Investigation on Early-stage Internal Short Circuit Identification for Power Battery Pack

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***Abstract*—The spontaneous internal short circuit is a very important way for the thermal runaway of lithium-ion battery. Identification of the internal short circuit accurately and in time during the working process is critical for the safety of lithium-ion battery. In this study, a modified algorithm for the early-stage internal short circuit identification is investigated. This method is based on the mean-difference model and the recursive least square algorithm. An equivalent experiment is setup to validate the feasibility of this method for the identification of early-stage internal short circuit. The results indicate that this method can identify the internal short circuit only when the SOC is very low. For ordinary operation conditions of the power battery pack, this method is not suitable for early-stage internal short circuit identification.**

Keywords—lithium-ion battery; internal short circuit; identification algorithm; mean-difference model; early stage

I. INTRODUCTION

Energy conservation and environment protection are two critical tasks for the society development. With the progress of energy storage technology and the development of renewable energy, electricity becomes cleaner, convenient, and economic, which is benefical for the applications of electric vehicles. Lithium-ion battery is a key component in an electric vehicle. To date, its safety problem caused by thermal runaway still needs to be solved [1, 2].

Thermal runaway of lithium-ion battery may be caused by mechanical, electrical, or thermal abuse [3]. When the internal short circuit occurs, an electrical path is formed between the positive and negative parts of the battery, which is a typical type of thermal runaway. For a lithium-ion battery with Ni-rich cathode, the chemical crosstalk between the positive and negative electrodes also can cause thermal runaway [4]. The generation of spontaneous internal short circuits normally has no clear external manifestation at the early stage. Some self-induced events of the internal short circuit take a long time (hundreds of hours) to develop and finally reach to thermal runaway in a short time, some others may only cause an increase of the self-discharge rate and a decrease of the battery capacity during the battery life cycle. Generally, the internal short circuits can be classified into four categories [5].

Internal short circuits can take place under the practical vehicle operating conditions although many prevention and suppression measures are employed [6]. Therefore, some methods have been adopted to investigate the internal short circuit. The Japan Battery Association proposed a method, which disassembled a fully charged battery and placed a metal particle inside the battery. Subsequently, it was assembled again and the position was externally squeezed to induce an internal short circuit [7]. Keyser et al. invented a triggering device for the internal short circuit using a phase change material [8]. Zhang et al. used a memory alloy to trigger the internal short circuit which could be controlled by the temperature of the battery [9]. This method can control the type of the internal short circuit with a good repeatability. Feng et al. adopted the equivalent resistance method to simulate the internal short circuit [10].

The equivalent experiment uses an equivalent resistance connected to a cell in parallel and the electrical characteristics of the internal short circuit can be simulated. This method is used for the early-stage internal short circuit identification in this paper. The identification method is based on the mean-difference model and the recursive least square (RLS) algorithm. Based on the measured results, the feasibility of this identification method for early-stage internal short circuit of lithium-ion battery is investigated.

II. MEAN-DIFFERENCE MODEL AND RECURSIVE LEAST SQUARE ALGORITHM

The mean-difference model describes the difference in performance between all batteries and the averaged one. After that, ΔEi and ΔRi can be identified by the recursive least square (RLS) algorithm with a forgetting factor [11]. The RLS algorithm seeks an optimal estimation of the parameters based on the principle of minimizing the rooted mean squared errors between the measured and predicted data. The forgetting factor can increase the weight of new data and reduce the influence of old data, thus realizing a near real-time estimation of the tracking parameters. In this algorithm, ΔEi and ΔRi are the parameters needed to be identified.

III. Significance Calculation and Experimental Results

The parameter effect is the identified discrepancy caused by the internal short-circuit branch, leading to a decrease of the OCV or the internal resistance, the depleting effect is caused by self-discharge [11]. Self-discharge is an accumulation process, yielding a decrease of the OCV. However, the internal resistance may increase or decrease according to the SOC. This study uses two characteristic parameters(ΔE and fluc(ΔR)) to identify internal short circuits. The fluctuation value fluc(ΔR) of the internal resistance is obtained as the standard deviation of 150 continuous sampling points adjacent to the current moment.

