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Improving temperature uniformity of a lithium-ion battery by intermittent heating method in cold climate

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ABSTRACT

The charge-discharge performances of lithium-ion batteries in hybrid electric vehicles (HEVs) and pure electric vehicles (EVs) decline rapidly at low temperatures. Many heating methods have been proposed to improve low-temperature performance, but these heating methods require long heating time and lithium-ion batteries at the end of heating have poor temperature uniformity. Recently, a self-heating lithium-ion battery (SHLB) has been proposed to recover charge-discharge performances of lithium-ion batteries at low temperature in short time. However, temperature uniformity of a lithium-ion battery heated by SHLB is also poor. A three-dimension heating finite element model is established in this work to analyze temperature gradient of a lithium-ion battery heated by SHLB heating method in detail, and intermittent SHLB heating method is proposed. For the intermittent SHLB heating method, a lithium-ion battery is heated for some time and stopped heating for some time instead of continuing heating. Through simulation analysis and comparison, heating for 0.1 s and stopping heating for 0.3 s is proposed to decrease the temperature gradient, and temperature difference is decreased from 10–11 K to 2–3 K.

1. Introduction

Lithium-ion batteries are taken as the dominant power batteries used in hybrid electric vehicles (HEVs) and pure electric vehicles (EVs) because lithium-ion batteries have advantages of the high energy density, power density, low self-discharge rate, and long cycling life. However, in cold environment, the charge-discharge performances of lithium-ion batteries decline significantly [1–5]. Lei and coworkers [6–8] conducted a series of experiments on the 35 Ah lithium manganate battery about the charge-discharge performances at various cold temperatures. Experimental results showed that the charge-discharge performances of lithium-ion batteries dropped substantially (under 263 K, the battery could only be charged to 60.23% of its rated capacity at 10 A, and under 233 K, only 22% of rated capacity could only be discharged at 10A), and internal resistances significantly increased. Fig. 1 showed discharge curves of the 35 Ah lithium manganate battery that discharged at 2C rate at various low temperatures. With decreasing temperature, the discharge volt and discharge capacity decreased rapidly. Many researches show that it is very difficult to improve the charge-discharge performances of lithium-ion batteries in cold climates through innovations in lithium-ion batteries' materials. Because the low-temperature and high-temperature performances of lithium-ion batteries are contradictory. In other words, as the low-temperature performance of lithium-ion batteries is improved by changing batteries' materials, the high-temperature performance of lithium-ion batteries will be declined. Therefore, many preheat methods to heat lithium-ion batteries in cold climates have been developed.

Preheat methods of lithium-ion batteries mainly include external heating and internal heating. The external heating methods are first to be applied on the thermal management of power batteries, and they are relatively easy to implement. Hallaj and Selman [9] suggested the stored heat in PCM could be used to keep warm lithium-ion batteries in cold weather. Alaoui and Salameh [10] proposed a Peltier-effect thermal management system, and applied the Peltier-effect on thermal management system of lithium-ion batteries. Lei and coworkers [11–14] developed the wide-line metal film method (WLMF) for heating prismatic lithium-ion batteries. A series of experiments on heating lithium-ion batteries by the WLMF heating method at various cold temperatures were conducted. The low-temperature charge-discharge performances of lithium-ion batteries could be improved in a short time, and heating time mainly depended on heating power and environment

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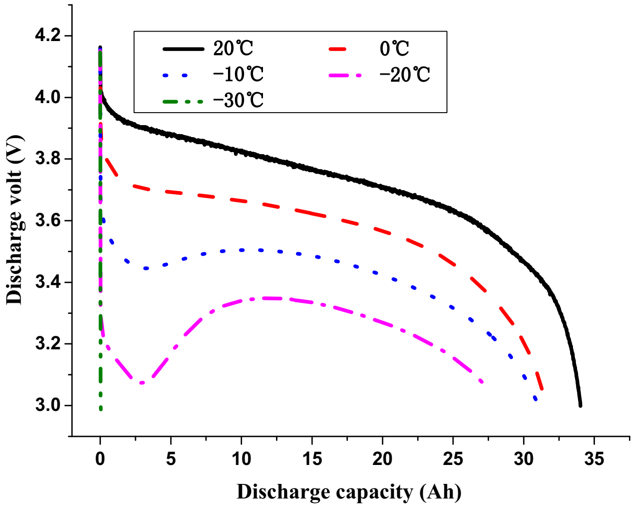

Fig. 1. A lithium-ion battery discharged at 2C in various low temperatures.

temperature. The above three heating methods belong to external heating method.

