An Accurate Estimation for the State of Health of Lithium-ion Batteries by Using Fuzzy Logic System

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Abstract— Lithium-ion batteries have been widely used as a power source for electric vehicles and the lack of accurate estimation for the state of health (SOH) has seriously affected the practical applications of lithium-ion battery packs, so it is very imperative to find a good solution. In this paper, we propose an accurate estimation method for the SOH by using a fuzzy logic system. We first perform charging and discharging experiments for the lithium-ion batteries to obtain the residual capacitance and equivalent DC resistance under different SOHs. Then a fuzzy logic system is figured out according to the relationship between the equivalent DC resistance and the SOH. The SOH of the batteries is estimated online through inputting the calculated equivalent DC resistance into the fuzzy logic system. Experimental results show that this method is very effective to calculate the SOH of lithium-ion batteries.

1. INTRODUCTION

Recently, energy crisis and environmental pollution has become increasingly serious and the development of lithium-ion batteries as a power source has been very essential. One of the most important applications of the lithium-ion batteries is to be the power source of electric vehicles and whether electric vehicles will be widely used or not mainly depends on the performance of the batteries. Thus we must properly monitor and evaluate the state of health (SOH) of batteries to ensure that electric vehicles can operate safely and reliably [1].

The SOH and state of charge (SOC) are the two important indexes reflecting the state of batteries. In recent years, many attentions have been paid to the estimation methods of SOC such as Coulomb counting or Ah counting, adaptive Kalman filtering, extended Kalman filter [2], artificial intelligent methods and impedance spectroscopy. In contrast, the study on the SOH has not received a sufficient attention [3]. The SOH estimation belongs to a nonlinear problem which requires a highly accurate solution and the traditional linear estimation methods cannot meet the estimation requirements. As there has not been a mature estimation method for the SOH so far, it is imperative to find a solution for the lithium-ion batteries.

The SOH is a figure of merit for the condition of a battery (or a battery pack) compared to its ideal conditions. Typically, a battery's SOH will be greater than or equal to 100% at the time of manufacturing and then will decrease over time and use. IEEE standard 1188-2005 specifies that when the battery's capacitance decreases to 80%, the battery should be replaced. In fact, the degradation of lithium-ion batteries can be attributed to its change of internal chemical composition [4]. During the charging and discharging process, the lithium-ion batteries will also produce some irreversible side effects in addition to have a specific oxidation and reduction reaction. The side effects often generate lithium salt which adheres to the electrode and increase the equivalent DC resistance of the battery [5]. The lithium in the lithium salts will no longer take part in the charge and discharge reaction in the form of li-ion. That is to say, the maximum capacitance of a battery is reduced from a macroscopic view. In addition, in the initial stage of charging and discharging process, the battery's materials will react with electrolytes on the interface between a solid and liquid phase and form a passivation layer, called solid electrolyte interface (SEI), covering the surface of the electrode's materials. Li-ion will encounter some obstacles when getting through the SEI. These obstacles are the so-called internal resistance of the battery. The thicker the SEI film is, the bigger the equivalent DC resistance of the battery is. Thus the maximum capacitance of the battery is relatively reduced and its SOH can be obtained by measuring the equivalent DC resistance in its different life stages.

In this paper, we propose an appropriate method to accurately estimate the SOH for lithium-ion batteries. The charging and discharging experiments are performed first and the corresponding fuzzy rule table can then be defined according to the relationship between the equivalent DC resistance and the SOH. Also, the static estimation and dynamic estimation are combined together so that the system reliability and the estimation accuracy can be improved. The simulated results show that the method can remarkably enhance the estimation accuracy for the SOH of lithium-ion batteries and it could be very useful in electric vehicles.

2. CALCULATION OF EQUIVALENT DC RESISTANCE

Lithium-ion batteries usually adopt a constant current at the beginning and then take a constant voltage to charge. When the terminal voltage of the battery does not reach 3.65 V, the constant-current charging method is adopted. When the terminal voltage reaches 3.65 V, the constant-voltage charging method with 3.65 V is used. During the constant-current charging process, the equivalent DC resistance can be obtained by periodically shutting off the charging current in a short time (less than 1%). The equivalent DC resistance can be calculated by

$$r_n = \frac{U_{cn} - U_{ocvcn}}{I_c} \tag{1}$$

where r_n is the equivalent DC resistance of the nth ($n = 1, 2, 3, \ldots$) sample point, U_{cn} is the last charging voltage before cutting off the current of the nth charging cycle, U_{ocvcn} is the last terminal voltage during the process of cutting off the current in the nth charging cycle, and I_c is the charging current. The advantage of this method is that during the constant-current charging process, the equivalent DC resistance can be obtained simply by measuring the battery's terminal voltage at different times. Figure 1 shows the changes of the equivalent DC resistance at different SOHs during the constant-current charging process.

