Battery Equalization Strategy for LiMn$_2$O$_4$ Battery Based on Fuzzy Control

Songming Zhang$^1$, Xiao Ma$^1$ and Danfeng Qiu$^{1,*}$

$^1$Key Laboratory of Radar Imaging and Microwave Photonics (Nanjing Univ. Aeronaut. Astronaut.), Ministry of Education, College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China

*Corresponding author

Abstract. With the pollution of the environment and the shortage of energy, new energy vehicles, especially electric vehicles (EVs), have received more and more attention. Power batteries are the most important part of new energy vehicles. Electric vehicles usually require hundreds or even thousands of batteries as the power source, but there are inconsistencies between these batteries due to manufacturing process limitations. This situation will cause over-charging and over-discharging of the batteries, which seriously affects the safety of the battery packs. In order to solve this problem, this paper proposed a battery equalization strategy based on fuzzy control, and simulated the strategy in MATLAB/SIMULINK. The result proved that the scheme could automatically balance the batteries, which effectively prevented over-charging and over-discharging of the batteries.

Keywords: Battery equalization; Fuzzy control; MATLAB/SIMULINK.

1. Introduction

With the continuous development of society, the global car ownership continues to grow. But as global warming and energy crises continue to intensify, internal combustion vehicles have become unsuitable for the times. Therefore, countries around the world have accelerated the research of new energy vehicles because of the high efficiency, energy saving, low emission and zero emission. As the key component of electric vehicles, battery performance directly determines the performance of the electric vehicles. However, battery technology has not made breakthrough in power, environmental protection, cycle life, cost and so on, which has become the bottleneck of the industrialization and marketization of electric vehicles [1].

In theory, the performance of the same batteries should be identical. However, due to the influence of the battery manufacturing process, large inconsistencies exist between the same batch of batteries. Moreover, the inconsistency of the battery groups will gradually increase with the increase of the charging and discharging times [2]. The inconsistency of the individual cells in the battery groups will seriously restrict the practical application of the power batteries and the overall performance of the electric vehicles. In the charging and discharging process of battery packs, batteries with small capacity or high internal resistance can easily result in overcharge and over-discharge while the large capacity batteries easily result in undercharge and under-discharge, which leads to the inconsistency between the batteries [3-4]. This situation will lead to the shortened life of batteries and the increase of insecurity. Therefore, battery equalization is of great importance to BMS (Battery Management System).

LiMn$_2$O$_4$ batteries are a type of lithium ion batteries with the spinel structure. Generally speaking, the spinel structure is more stable than the layered structure. The advantages are more prominent in comparison: low temperature resistance, good rate performance and easier manufacturing. Because of
the widespread presence of manganese, the cost advantage of LiMn$_2$O$_4$ batteries are also obvious [5-7]. Therefore, LiMn$_2$O$_4$ batteries are selected as the experimental batteries. Because the ordinary mathematical model cannot accurately describe the state of the battery, the fuzzy control method is used to design a battery equalization system in this paper, and the system is simulated with the Simulink module in MATLAB/SIMULINK. The experimental results show that the designed system can control the equalization current of the battery.

2. Equalization Methods

2.1. Equalization index

The capacity of the lithium battery packs is the same as the capacity of the lithium battery with the smallest capacity, so the difference in capacity will directly affect the battery life cycle. In order to ensure the maximum performance of the battery groups, the balance control of the battery packs must be carried out [8]. At present, there are three commonly used equalization indicators: battery voltage, battery capacity and battery SOC (State of Charge).

1) Equalization based on battery voltage: This method balances the abnormal battery voltage in the battery packs. Because battery voltage is easy to measure and intuitive, many studies use battery voltage as an evaluation index [9].

2) Equalization based on battery capacity: The equalization scheme takes battery capacity as the research object and improves capacity utilization as the research objective. Because this method keeps the capacity of the battery consistent, it is a method that best fits the equalization purpose. However, battery capacity can only be obtained under static conditions, so it is not suitable for online balancing. Therefore, the method based on battery capacity is no longer used.

