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Abstract: Battery consistency is an important factor for battery pack performance. Excellent battery consistency can make battery packs more energy efficient and electric vehicles can have longer mileage and higher safety. Thus, in this study a comprehensive intelligent clustering methodology for the design of Li-ion battery pack on the basis of uniformity and equalization criteria of the cell was proposed. Firstly, multiple parameters (capacity, voltage, temperature and resistance) test of single cell performance was performed. Secondly, a clustering method combine with self-organizing map neural network (SOM) was proposed. Furthermore, a validation experiment (pack level) was carried out to verify the accuracy of proposed clustering algorithm. It can be concluded that the battery pack formed from SOM sorting results perform better than the battery pack having random cells combination as well as the pack originally purchased from the manufacturer.

Keywords: Battery pack imbalance; Electric vehicles; Electrochemical performance; Clustering analysis

1. Introduction

With the deterioration of global warming and other environmental problems, more and more attention has been paid to the use of new energy sources. The electric vehicle (EV) industry based on lithium-ion battery has developed rapidly [1]. However, electric vehicles still face many challenges in the actual application. For example, short mileage, frequent safety problems and high cost etc. [2]. The main reasons for these problems include the limited energy density of single lithium battery, the shortage of metal materials such as lithium and cobalt, and the inconsistency of lithium-ion battery

etc[3]–[5]. Therefore, improving the consistency of lithium-ion batteries in battery pack is one of the effective ways to improve the performance of battery pack used in EV. Researchers have carried out a series of research work for this objective. Lee et al. [6] proposed an active cell-to-cell balancing circuit for lithium-ion batteries during the using of EV. According to their experiment results, the power-transfer efficiency can achieve 80.4% at an equalization power of 0.78 W when under a static condition. The disadvantage of this method is that complicated control procedures. Although there is a passive balance method which procedure is more simplify for battery equalization, the lower capacity is available[7].

Therefore, to maximize the utilization efficiency of battery pack capacity i.e. improving the original consistency of lithium ion battery, applied impactful clustering for lithium ion batteries before forming a new battery pack is necessary. Kim et al.[8] have done experimented to investigate the effectively ways of clustering new lithium-ion battery. Discharge capacity screening and resistance screening are put forward and the value of test parameters are obtained through few test steps. The disadvantage of their method is that the sorting parameters are carried out one by one and the final clustering results were relying on the operator. For the purpose of combing more clustering parameters and higher accuracy, some modern intelligent clustering methods have sprung up and applied [9-10]. However, the validation results are both obtained from simulation. In addition, a self-organizing map algorithm combine with actual test experiment was presented by He et al.[11]. Nevertheless, the clustering parameters only include temperature and capacity. Meanwhile, the design of validation test was not considered in accordance with the actual application.

Therefore, an extraordinary research method for the design of Li-ion battery pack on the basis of uniformity and equalization criteria of the cell was proposed. A multiple parameter (capacity, voltage, temperature and resistance) of single cell performance test was performed firstly. Then self-organizing map was applied to execute clustering. Furthermore, a validation experiment (pack level) was carried out to verify the accuracy of proposed clustering algorithm.

2. Research problem statement

Lithium-ion battery inconsistency is a mainly influencing factor of battery pack performance. The difference of capacity, temperature and resistance of each single cell will result in batteries inconsistency of battery pack. In this case, three problems will be carried out on battery packs used in the electric vehicle: 1) The utilization efficiency of battery pack capacity will be reduced. 2) The life cycle of battery pack will be shorter. 3) Thermal runaway and safety problem are possible to arise because of the big temperature difference between different modules and cells. Thus, to avoid the safety problem and extend the life cycle of battery pack as well as higher electrochemical performance, an intelligent comprehensive methodology was proposed in this study. Firstly, the inconsistency between different 48 cells is measured. Secondly, the battery clustering process was performed with SOM neural network. Thirdly, a validation experiment was designed and executed.

3. A comprehensive experimental and analysis methodology

3.1 Design of experimental method

To validate the advantage and accuracy of clustering method used in this study, a comprehensive methodology combine experiment and analysis was performed as follows:
Stage I: Single cells performance test
Five original battery packs which manufactured by the company are used in this process. Battery pack A to D were dismantled to 48 cells. To get the knowledge of the single cell performance, battery charging and discharging test process was applied based on neware battery test system.
Stage II: Self-organizing Map (SOM) clustering process
After obtaining the test data of each single cell, the Self-organizing Map (SOM) was performed base on the experiment results. Clustering parameters include capacity, voltage, battery surface temperature and resistance.