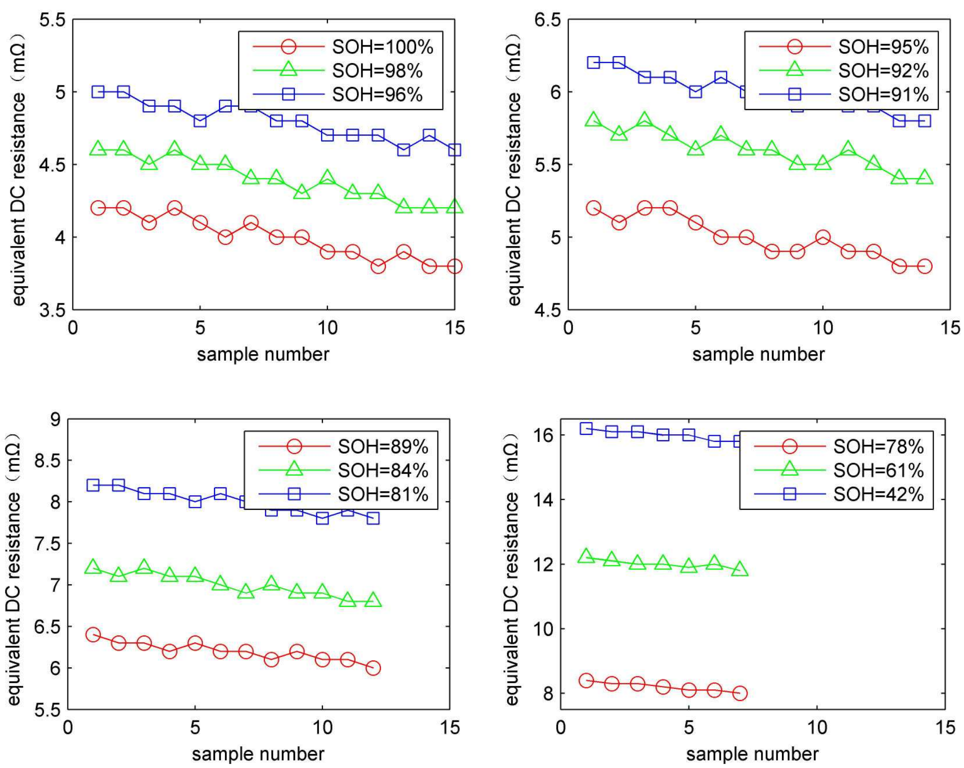

Figure 1: Equivalent DC resistance at different SOHs during the constant-current stage.

3. RELATIONSHIP BETWEEN EQUIVALENT RESISTANCE AND SOH

The battery used in this paper is a lithium-iron-phosphate power battery with 3.2 V and 100 Ah. The discharge cut-off voltage of the battery is 2.5 V, the charge cut-off voltage is 3.65 V, the charging current is 0.2C, and the discharge current is 0.5C. The charging and discharging experiment is conducted under different SOHs. In the constant-current charging stage, the current is shut off for 5 seconds every 15 minutes, and the U_{cn} and U_{ocvcn} are then recorded, respectively. The equivalent DC resistance of each sample point can be calculated and the average value of all points is regarded as the equivalent DC resistance of the battery. Figure 2 shows the relationship between the equivalent DC resistance of a lithium battery and its SOH.

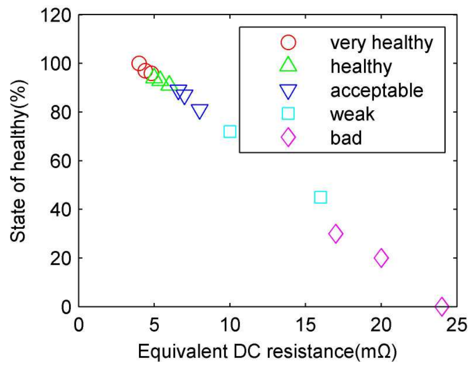

Figure 2: Relationship between the equivalent DC resistance and SOH of a lithium battery.

4. SOH ESTIMATION

The fuzzy logic method is an effective way to estimate the SOH of a lithium battery by using the equivalent DC resistance [6]. The parameters about the equivalent DC resistance and SOH of lithium-ion batteries mentioned in Figure 1 can be used as the samples of establishing the fuzzy system and the fuzzy system can serve to online estimate the batteries under other health conditions. The input to the fuzzy logic system is the average value of equivalent DC resistances during the constant-current charging phase and the output is the estimated SOH. The fuzzy rules, which are defined based on the data given in Figure 2, are shown in Table 1. The output of the fuzzy logic system is in the range of [0, 1.2] and the fuzzy membership functions in shown in Figure 3. The fuzzy logic system is constructed by using the singleton fuzzifier, the centroid defuzzifier, and the Mamdani product inference engine [7]. All the aforementioned procedures for constructing the proposed SOH estimator are performed offline.

