Sorting method of lithium-ion batteries in mass production

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Abstract. To improve the level classification accuracy of the method used in the lithium-ion battery production lines, the sorting method suitable for mass production lines is studied. Based on the developed single-cell battery detection system, this paper proposed a method that combines multi-parameter sorting and fuzzy C-means clustering to realize level classification of single-cell batteries. A cycle life test was designed for comparison and verification to perform random packing, OCV and internal resistance sorting packing, multi-parameter sorting and fuzzy C-means clustering combined packing experiments. The experiment results show that the classification method combining multi-parameter sorting and fuzzy C-means clustering can improve the consistency of the batteries after grouping, and further prove that the cycle lifetimes of the battery packs increase.

1. Introduction

In the conventional use of lithium-ion batteries as power batteries, single cell generally cannot meet the actual high-power and high-capacity requirements. A common approach is to combine multiple batteries to form a battery pack. The consistency of batteries directly or indirectly affects the power and capacity of the pack¹. In order to fundamentally solve the problem of lithium-ion battery consistency, it is necessary to improve the battery structural performance and production process which require huge investment in time and cost. Considering the development cycle and cost comprehensively, under the conditions of the existing battery production process, select a suitable sorting method to accurately classify is a practical method to improve battery consistency². At present, due to cost and production efficiency limitations, most battery production lines use the static parameter method. The advantages of this method are simple principle and high sorting efficiency. However, because only the external static parameters are considered, the difference in battery dynamic characteristics are ignored in which case its sorting accuracy is limited³. With the improvement of the classification accuracy requirements brought by the upgrade of the lithium-ion battery industry, the difference in the dynamic characteristics has gradually become a factor that cannot be ignored. The charging and discharging curve of sorting reflects the parameter changes in the dynamic process, which can make up for the shortcomings of the static parameter sorting method. With the improvement of the computing capacity of the battery production line detection management system, it gradually makes the application of sorting algorithms possible, and scholars also explored and studied this. Yu Zhilong⁴ used capacity, AC resistance, and self-discharge current as input parameters of the battery classification model, and adopted fuzzy c-means clustering analysis and support vector machine to classify and identify batteries based on a cross-validation algorithm. Ran Li⁵ proposed a multi-step FCM algorithm for silver-zinc battery separation in order to solve the consistency problem of...
silver-zinc batteries after grouping. Based on the fuzzy clustering algorithm, this paper combines the battery open circuit voltage (OCV) and internal resistance parameters with the charge and discharge curves to improve the multi-parameter battery sorting method. The overall design of the detection system that implements the algorithm is adopted, and the SOH index is used to evaluate battery performance and sorting effects.

2. **Single-cell power battery detection system**

The single-cell power battery detection system is composed of a host computer and a local controller. The host computer is realized by industrial computer, which mainly provides display interface and human-machine interaction interface for the field operators of the battery production line to complete the analysis and processing of data collected by the tester. The local controller receives commands from the host computer, executes tasks assigned from the host computer, and implements control of the underlying equipment. The overall design of the system is shown in figure 1.

2.1 The local controller

The lithium-ion battery performance detection system uses a PLC-based local control scheme. The main components are as follows: firstly, use Mitsubishi Q13 UDEH as the main controller and interact with the host computer through a network cable, and then get a decision plan to drive the corresponding actuator; Mitsubishi Q13 UDEH communicates with the code scanner through the serial port to obtain the corresponding tray information and the binding information of the battery; receives photoelectric sensor signals through I/O ports to drive actuators such as cylinders, motors, etc.; interacts with the touch screen through the network port to obtain the real-time status of production line, or use the touch screen to control specific control points; receive feedbacks from the field through the human-machine interface and drive operation instructions to coordinate the corresponding actuators. At the same time, select Mitsubishi GS touch screen as the operation interface for users to perform some routine operations, and realize real-time monitoring recording of status and fault diagnosis conveniently. Finally select HIOKI BT3562 and Agilent 34980A tester to complete the battery performance parameter data collection of the test system.