Stage III: New battery pack assembling process and pack contrastive experiment
Two new packs will assemble according to the SOM clustering results. One consist of cells which have similar performance while another one is composed of randomly selected cells. A contrastive experiment will execute between two newly formed packs and pack E (Pack E is original from the manufacturing company).

3.2. Experiment process

3.2.1. Single cell test process. As shown in figure 1, battery pack A to E will be dismantled first. Discharging procedure will apply to each battery pack in case of safety problem. The most time-consuming part during the whole disassembling process is removing the connections (the material is nickel) between each cell. Secondly, single cell test based on neware battery system will perform. Parameters used for testing include single cell charging and discharging voltage, average capacity, surface temperature and battery internal resistance. In addition, the battery test procedures are composed of charging and discharging processes. Testing cycle number of each cell is twenty. Experiment results which include charging and discharging process are shown in figure 2. It can conclude that the inconsistency phenomenon exists between batteries even though they came from the same battery pack.

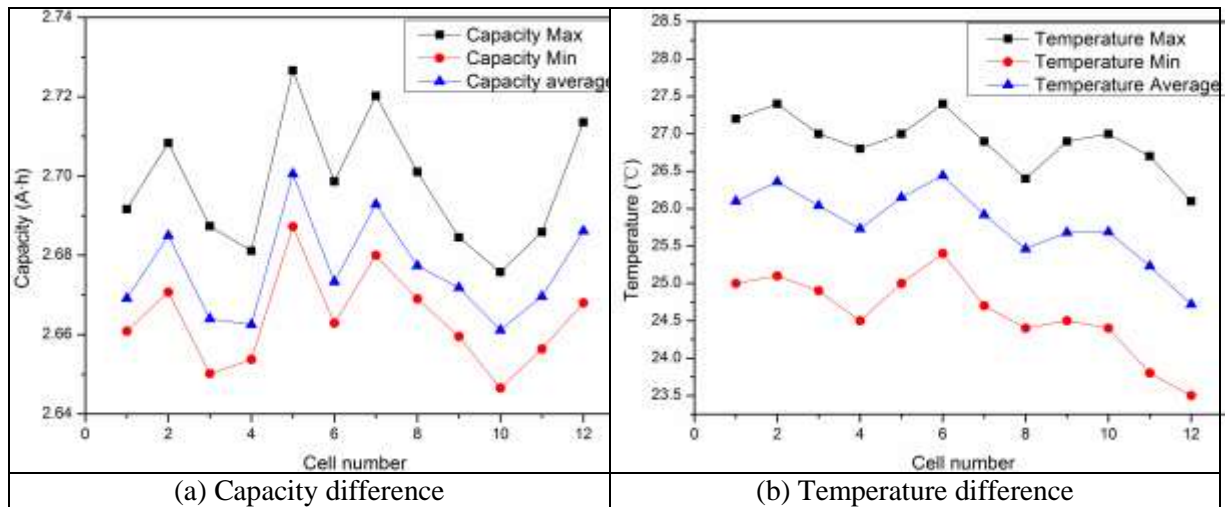**Figure 1.** Battery pack dismantling and single cell test process

| (a) Capacity difference | (b) Temperature difference |

Figure 2. Capacity and temperature inconsitancy of batteries from same pack

3.2.2. SOM clustering process. Based on the data obtained from the experiment, self-organizing map clustering algorithm was used to sorting cells with similar performance. Self-organizing map is utilized for data visualization which explores the properties of the data set [12], [13]. It is a type of artificial neural network also called Self-Organizing Maps (SOM) was developed by Tuevo Kohonen in 1982[14]. Considering the cells number of original battery pack and the number of cells to be sorted (which is 12 and 48 respectively), cluster number was set from one to four. Thus, the range of values of sorting dimensions i.e. topological height and topological width is between one and two. Clustering parameters used in this study are four test parameters mentioned above. Eighty percent of experiment data are used for training and the cycles number of training is 1000. The remaining data is used for testing and validating the training results. Furthermore, the range value of learning rates and neighbourhoods are between 0.1 to 0.02 and 3 to 0. All the clustering process was executed on STATISTIC 12. The clustering results are shown in table 1.