The significance value of each cell for both of the characteristic parameters is determined based on the average value μ excluded extreme values and the standard deviation σ. The results of σ from the significance calculation indicate the degree of the maximum value of the characteristic parameter deviating from the average value μ. The positive and negative significances can be obtained by using a threshold of ±3 due to the 3 sigma principle. The significance calculation can be understood in such that the difference between the extreme value of the characteristic parameter and the mean μ is the offset by how many σ. It should be noted that when 80% of the 150 data points exceed the threshold and both characteristic parameters satisfy this condition at the same time, the internal short circuit is diagnosed.

When an internal short circuit occurs at the early stage, the internal short circuit resistance is large and the variations of the electrical characteristic parameters are small, making itself very difficult to be identified. The feasibility for the early-stage internal short circuit identification is investigated in this section. An external resistance of 1000 Ω is connected to Cell 1 in parallel and an equivalent experiment is performed. The results are shown in Fig.1.

Although the variation magnitudes of ΔEi and fluc(ΔRi) are very small, the modified identification method still can identify the inernal short circuit after a relative longer operation time at the end of the discharging process, wherein the SOC of the lithium-ion battery is close to 0. It takes 8h and 40min to identify the internal short circuit for the case of 1000 Ω. Because the internal short circuit resistance is large, the parameter effect and the depleting effect are much smaller. In addition, the maximum discharge rate of the DST cycle for this test is 1C. It is worth mentioning that the normal battery does not exhibit too much ΔE sudden drop and fluc(ΔR) fluctuation. After the internal short circuit occurs, the total resistance of the battery decreases, resulting in self-discharge and resistance fluctuation. At the same time, the internal short circuit will affect the internal polarization of the battery, especially the lithium-ion solid phase diffusion at the end of the discharge, resulting in abnormal ΔE sudden drop and fluc(ΔR) fluctuation. Therefore, according to the significance calculation result, a 1000Ω internal short circuit can be identified at this moment.

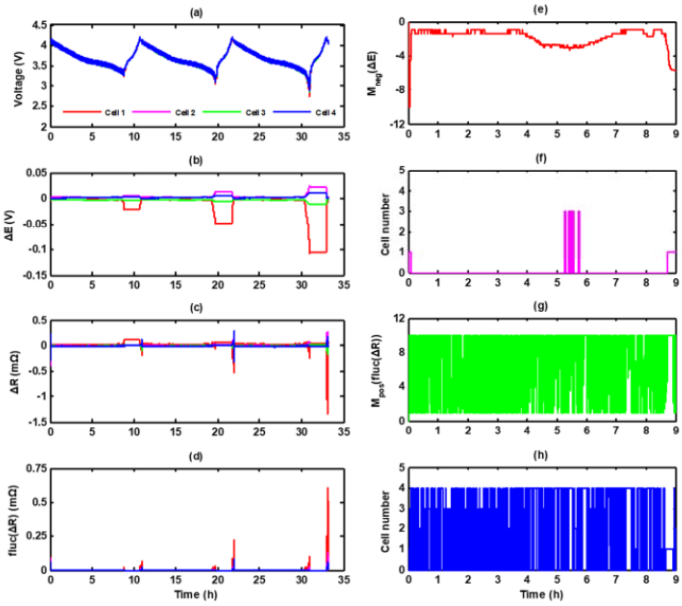

FIGURE I. Results for the early-stage short circuit identification with an external resistor of 1000 Ω: (a) the measured terminal voltage; (b) ΔE_i; (c) ΔR_i; (d) *fluc*(ΔR_i); (e) the negative significance of ΔE; (f) the relative cell number of $M_{neg}(\Delta E)$;(g) the positive significance of *fluc*(ΔR); (h) the relative cell number of M_{pos} (*fluc*(ΔR))

In this study, the internal short-circuit replacement experiment is employed. The resistance are connected directly to the positve and negative terminals outside of the battery cells. In fact, the internal short-circuit is mainly caused by lithium dendrites, production defects, and impurities of materials, which may increase the inconsistency of the battery, leading to the internal electrochemical reaction and the temperature variation of the battery. The variation of the OCV and the fluctuation of the internal resistance will be greater than the results of this equivalent experiments. Therefore, the detection time will be shorter in practical application.

