Lithium-ion battery state of function estimation based on fuzzy logic algorithm with associated variables

L Gan1,a, F Yang2,b, Y F Shi3,c and H L He4,d
1,2,3,4 School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
a ganl2015@163.com, b fyang@uestc.edu.cn, c shiyafeng2015@163.com, d 18428002350@189.cn

Abstract. Many occasions related to batteries demand to know how much continuous and instantaneous power can batteries provide such as the rapidly developing electric vehicles. As the large-scale applications of lithium-ion batteries, lithium-ion batteries are used to be our research object. Many experiments are designed to get the lithium-ion battery parameters to ensure the relevance and reliability of the estimation. To evaluate the continuous and instantaneous load capability of a battery called state-of-function (SOF), this paper proposes a fuzzy logic algorithm based on battery state-of-charge (SOC), state-of-health (SOH) and C-rate parameters. Simulation and experimental results indicate that the proposed approach is suitable for battery SOF estimation.

1. Introduction
Nowadays the lithium-ion battery (LiB) has drawn a vast amount of attention as the most important onboard energy storage part for both electric vehicles and smart grid applications. For online applications of LiB, BMS (battery management system) is the key component to keep the LiB work safely and efficiently. And one of the most important things for BMS is to get battery reliable parameters such as voltage, current, state of charge (SOC), state of health (SOH), state of function (SOF) [1]. For offline applications, after the recession of LiB, a lot of retired LiB urgently request to be picked out such as what kind of batteries should be reused or recycled that need to give the battery parameters which include SOH, SOF mainly to classify these LiB.

Contrast with the LiB SOC research results, researches about SOH and SOF especially SOF are far less. SOH mainly focus on the total capacity of batteries and SOF focus on the battery specific continuous or instantaneous power output capability in period. Two metrics have been proposed for defining SOF: digital in range [0,1] or continuous in range 0~1 [4]. The digital definition of SOF shows whether the battery has sufficient power capability to carry out a specific function (e.g., engine starting) and the continuous one gives the current battery power capability contrast with the primary power capability. Since SOF in range 0~1 can show the power capability more accurately which has the potential to be utilized in online BMS, take the definition that SOF is in range 0~1.

Different approaches are proposed to achieve the SOF estimation which can mainly be divided into two categories: methods based on (adaptive) characteristic maps and methods based on models like equivalent circuit or electrochemical models [2-5]. The methods based on (adaptive) characteristic maps need to choose characteristics that mainly include: SOC, Temperature, Duration of the power pulse, Required power, Battery voltage [1]. But the degree of correlation between these characteristics to SOF is not that clear and the mapping process may cause deviations especially with the decay of the
battery life which will be considered in this article. Another intends to use a model to simulate the battery as accurate and simple as possible to balance the difficulty and accuracy of estimation then utilize many algorithms such as Kalman filter (KF) and artificial neural network (ANN) to get the model parameters that required. It needs to be figured out that the model selection will greatly make difference to the estimation but there is no entirely accurate model and some of these algorithms are difficult to realize because the giant data of batteries are needed before estimation [3-6].

In this paper, the fuzzy logic algorithm is utilized to estimate SOF because it’s easy to implement and it has the potential to be extended. For selecting the main parameters to estimate SOF we do some experiments mainly include charge-discharge test with different batteries or different conditions. Then based on the SOF characteristics we choose three parameters SOC, SOH, C-rate as the inputs of fuzzy logic controller and the simulation results are given. The advantages are that data acquisition is not that complicated and the algorithm is feasible to realize. At last, we validate the effectiveness of this algorithm by the contrast of simulation and experimental results.

2. parameter selection
At first we can see the main frame of this article in Figure 1. Due to SOF is a variable that can fluctuate between 0~1, we choose the fuzzy logic algorithm to achieve the estimation and SOF is the only output. Then we must elect which parameters should be input variables. Based on the number of parameters that influence SOF and the complexity of fuzzy controller and the battery characteristics we elect three-dimension fuzzy controller which means we choose three input variables that include SOC, SOH, C-rate.

The fuzzy input space consists of input of fuzzy control rules and the premise of language variables. The number of input variables of fuzzy controller is called the dimension of the fuzzy controller in general. In theory the higher of the dimension, more accurate of the result. But when the dimension is too high, the rules of fuzzy control will be too complex to implement. There are actually other variables are related to SOF such as voltage and temperature(T). The voltage is associated with SOC and for T, many applications will make the T to be in very small scope such as cooling system to achieve this goal so these parameters are not considered.

2.1.SOC
We can easily find the SOC-OCV fitting results in many articles that focus on the relationship between SOC and battery open-circuit-voltage (OCV) [6]. To judge their change trend roughly, we can conclude that they are positive correlation which means choose one of them or both of them are all feasible. At last we choose the SOC as one of the inputs of fuzzy controller. Another reason to choose the SOC is that it reflects the total capacity of battery at present.

