – SOC_K is obtained by applying the first order RC equivalent circuit model and using the extended Kalman filter algorithm. In practical applications, the statistical characteristics of noise may be partly known, approximately known or completely unknown. The design of Kalman filtering algorithm based on the inaccurate or wrong statistical characteristics of noise can lead to poor filtering performance and even filter divergence. In order to avoid the phenomenon of filtering divergence, the optimization decision method of T–S fuzzy model is introduced.

OPTIMIZATION DECISION BASED ON T–S FUZZY MODEL

T－S Fuzzy Model

T—S fuzzy model can be described as [5]: If x_1 is A_1^i, x_2 is A_2^i ..., x_m is A_m^i , then

$$y^i = p_0^i + p_1^i x_1 + p_2^i x_2 + \ldots + + p_m^i x_m \tag{3}$$

Suppose a generalized input variable is given as $(x_{10}, x_{20}, \ldots\ldots, x_{m0})$,Then the total output of the system can be obtained by the weighted average of the output of the rules y^i (i=1, 2..., n):

$$\hat{y} = \frac{\sum_{i=1}^{n} \mu^i y^i}{\sum_{i=1}^{n} \mu^i} \tag{4}$$

In the formula, n in the formula, n is the number of fuzzy rules. y^i is the conclusion equation of rule i. μ^i is the degree of membership of the rule i that corresponds to the generalized input vector. And μ^i is determined by the following formula:

$$\mu^i = \prod_{j=1}^{m} A_j^i(x_{j0}) \tag{5}$$

In the formula, $\prod$ is a fuzzy operator, and usually using small operation or product operation [6].

Fuzzy Inference

In this paper, the SOC_T is used to express the open circuit voltmeter to query the SOC value, and SOC_K is used to express the Kalman filter algorithm to estimate the SOC value.

In the formula:

The domain of SOC_T and SOC_K: [0 100];

The language variables of SOC_T: T_L, T_M, T_H;

The language variables of SOC_K: K_L, K_M, K_H;

SOC_T's membership function expression:

μ T_L = exp(–(x – 30).^2/(2*15^2));

μ T_M = exp(–(x – 70).^2/(2*5^2));

μ T_H = exp(–(x – 100).^2/(2*5^2));

The membership function of SOC_T is shown in Figure 4;

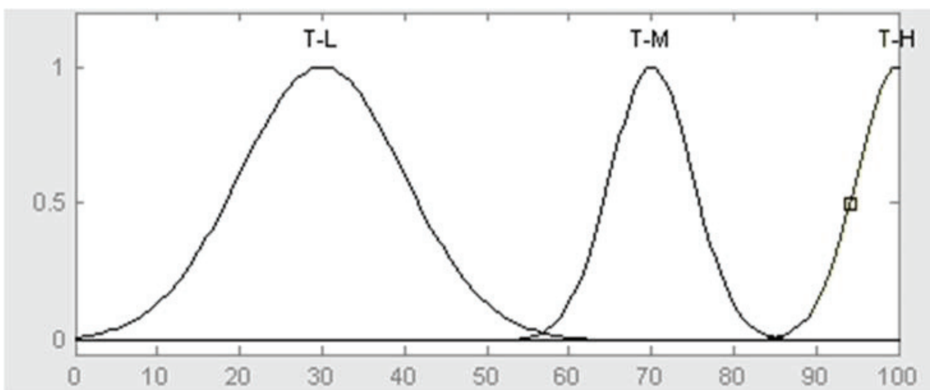

FIGURE 4. The membership function of SOC_T

The membership function expression of SOC_K:

μ K_L = exp(–(x – 5).^2/(2*10^2));

μ K_M = exp(–(x – 50).^2/(2*10^2));

μ K_H = exp(–(x – 85).^2/(2*5^2));

The membership function of SOC_K is shown in Figure 5.

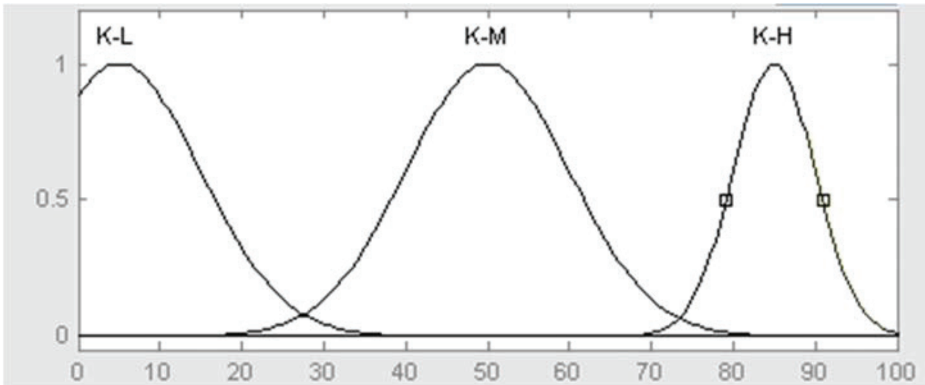

FIGURE 5. SOC_K membership function

The decision table based on the fuzzy optimization method is shown in Table 2.