Table 1. Clustering results of experiment data

Clustering parameters: Capacity, temperature, voltage and resistance		
Clustering	Groups of cells with similar performance	Cell Number
1st cluster	1	1,2,3,4,8,10,11,12,13,15,25,27,29,30,31
	2	16,17,19,21,26,28,32,33,34,36,38,39,40,41,42,43,44,45
2nd Cluster	1	1,2,3,4,8,10,11,12,13,15,25,27,29,30,31
	2	17,19,21,26,32,33,36,39,40,41,42,43,44
	3	16,28,34,38,45
3rd Cluster	1	1,2,3,4,8,11,12
	2	10,13,15,25,27,29,30,31
	3	16,28,34,38,39,45
	4	17,19,21,26,32,33,36,40,41,42,43,44
4th Cluster	1	10,25,27,29,30,31
	2	2,4,11,12,13,15
	3	1,3,8
	4	17,19,21,26,32,33,36,40,41,42,43,44
	5	16,28,34,38,39,45

Figure 3. Battery pack forming process and performance test

3.2.3 Battery pack forming process and battery pack performance test. In this section, two new packs will be formed according to the clustering results in table 1. The twelve cells of battery pack three are selected from similar performance screening group, which number are 17,19,21,26,32,33,36,40,41,42,43 and 44. On the contrary, the battery pack two was comprised by another twelve randomly chosen batteries. Battery pack forming process was performed before battery pack test, which is shown in figure 3. The material used in forming process include lithium-ion battery welding machine, lithium battery pack charging and discharging protection plate, nickel sheet, battery plastic clamps and lithium-ion batteries (see figure 3-1). The welding process generally took around half an hour. Battery pack performance test will carry out for three packs after forming process finished (see figure 3- 6&7). Battery pack one was from the manufacturing company, pack two and three are formed based on the clustering results. During the test process, the three battery packs will experience charging and discharging process for 20 cycles. Battery performance comparison experimental parameters include temperature and capacity. The data of temperature of the battery pack are collected by six temperature sensors, which are located in different places of battery pack. Thus, the data used for battery pack performance comparison is the average value of temperature obtained from six temperature sensors. While the capacity was recorded automatically by test system due to that the experiment was based on the Neware battery pack test machine. Experiment results are shown in the next section.

4. Experiment results discussion
In this section, the test results of validation experiment are shown in table 2. The temperature performance and capacity of battery pack will consider as two characteristic parameters of battery pack performance. According to results obtained from the experiment, the lowest capacity pack was pack two and the highest one was pack three. The reason is that the cells were screened first by the manufacturing company before forming a battery pack. Thus, the temperature performance is considered as the main influencing factor in this study. In figure 4, the temperature performance of three battery packs are exhibited. The figure of each battery pack was generated based on the data obtained from six temperature sensors. From the results of battery pack one, it can be seen that highest temperature is generated from position 1 and 6, which was recorded by temperature corresponding sensor 1 and 6. While for battery pack two, the temperature of sensor 4 and 5 are highest. Additionally, the highest temperature of battery pack three was original from sensor 3 and sensor 4. Moreover, the range of temperature fluctuation of each battery pack at different positions are different. The reason for the phenomenon mentioned above include that: a) the surface temperature of each single cell was different. b) the current value at the position which near the charging and discharging protection board

was higher than other place because of the connection ways between each cell. c) the different stage of charging and discharging process of each cell which caused by the inconsistency of batteries. Therefore, to investigate the temperature performance difference, the average temperature value of battery pack at different positions was used for comparison parameter (see figure 4-d). It can be seen that highest value of temperature data of pack one to three were 41.5 ℃ , 38.2 ℃, and 36.4 ℃, respectively. In addition, it was obvious that the temperature changing range of pack three was the smallest. The reason is that the consistency of batteries of pack three was the best among three packs. This can validate that the clustering algorithm used in this study can contribute to lithium-ion battery clustering and forming battery pack with higher performance.