Table 1: Fuzzy rules for estimating the SOH.

FUZZY RULES
1 IF equivalent DC resistance is very small, THEN SOH is very healthy
2 IF equivalent DC resistance is small, THEN SOH is healthy
3 IF equivalent DC resistance is medium, THEN SOH is acceptable
4 IF equivalent DC resistance is large, THEN SOH is weak
5 IF equivalent DC resistance is very large, THEN SOH is bad

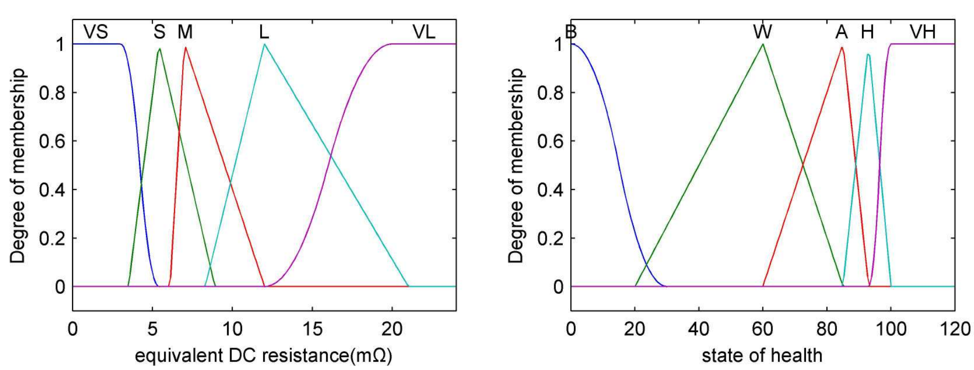

Figure 3: Fuzzy membership functions for the input and output variables of the fuzzy logic system.

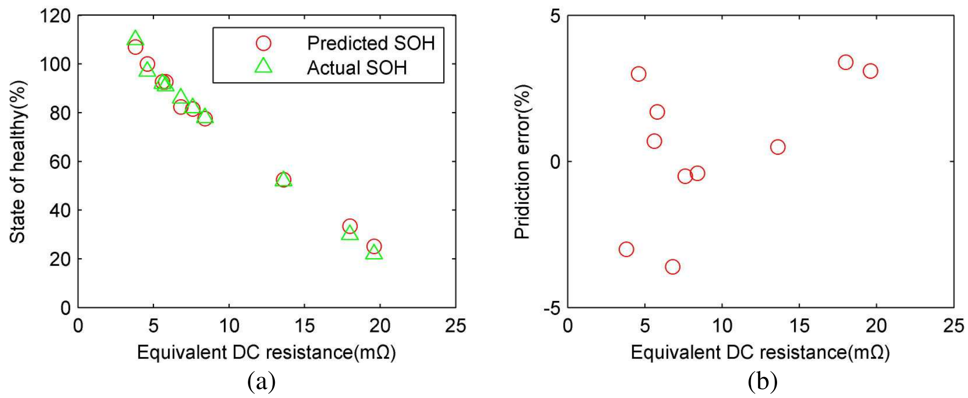

Figure 4: A comparison of the estimated SOH with the actual SOH and the prediction error.

5. EXPERIMENTAL RESULTS

In the above section, we have introduced the method of using the fuzzy logic to estimate the SOH of a lithium-ion battery. However, all these steps are achieved offline. In this section, we propose an online estimation method by using the previously-established systems. During the constant-current charging stage, the current is shut off for 5 seconds every 15 minutes, and U_{cn} and U_{ocvcn} are recorded respectively. Then the equivalent DC resistance of each sample point and the average value of all points can be calculated. The SOH of a battery can be obtained online through inputting the calculated average value of equivalent DC resistance into the fuzzy inference engine. The experiment results and prediction error are shown in Figure 4. It can be seen from Figure 4(b) that the estimation error of this method is less than 5%, meaning that it is a good method to accurately estimate the SOH of a battery.

6. CONCLUSION

In this paper, a new method for estimating the SOH of lithium-ion batteries has been investigated. By taking the calculated equivalent DC resistance of lithium-ion batteries during the charging process as the input of the pre-established fuzzy logic system, the estimation of SOHs will be online. The experimental results show that the error of using this method to estimate the SOH is not more than 5%, which can well satisfy the requirement of electric vehicles. Moreover, we can effectively extend the service life of a battery pack by replacing the individual battery cell whose health condition declines to its critical value. This method can greatly reduce the cost and show a high economic value. Meanwhile, it can also provide the necessary reference for estimating the SOC of lithium-ion batteries, equalizing and fault diagnosis of electric vehicles.

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