For internal heating methods, there are two main types. The first type of internal heating method is the AC heating method. Hande and coworkers [15–18] proposed low- or high-frequency alternating current (AC) heating approaches. A series of experiments about heating lead acid and NiMH batteries by the two heating methods were conducted. The experimental results showed that it was possible to recover the performance of both lead acid and NiMH batteries heated by low- or high-frequency AC heating methods in several minutes at various cold temperatures. They also pointed out that the device of low frequency AC heating method was larger and heavier, and was attractive for stationary charging applications because of its low-cost. For the high frequency AC heating method, it was more suitable for on-board heating applications. Zhang et al. [19] developed a sinusoidal alternating current (AC) heating method. A 18650 battery was heated with an amplitude of 7 A (2.25 C) and a frequency of 1 Hz sinusoidal AC at 253.15 K; the cell was heated from 253.15 K to 278.15 K in 15 min and the temperature uniformity of the cell was good. The second type of internal heating method is embedding the heating elements inside the battery. Wang's group [20–21] established a self-heating lithium-ion battery structure. A nickel foil heating element was embedded in the middle of a lithium-ion battery thickness. In the extreme cold condition, the self-heating lithium-ion battery can still be charge fast. Zhang et al. [22] analyzed temperature uniformity of a self-heating lithium-ion battery structure with a nickel foil heating element, and proposed a new self-heating lithium-ion battery structure with two nickel foil heating elements at one fourth and three fourths of cell thickness. They experimentally demonstrated that the new self-heating lithium-ion battery structure could achieve more uniform internal temperature distribution. Yang et al. [23] discovered that temperature gradient of the self-heating lithium-ion battery structure with two nickel foil heating elements led to highly non-uniform current distribution, and presented a self-heating lithium-ion battery structure with several nickel foil heating elements.

For the external and internal heating methods, some researchers compared them. Vlahinos and Pesaran [24] compared internal core heating, internal electric heating, internal fluid heating, external electric heating, and external fluid heating by the required energy and time. They concluded that internal core heating with the highest energy efficiency required least heating time, and the temperature uniformity of the heated batteries was best. Ji and Wang [25] employed an electrochemical-thermal coupled model to simulate the lithium-ion batteries that were heated by different heating strategies at various low temperatures. Different heating strategies were evaluated by four criteria of energy consumption, heating time, system durability, and system cost.

Although the charge-discharge performances of lithium-ion batteries can be recovered by above preheat methods in the extreme cold condition, large temperature gradient appears inside the lithium-ion battery. Temperature uniformities of a lithium-ion battery heated by low- or high-frequency AC heating methods are good. However, it takes more time to recover charge-discharge performances of lithium-ion batteries by the two heating methods than by some heating methods, and it requires a device to produce the low- or high-frequency AC. So low- or high-frequency AC heating methods are not best choice. Except for AC heating method, temperature gradient of a lithium-ion battery heated by self-heating lithium-ion battery structure (SHLB) heating method is relatively small, because heating elements are embedded in the lithium-ion battery. However, for SHLB heating method with two nickel foil heating elements, temperature uniformity in a lithium-ion battery is still poor in the process of heating. Although Yang et al. [23] pointed out that the temperature uniformity of a lithium-ion battery could be improved by increasing the nickel foil heating elements, there is the safety issue by embedding more nickel foil heating elements into a lithium-ion battery. Two nickel foil heating elements are enough to make structure of a lithium-ion battery become complicated. In this work, the temperature uniformity of a lithium-ion battery is improved by intermittent SHLB heating method instead of increasing nickel foil heating elements.

2. Problem statement

In general, there is temperature gradient inside a heated lithium-ion battery in cold climates. Temperature gradient is caused by heat transfer in the thickness direction in the process of heating. Therefore, it is almost impossible to completely eliminate temperature gradient during heating if heating methods generate heat from extra heating elements instead of lithium-ion battery's electrochemical reactions. For lithium-ion batteries, the heat from electrochemical reactions is little for tiny cell internal resistance, and it is difficult to recover charge-discharge performances of a lithium-ion battery in a short time. Recently, SHLB heating method presented in [20–22] could improve the low-temperature performance of a lithium-ion battery in a short time. Temperature distribution of a lithium-ion battery heated by SHLB heating method is more uniform than that using other external heating methods. However, temperature uniformity in the process of heating still need to be improved. Obviously, for SHLB heating method, temperature uniformity can be improve by increasing nickel foil heating elements in a lithium-ion battery. But the structure of a lithium-ion battery will become complicated, and the safety of lithium-ion batteries will be reduced. Therefore, in this work, the three-dimension transient heating finite element model of SHLB heating method is established, and temperature gradient of a lithium-ion battery heated by SHLB heating method by the transient heating model is analyzed. The intermittent SHLB heating method is presented to improve temperature uniformity of a lithium-ion battery in the process of heating.

For the intermittent SHLB heating method, a lithium-ion battery is heated intermittently instead of continuing to be heated for a long time. In other words, during heating, as temperature gradient inside the lithium-ion battery begins to increase, heating will be stopped for a while. Meanwhile, the appropriate heating time and stopping heating time are presented. In this study, the