TABLE 2. Fuzzy optimization decision table

SOC_K / SOC_T	K_L	K_M	K_H
T_L	SOCk μ K_L+ SOCT μ T_L	SOCk μ K_M+ SOCT μ T_L	SOCk μ K_H+ SOCT μ T_L
T_M	SOCk μ K_L+ SOCT μ T_M	SOCk μ K_M+ SOCT μ T_M	SOCk μ K_H+ SOCT μ T_M
T_H	SOCk μ K_L+ SOCT μ T_H	SOCk μ K_M+ SOCT μ T_H	SOCk μ K_H+ SOCT μ T_H

The Optimal Value of SOC

By formula (4):

$$\hat{y} = \frac{\sum_{i=1}^{9} \mu^i y^i}{\sum_{i=1}^{9} \mu^i} \tag{6}$$

In the formula, n is the number of fuzzy rules. y^i is the conclusion equation of rule i. μ^i is the degree of membership of the rule i that corresponds to the generalized input vector.

EXPERIMENTAL VERIFICATION

In this article, a contrastive approach is used to verify the advantages and disadvantages of the methods. By discharging a known power cell group 10 times with a 1C discharge current, the SOC of the power cell group will have a staircase decline. At the same time, SOC is estimated by different methods, by comparing the estimated value to the actual value, the accuracy of the estimation algorithm can be verified.

First, the Kalman filtering algorithm is verified, as shown in Figure 6, the real line is the SOC value of the actual test, and the dotted line is an estimated value based on the Kalman filter algorithm.

It can see from Figure 6, during the first discharge process, the estimated value overlaps with the actual value. That is to say, the estimated SOC consistency of this method is very good, and the estimation error is small. In the next 9 discharge processes, the estimated value is slightly lower than the actual value. That is to say, the error begins to increase, and the precision is also beginning to fall.

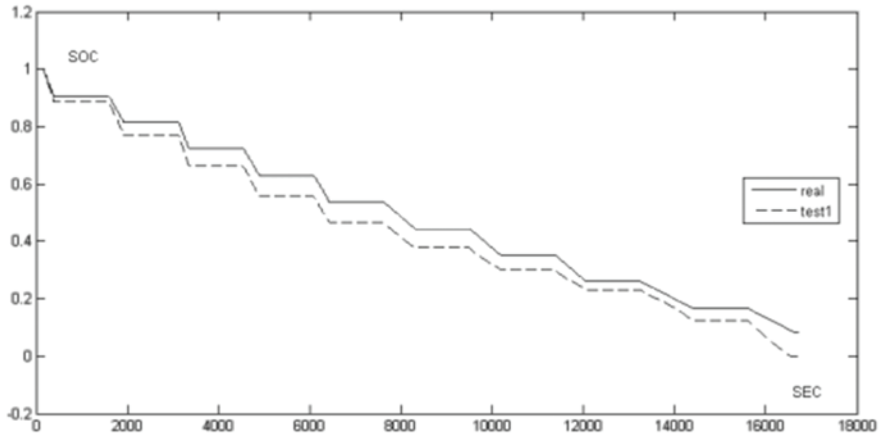

FIGURE 6. Verification diagram of Kalman filter algorithm

Then, the method based on fuzzy optimization decision is verified. In Figure 7, the real line is the SOC value of the actual test, the dotted line is an estimated value based on the fuzzy optimization decision method. As shown in Figure 7, in the first 5 discharge, the estimated value and the actual value is difficult to separate, which shows that the error of the estimation is very small. Starting from the sixth discharge, there was a little separation, but the difference was very small. Therefore, the estimation accuracy based on fuzzy optimization decision method is high.

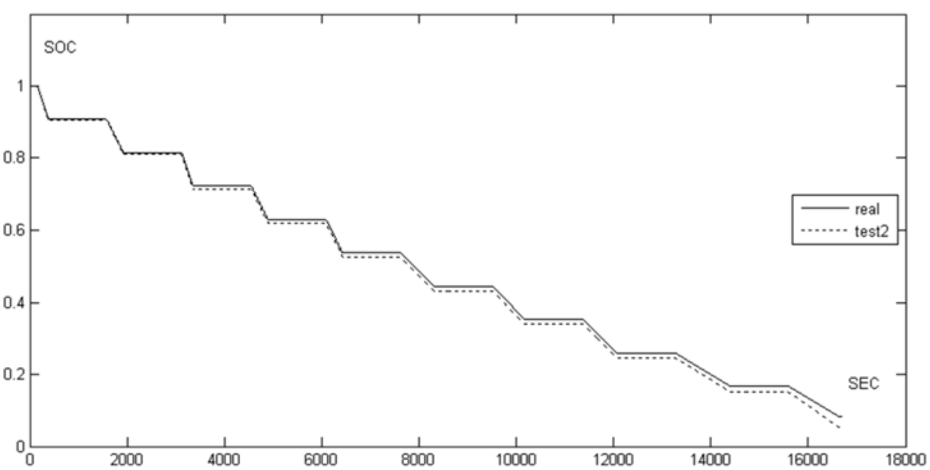

FIGURE 7. Method verification diagram for fuzzy optimization decision

CONCLUSION

This article is simply to do some research on the combination of the two methods. It is not perfect, and there are many places to be improved. For example, the table open circuit voltage can be obtained at 5% or smaller range, and the result will be more accurate.

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