2.2 The host computer

The host computer software is a platform for interaction with operators that manages each charge and discharge channel and coordinates the operation of the entire system. The main functions include: collecting the battery performance parameters generated by the detection device in real time and recording them in the database; analyzing, comparing and classifying the battery characteristic parameters; and displaying the classification results on the tray at the sorting station.

3. **Research on battery sorting method based on fuzzy clustering algorithm and multi-parameter sorting**

A battery is a system affected by multiple elements. To comprehensively reflect the performance of the battery, it is necessary to combine the dynamic and static characteristics of the battery. This paper combines the dynamic characteristic parameters (charge and discharge curves) that reflect the performance of the battery with important static parameters (open circuit voltage and internal resistance) that affect the battery performance. The fuzzy C-mean (FCM) algorithm and multi-parameter combination sorting method are used to perform battery classification. On the
lithium-ion battery production line, 110 lithium battery samples were selected for classification, and a full-life experimental verification was designed for the classification results. According to the classification results, the batteries are grouped, and the cycle life of the battery packs obtained by different sorting methods is tested to prove the effectiveness of the above sorting methods.

3.1 Algorithm Overview
Compared with the ordinary C-means algorithm, the FCM clustering algorithm is a classification algorithm for flexible fuzzy partitioning of data. The idea of the FCM clustering algorithm is: first manually assign the membership degree of each data to each cluster randomly, then calculate the centroid of each cluster according to the membership degree, and then re-divide until the set objective function is less than the set threshold (The iteration termination threshold affects the clustering accuracy slightly, and the default value is generally 1e-5), end the loop, and the division result is finally obtained.

Let U be a \( c \times n \) matrix, and the membership degree of the internal elements \( u_{ij} \) represents the membership degree of the j-th cell to be classified as the i-th class. Since the total membership of a particular battery sample of each cluster is equal to 1, the constraint condition shown in equation (3-1) must be satisfied.

\[
\sum_{i=1}^{c} u_{ij} = 1, \forall j = 1, ..., n
\]  

The objective function of the algorithm follows the "minimum sum of squared weighted errors within a class" criterion and is defined as:

\[
J(U, C) = \sum_{i=1}^{c} \sum_{j=1}^{n} \mu_{ij} m d_{ij}^2, m \geq 1
\]  

Among them, \( c_i \) represents the algorithm to calculate the cluster center of the i-th sample data of \( u_{ij} \), and \( d_{ij}^2 = ||x_i - c_i||^2 \) represents the Euclidean distance between the cluster centers of two types of samples i and j.

In order to optimize the objective function of equation (2), consider the Lagrange multiplier \( \lambda \) as the weight, and the improved objective function is defined as:

\[
F = \sum_{i=1}^{c} \mu_{ij}^m d_{ij}^2 + \lambda \left( \sum_{i=1}^{c} \mu_{ij} - 1 \right)
\]

Among them, \( \lambda \) is the Lagrangian multiplier. The objective function of minimization improvement is shown in equations (4) ~ (6):

\[
\frac{\partial F}{\partial \lambda} = \left( \sum_{i=1}^{c} \mu_{ij} - 1 \right) = 0
\]

\[
\frac{\partial F}{\partial \mu_{ij}} = [m(\mu_{ij})^{m-1}d_{ij}^2 - \lambda] = 0
\]

\[
\frac{\partial F}{\partial c_i} = \left( \sum_{j=1}^{n} (\mu_{ij})^m x_j - \sum_{j=1}^{n} (\mu_{ij})^m \right) = 0
\]

Solving the above optimization conditions can obtain the necessary conditions for the minimum value of equation (2), such as equations (7) and (8):

\[
u_{ij} = \frac{1}{\sum_{k=1}^{c} \mu_{kj}^m d_{kj}^2}
\]

\[
c_i = \frac{\sum_{j=1}^{n} \mu_{ij}^m x_j}{\sum_{j=1}^{n} \mu_{ij}^m}
\]

3.2 Selection of charge and discharge rate
To choose appropriate charge and discharge rate for our experiment, the difference between charge and discharge curves of the single-cell battery at different rates should be analyzed. As figure 2 illustrates,
with the increase of the current rate, the smaller the single-cell voltage platform is, the faster the capacity decays and the greater the difference in battery performance is. Thus, choose the charge and discharge curve of the single-cell under the maximum working rate of the battery pack, to be the dynamic performance parameter of the battery classification.