3) Equalization based on battery SOC: The principle of this method is to balance the batteries with different states. The hardware circuit of this control method is simple and the equalization effect is better for series batteries [10]. Considering the convenience and accuracy, the battery voltage was used as the basis for battery equalization in this paper.

2.2. Equalization technology

The scheme of resistance energy consumption equalization in passive equalization is more mature in practical application. The balanced circuit parallels each single cell with a discharging resistor, using resistance shunt to suppress the rise of the battery voltage, which will release the energy of unevenly high energy batteries in the form of heat. However, passive equalization is a kind of method that dissipates the excess quantity of lithium battery directly in the form of heat. Energy will be lost, the efficiency is low, and the effect of heat must be prevented. Therefore, the passive equalization method is less used in practice.

Active equalization is mainly composed of MOSFET and inductance and capacitance. Because of the inductance and capacitance, there is no energy loss. This method is widely used at present. Commonly used active equalization methods include switched capacitance circuit, shared energy conversion equalization circuit, Buck-Boost balancing circuit, bidirectional isolation DC/DC equalization circuit etc.
In this paper, the Buck-Boost equalization circuit was used. The circuit topology was shown in Figure 1 [11]. Bat1 and Bat2 were chose as the example, assuming that the SOC of the Bat1 was higher, the MOSFET switch tube Q1 was opened and the MOSFET switch tube Q2 was turned off. Bat1 would be discharged. The inductance L1 stored the energy and charged Bat2. This state would repeat until SOC of two batteries tend to be consistent, that was to achieve the balance between Bat1 and Bat2. Similarly, the equalization of other neighboring battery could be realized and the SOC equalization of all batteries in the whole battery pack would eventually be achieved [12-14].

3. Design of Fuzzy Controller

In this paper, LiMn$_2$O$_4$ batteries were measured. The LiMn$_2$O$_4$ cathode material exhibited low cost, safe operation, and low-temperature properties. However, the material was unstable and easily decomposes. This material was mainly used in large and medium-type batteries, such as power batteries. Table 1 showed some basic parameters of the experimental battery [15-17].

| Parameter                  | Value          |
|----------------------------|----------------|
| Rated capacity [Ah]        | 30             |
| Nominal voltage [V]        | 3.6            |
| Internal impedance [mΩ]    | 1.12           |
| Cutoff voltage [V]         | 4.25           |
| Minimum discharge voltage [V] | 2.4         |
| Maximum discharge current [A] | 120 [4C]    |
| Fast-charge current [A]    | 60 [2C]        |
| Working temperature [°C]   | −20–55         |
| Cycle life                 | ≥1500          |

Because of the use of hundreds of thousands of lithium ion batteries in electric vehicles, ordinary mathematical models could not accurately describe the controlled objects, so the conventional control theory and control algorithms could not solve the equalization problem of lithium ion batteries. Compared with the traditional controller, fuzzy controller had the following characteristics [18-20]:

1. The use of language methods did not require accurate mathematical models, and its structural parameters were generally not clear.
2. Fuzzy control was based on heuristic knowledge and language decision rules, simulating the process and method of manual control, enhancing the adaptability of the system.
3. The fuzzy control system had strong robustness, and the changes of interference and parameters had little influence on the system. It was more suitable for controlling nonlinear, strong coupling,
time-varying and lagging systems. The fuzzy controller was the most important part of the whole fuzzy control system. The design of the fuzzy controller included four steps as shown in Figure 2: determining the input and output variables, the fuzzification of the exact quantity, establishing fuzzy rules and defuzzification.