Table 2. Battery pack capacity test results

Parameters	Pack one	Pack two	Pack three
Highest value of capacity (Ah)	10.79	10.61	10.79
Lowest value of capacity (Ah)	10.7	10.28	10.71
Average value of capacity (Ah)	10.738	10.5335	10.744

(a) Temperature data of battery pack 1   (b) Temperature data of battery pack 2

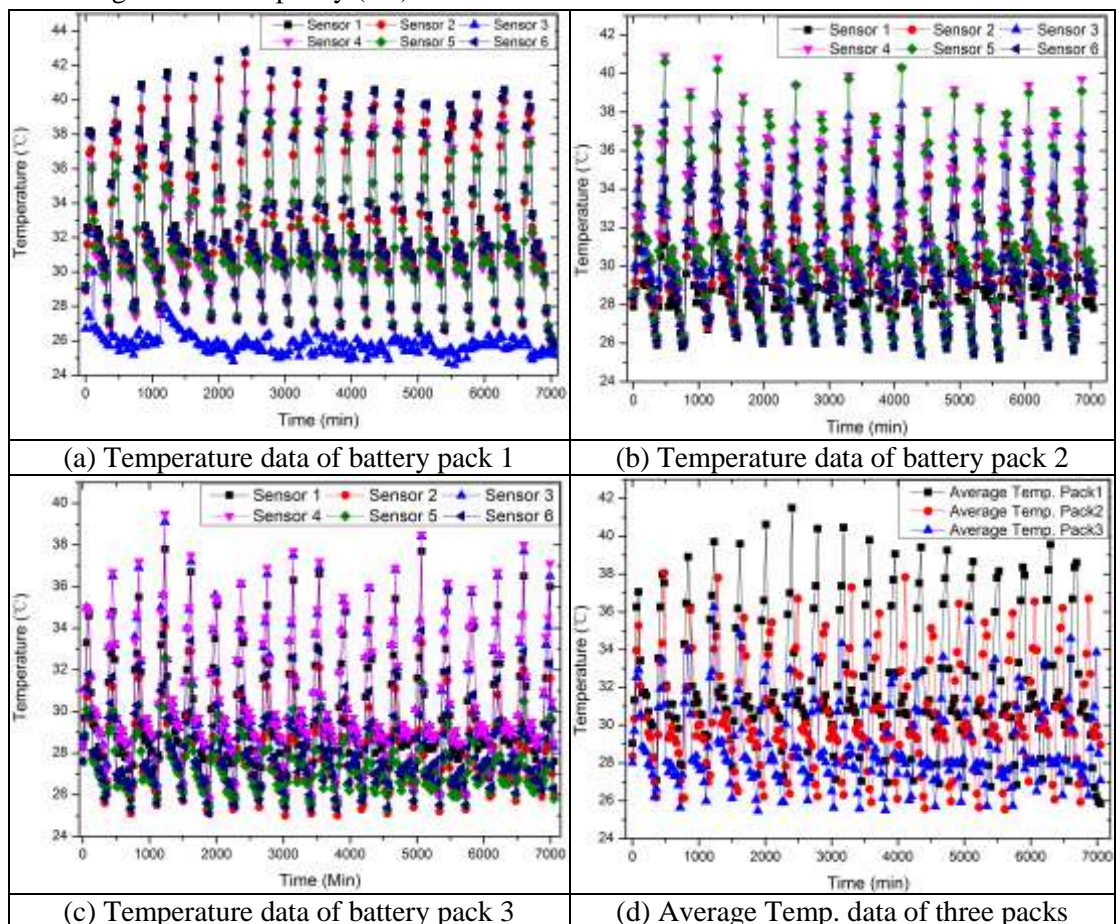(c) Temperature data of battery pack 3   (d) Average Temp. data of three packs

Figure 4. Battery pack temperature performance test results and comparison

5. Conclusion

The present work highlighted the research problem on uniformity and equalization of Li-ion cells used in a battery pack for electric vehicles. To counter this problem, thiswork proposed a comprehensive methodology for the design of Li-ion battery pack on the basis of uniformity and equalization criteria of the cell. To measure the non-uniform behavior of cells, the charging-discharging tests on forty-eight

cells were performed. SOM was then applied on the collected data to enhance the results of battery screening process. Based on the experimental results, the following are the conclusions:

a) The temperature distribution inside the battery pack varies, the maximum difference can reach 7 degrees Celsius.
b) The effective battery sorting process can improve the utilized capacity of battery pack.
c) The proposed battery screening method can enhance the consistency of temperature distribution inside the battery pack, which highest temperature was 4-5 degrees Celsius lower than the other packs. In addition, the temperature floating range was 2.6 degrees Celsius lower.

Acknowledgement

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