![Figure 2. Discharging curves at different rates.](image)

18 battery samples are randomly selected, and charge and discharge experiments are performed at the rate of 0.2C and 1C separately. As is shown in the figure 3 and figure 4, the charge and discharge curve clusters of the battery are respectively obtained.

![Figure 3. Charging and discharging curves at 0.2C rate.](image)  ![Figure 4. Charging and discharging curves at 1C rate.](image)

Observing from the figures, the change in the difference of charge and discharge curves of the lithium-ion battery increases with the increase of the current rate. The paper selects charge and discharge curves at 1C rate to be the sorting basis for batteries.

3.3 Acquisition of sorted samples
100 battery samples of the same batch are taken as samples 1 to 100, and 90 batteries are randomly selected as samples 1 to 90 for sorting experiments. The remaining 10 batteries are taken as samples 91 to 100 for controlled trials. Taking another 10 batteries of the same batch without any sorting as blank control. The method of sampling the charge and discharge curve of a single-cell battery every 30 seconds is applied to these experiments. The eigenvector of a single-cell lithium-ion battery’s characteristics is a complete cycle of sampled data. The eigenvectors of all batteries in the experiment are the battery sample set matrix.

3.4 Data processing and algorithm implementation
Select 90 battery cells from samples and sample charge and discharge curves of the cells every 30 seconds. The sample points collected by each battery constitute the eigenvector of batteries. The
matrix composed of 90 batteries’ eigenvectors is taken as the input data set of the algorithm. Further determine the number of clusters 9, fuzzy factors ($m=2$) and set the iteration termination threshold ($1e^{-5}$). The classification results are finally obtained by a computer program. The specific implementation process is shown in figure 5.

3.5 Experiment results and analysis
The sorted lithium-ion batteries are connected in parallel to form battery packs to perform a cycle life test experiment. The experiment obeys the following charging and discharging rules: constant-current charging at a 0.5C rate, the cut-off voltage is 4.2V; constant-voltage charging maintained at 4.2V, the cut-off current is 20mA; let stand for 30 minutes; then constant-current discharging at a 0.5C rate, the cut-off voltage is 3.6V; let stand for 30 minutes; the charging and discharging are repeated until the capacity drops to 1600 mAh.

Illustrated by the figure 6, among battery packs 1 to 4, battery pack 1 and 2 can still maintain a health of more than 90% at the 500th cycle. It indicates that among three classification results, the first two that made up by corresponding single-cell batteries sorted by FCM algorithm, have good consistency.

The fourth pack that is assembled randomly, after around 400 cycles, its SOH index dropped to 80%, which shows that the consistency of battery samples in this pack is bad. In addition, unlike battery packs 1, 2, and 3, battery pack 4 is randomly packed, in which case it can be observed that its cycle life is lower than the other three packs. This group of experiments proves that with the sorting method, the decline trend of packs’ cycle life decaying rate is effectively suppressed and the consistency is higher than battery packs without any sorting method. The sorted packs cycle more, and the consistency of packs sorted by FCM combined with multi-parameter is greater than that sorted by OCV and internal resistance.
4. Conclusion
Based on the developed single-cell battery detection system, this paper proposed a method that combines multi-parameter sorting and fuzzy C-means clustering to realize level classification of single-cell batteries.
A cycle life test was designed for comparison and verification to perform random packing, OCV and internal resistance sorting packing, multi-parameter sorting and fuzzy C-means clustering combined packing experiments. The experiment results show that after the 500th cycle, after the combination of multi-parameter sorting and fuzzy C-means clustering, the battery pack can still maintain more than 90% health; after OCV and internal resistance sorting, the SOH index is less than 90%; and for randomly assembled battery packs, the SOH index drops to 80% after about 400 cycles.
The experiment results show that the classification method combining multi-parameter sorting and fuzzy C-means clustering can improve the cycle life of battery packs, and further prove that the consistency of battery packs improves.

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