As the battery degrades gradually, the cells begin to lose active material and the active interface areas of the electrodes decrease. The the internal resistance of the cell becomes larger and the cell is more sensitive to the current fluctuations. Accordingly, the variation of the OCV and the internal resistance are more significant. It will be easier to identify the internal short circuit based on the mean-difference model.

IV. Summary

The internal short circuit resistance is very large at the early stage of an internal short circuit event, which makes it very difficult to be identified. In this study, an equivalent resistance of 1000 Ω is used to simulate the internal short circuit at the early stage. The results indicate that the variations of the electrical characteristic parameters are much smaller and the internal short circuit cannot be detected when the SOC is high. Only when the SOC is close to 0, this identification method can identify the internal short circuit. In practice, the SOC of the lithium-ion battery normally situates between 0.25 and 0.8. It is not possible for this method to identify the early-stage internal short circuit of lithium-ion battery.

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REFERENCES

[1] Feng X, Ren D, Zhang S, He X, Wang L, Ouyang M. Influence of aging paths on the thermal runaway features of lithium-ion batteries in accelerating rate calorimetry tests, International Journal of Electrochemical Science. 14(2019)44-58.

[2] Bugryniec PJ, Davidson JN, Cumming DJ, Brown SF. Pursuing safer batteries: Thermal abuse of LiFePO4 cells, Journal of Power Sources. 414(2019)557-568.

[3] Yokoshima T, Mukoyama D, Maeda F, Osaka T, Takazawa K, Egusa S, Naoi S, Ishikura S, Yamamoto K. Direct observation of internal state of thermal runaway in lithium ion battery during nail-penetration test, Journal of Power Sources. 393(2018)67-74.

[4] Liu X, Ren D, Hsu H, Feng X, Xu G, Zhuang M, Gao H, et al. Thermal runaway of lithium-ion batteries without internal short circuit, Joule. 2(2018)2047-2064.

[5] Santhanagopalan S, Ramadass P, Zhang J. Analysis of internal short-circuit in a lithium ion cell, Journal of Power Sources. 194(2009)550–557.

[6] Lamb J, Orendorff CJ. Evaluation of mechanical abuse techniques in lithium-ion batteries, Journal of Power Sources. 247(2014)189-196.

[7] Zhang Z, Ramadass P, Fang W. Safety of lithium-ion batteries. In: Lithium-ion Batteries: Advances and Applications, Editor, Pistoia G. Amsterdam: Elsevier 2014: 409-435.

[8] Keyser M, Long D, Jung YS. Development of a novel test method for on-demand internal short circuit in a Li-ion cell. Advanced Automotive Battery Conference. Pasadena, 2011.

[9] Zhang M, Du J, Liu L, Stefanopoulou A, Siegel J, Lu L, He X, Xie X, Ouyang M. Internal short circuit trigger method for lithium-ion battery based on shape memory alloy, Journal of the Electrochemical Society.164(2017)3038-3044.

[10] Feng X, Pan Y, He X, Wang L, Ouyang M. Detecting the internal short circuit in large-format lithium-ion battery using model-based fault-diagnosis algorithm, Journal of Energy Storage. 18(2018)26-39.

[11] Ouyang M, Zhang M, Feng X, Lu L, Li J, He X, Zheng Y. Internal short circuit detection for battery pack using equivalent parameter and consistency method, Journal of Power Sources. 294(2015)272-283.