**Figure 2.** The basic structure of fuzzy controller.

To design a reasonable fuzzy controller, the input and output of the controller would first be defined. In this paper, the fuzzy controller contained two input variables and one output variable. The input variables included two parts: the voltage difference between the single cell \( \Delta U \) and the average voltage \( U \). The output variable \( I_{eq} \) was the balanced current. The input variable expression was shown in the following form [12].

\[
\Delta U = U_{j} - U_{j-1}
\]

\[
\overline{U} = \frac{U_{j} + U_{j-1}}{2}
\]

\( \Delta U \) determined the time of equalization. The experimental environment was set at room temperature (20°C). The lower limit of voltage difference threshold was selected as 60mV, the upper limit of voltage difference threshold was selected as 100mV. The basic domain and the corresponding fuzzy set were shown below.

\[
\Delta U = \{60, 70, 80, 90, 100\}
\]

\( \overline{U} \) affected the efficiency and safety of the battery work. The optimum voltage range for large current charging and discharging was about 3.2V-3.6V. In this paper, the average voltage domain was 2.9-3.8V, the basic domain and the corresponding fuzzy set were shown below.

\[
\overline{U} = \{2.9, 3.2, 3.5, 3.8\}
\]

The output variable \( I_{eq} \) was related to the two input variables \( \Delta U \) and \( \overline{U} \). The equalization current determined the equalization time of the battery. When the balancing current was small, the equalization time was long. When the balancing current was large, the equalization time was short. It was very necessary to accurately design the balance current of the battery. This paper fully considered the actual value range of the battery and designed the domain to be \([0,5]\). The basic domain and the corresponding fuzzy set were shown as follows.

\[
I_{eq} = \{0, 1, 2, 3, 4, 5\}
\]

\[
I_{eq-F} = \{VS MS M ML VL\}
\]
The fuzzy control rules of the fuzzy controller of the battery balanced current designed in this paper were shown in Table 2.

| $I_{eq}$ | $\Delta U$ |
|----------|------------|
| VS       | MS         |
| S        | M          |
| L        | VS         |
| M        | MS         |
| ML       | M          |
| ML       | MS         |

4. Simulation and Analysis of the Battery Equalization System

In this paper, the SIMULINK module in MATLAB was used to simulate the system. The system included data acquisition module, equalization control circuit module and equalization circuit module. The data acquisition module collected the voltage value of each cell module in real time and sent it to the balancing control module. The equalization control module made a comprehensive judgement based on these data and sent out the instructions to start or exited from the equalization circuit. The equalization circuit module adjusted the balance current of the balance circuit. The following figure (Figure 3) showed the fuzzy controller in the equalization control module. According to the description in Chapter 3, the model was composed of battery model, adder, multiplier, fuzzy controller and so on.

This battery experiment used four batteries of the same nominal capacity in 20°C. The starting voltages were 3.9 V, 3.5 V, 3.2 V and 3.0 V, respectively. The experiment recorded data every 10 seconds. It could be seen from Figure 4 that the voltage of the battery pack with a low starting voltage rose slowly during the equalization process. Moreover, the voltage of the battery pack with a high initial voltage gradually decreased during the equalization process, and finally the voltage of each battery tended to be balanced. The equalization speed was fast. The equalization result was good and fully met the expected requirements.

5. Conclusion

Because of the nonlinear characteristics of the battery, the equivalent circuit model of the battery is
difficult to determine and the balance effect of the traditional battery balancing strategy is not good. Based on the actual control experience of battery equalization, a fuzzy rule control library is constructed and a battery balance control system based on fuzzy control is proposed in this paper. According to the simulation results of MATLAB/SIMULINK, the fuzzy controller can effectively solve the imbalance between the batteries, and has certain practical significance for the battery safety and charge discharge efficiency.

The method proposed in this paper has proven to be a reasonable and accurate battery equalization method, but there is still room for improvement. Further works include: (1) the complexity of the method is still not low, a more effective battery balancing method needs to be found; (2) more suitable battery balancing circuits can be found; (3) the effects of battery aging on the battery balancing strategy should be considered.

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