2.2.SOH
The definition of SOH shows the distinction of aging battery and new battery which is similar to SOF. To know the distinctions with the variation of LiB SOH we test different LiB discharge characteristics because the focus is on the discharge power as is shown in Figure 2. The SOH is 0.95 in (a), 0.93 in (b), 0.94 in (c) and 0.86 in (d). The results show that the aging battery voltage drop is very obvious and the current has bigger fluctuation. As we know the voltage and current is the main two variables to calculate the power, it's necessary to select SOH which can also indicate the power capability of batteries.

2.3.C-rate
It is worth noting that current and voltage change are the most conspicuous and visualized variables to show battery characteristics of the power capacity in the battery charging and discharging process. Many articles proposed to estimate SOF mainly focus on the current because of the voltage range is smaller so it's obvious to choose C-rate to be an input parameter. Most of the nominal batteries can be used sustainably by the discharge current not more than 2C. Here the 18650 LiB nominal capacity is
2600mAh means the sustainable current 2C is about 5A and the primary SOF power of these LiB is about 18.5W. The LiB discharge cures with different discharge C-rate can be caught in Figure 3. This battery recession is evident which can be acquired from (d) as the range of voltage drop is out of normal range especially when discharge current exceeds 1.2C.

Figure 1. Frame of SOF estimation

Figure 2. Discharge curves with 1A constant current for different SOH of batteries
3. The algorithm description and verification

3.1 Fuzzy logic algorithm

The fuzzy logic algorithm is developed to solve the phenomena of fuzzy and the basic idea is to realize the algorithm design with the help of the modern computer numerical computation work based on the fuzzy sets theory [7-8]. The principle of fuzzy logic algorithm system for estimating SOF is depicted in Figure 4. Here the most evident difference between this fuzzy logic algorithm and others is that the algorithm mainly utilizes the state parameters and the three variables input can balance the complexity and accuracy well. And the potential to extend this algorithm is also significant [9].

**Figure 4. The fuzzy logic algorithm principle**
3.2 simulation and simulation results
Now the three variables have been determined and the domain of SOC is [0%,100%], the domain of SOH is [0%,100%] and the domain of C-rate is [0C,2C]. To complete domain fuzzification, the fuzzy sets of SOC, SOH and C-rate are all divided into three fuzzy subsets {Low, Medium, High}. When SOC and SOH are below 25%, they are in subset low and between 25% and 75% they are in subset medium and up 75% they are in subset high. For C-rate, it's in subset low when C-rate is below 0.5C and in subset medium when C-rate is between 0.5C-1.2C and High when C-rate is 1.2C-2.0C.

All of the input variables take triangular membership functions to reduce the computation complexity and the simulation parameters can be seen in Figure 5. Then input the fuzzy logic rules if<SOC is A>and<SOH is B>and<C-rate is C>THEN<SOF is D> and fuzzy reasoning model Mamdani. Three-dimensional layouts show relationships between SOF and two of the three inputs SOC, SOH, C-rate. The output of SOF depicted in Figure 6 indicates the estimation result with different inputs and the outcome basically the same with our predictions.

Figure 5. Simulation membership functions, three-dimensional layouts.

Figure 6. The SOF estimation results with the variation of input.

3.3 experimental results
To know the actual distinctions and the degree of attenuation among different batteries, we choose retired LiB to be our experiment subject for more obvious consequences as is shown in Figure 7. The model of these LiB is 18650 which has been widely used by many manufacturers such as Tesla. All these retired LiB are from the same group which enable to more obviously show the disparity between different batteries in one group.
When the SOC is 100%, select the current range [3A–0.1A] and every 10s down 0.1A or [0.1A–3A] every 10s up 0.1A to test the SOF. The discharge curves in Figure 8 indicate that this battery is available to discharge with 3A but the voltage changes from 4.20V to 3.42V so the power is 10.2W and the SOF is about 0.55. After the SOC changes, we can learn from the Figure 8 that the SOF turns to 44%. To evaluate the effectiveness of the fuzzy logic algorithm, a group of 6 batteries are tested and the simulation result contrasted with the tested result is shown in Figure 9. The highest deviation is about 14%. Though the error may fluctuate from 0% to 14%, the convenience of this algorithm and probability to improve the accuracy by combined with other algorithms are significant advantages.

Figure 7. Experiment equipment and experiment object

Figure 8. SOF test

Figure 9. Simulation and experiment result comparison

4. Conclusion

The SOF is important for the battery load capability evaluation. In this paper, the fuzzy logic algorithm and the main variables SOC, SOH, C-rate associated with SOF are selected to realize the estimation of SOF. The experiments in this article are mainly focus on the offline batteries to lower the difficulty of
verification. The parameters are chosen based on the battery characteristics and the difficulty of algorithm implement. Some of simulation and experiment results are given. The proposed algorithm is easier to implement and the expandability is well such as change the input numbers and variables, extend the fuzzy logic algorithm with other algorithms. The results show that it's feasible to estimate SOF with the fuzzy logic algorithm based on the associated variables SOC, SOH, C-rate.

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