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On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 2. Fuzzy logic equalization

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HIGHLIGHTS

- We propose dissipative cell equalization (DCE) algorithm based fuzzy logic (FL).
- Cell capacities and SOCs are fuzzily identified in FL-DCE for battery pack.
- Pack capacity with FL-DCE is almost the same as DCE theoretical pack capacity.
- Adaptive FL-DCE algorithm is proposed to prevent over-equalization.
- Equalization capability of the adaptive FL-DCE algorithm is ample.

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ABSTRACT

In the first part of this work, we propose dissipative cell equalization (DCE) algorithm based on remaining charging capacity estimation (RCCE) and establish a pack model with 8 cells in series. The results show that RCCE-DCE algorithm is suitable for on-line equalization in electric vehicles (EVs) and no over-equalization happens. However, 1% pack capacity difference from the DCE theoretical pack capacity is observed with RCCE-DCE algorithm. Therefore, as the second part of the series, we propose fuzzy logic (FL) DCE algorithm based on charging cell voltage curves (CCVCs). Cell capacities and SOCs are fuzzily identified in FL-DCE algorithm by comparing cell voltages at the beginning and end of charging. Adaptive FL-DCE is further improved to prevent over-equalization and maintain the equalization capability. The simulation results show that pack capacity difference from the DCE theoretical pack capacity with the adaptive FL-DCE is smaller than that with RCCE-DCE algorithm, and the duration of the infant stage is also shorter. The proposed adaptive FL-DCE is suitable for on-line equalization in EVs and well prevents over-equalization.

1. Introduction

The inconsistency and safety issues of the battery pack system are the major problems for cells to be fully utilized. Because of the inconsistent manufacturing process, cells always have variations [1]. Cell variations enlarge due to the inhomogeneous operating environment [2]. As a consequence, power and capacity fade may occur and further result in safety issues. Cell screening process is necessary before pack construction. It diminishes cell inconsistency in the manufacturing process to some extent. Well-designed thermal management can also reduce cell inconsistency during operation. Nevertheless, on-line cell equalization is an effective means to prevent the enlargement of cell inconsistency.

In the first part of this work [3], we establish a battery pack system model to study cell variations and equalization methods. The model shows that even when the cells have good consistency, pack capacity falls significantly after several hundred cycles. And the preliminary result also shows that a capacity increase of only 2% can be achieved by non-dissipation cell equalization (NDCE) for packs with screened cell capacities. As a result, we prefer to use dissipative cell equalization (DCE) which is cheaper and easier to implement for on-line equalization. We discover and verify that remaining charging capacities (RCCs) can be on-line estimated based on the uniform charging cell voltage curve (CCVC) hypothesis [4]. As voltage- and SOC-based equalization algorithms (EAs) would suffer from over-equalization and cannot directly represent the ultimate purpose of the equalization, i.e. to maximize pack capacity, we propose DCE algorithm based on RCCE observer and prove later that RCCE-DCE algorithm is suitable for on-line equalization in electric vehicles (EVs).

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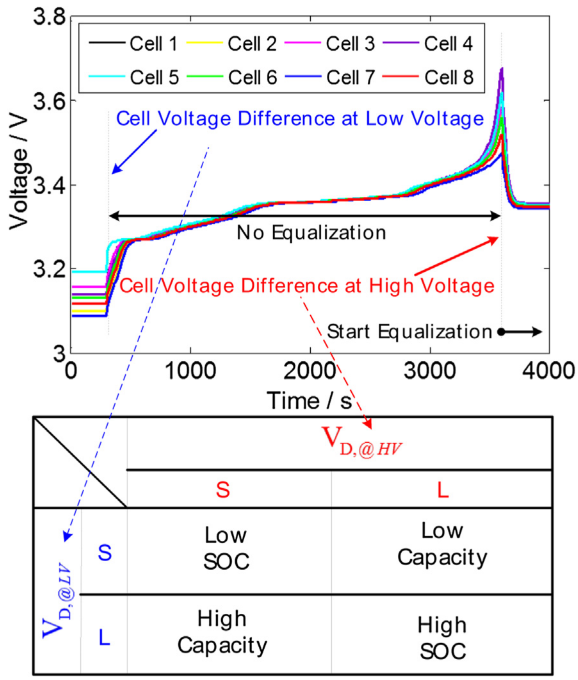

Fig. 1. Schematic diagram for the key idea of the proposed FL-EA.

However, pack capacity difference from the DCE theoretical pack capacity is observed with RCCE-DCE algorithm. Because the algorithm will force all cells to reach their charge cutoff voltage during charging, pack capacity will be constrained by all cells as a result. Regarding the ideal situation where pack capacity is constrained by the cell with the minimum capacity, the RCCE-DCE algorithm is not perfect enough. To minimize pack capacity difference from the DCE theoretical pack capacity, as the second part of the series, we propose fuzzy logic (FL) DCE algorithm based on CCVCs by comparing cell voltages at the beginning and end of charging.

EAs based on FL have been studied in literature [5–12]. D. Cadar et al. [5] proposed FL-EA based on cell voltage difference. Y. Lee et al. [6–8], R. Ugle et al. [9] and R. Ling et al. [10] further considered cell voltage difference at different cell mean voltage, and proposed FL-EAs base on cell voltage difference and cell mean voltage. Regarding cell internal resistance variation, J. Li et al. [11] proposed FL-EA base on the current and the cell voltage difference. J. Yan et al. [12] estimated cell SOCs and proposed FL-EA base on cell SOC difference and cell mean SOC.

FL-EAs in the above studies are voltage- or SOC-based EAs. As cell capacities are not considered in the algorithms, voltage- or SOC-based FL-EAs may lead to over-equalization. We suppose two cells are connected in series for example: Cell A has a capacity of 8 Ah and Cell B 12 Ah. Suppose cells are fully charged before connected in series, so the SOCs are all equal to 1 and the cell voltages are the same. After 6 Ah discharge, SOC of Cell A is 25% while SOC of Cell B is 50%. If voltage- or SOC-based FL-EAs of NDCE with ideal 100% energy transfer efficiency are implemented, Cell A need to be charged or Cell B need to be discharged gradually by the equalizer and when cells come to the “equalized state” with each 40% SOC, 1.2 Ah is transferred from Cell B to Cell A. The cells are charged in the next step, and when Cell A is fully charged, Cell B is still 80% SOC if not equalized. As a consequence, the equalizer will discharge Cell A and charge Cell B. For NDCE with ideal 100% energy transfer efficiency, no capacity losses during the equalization, but for voltage- or SOC-based FL-EAs with DCE, over-equalization lead to capacity loss and heat dissipation power increase and therefore must be prevented.

With appropriate feedback charging capacities, no over-equalization would occur using RCCE-DCE algorithm in the first part of this work. In this part, by comparing cell voltages at the beginning and end of charging, cell capacities and SOCs are fuzzily identified. The adaptive FL-DCE algorithm is subsequently proposed to prevent over-equalization and maintain the equalization capability.

2. FL-DCE based on CCVCs

The objective of pack capacity-based EAs for DCE is to make full use of the cell with the minimum capacity. Nevertheless the accurate cell SOCs and capacities are difficult to estimate on-line. As cell voltages directly reflect cell variation and CCVCs are easily to be achieved during EV charging, we use CCVCs to fuzzily identify cell SOCs and capacities. The key idea of the proposed FL-EA is demonstrated in Fig. 1. Once an EV begins the charging process, cell voltages are recorded and cell voltage difference at the beginning of charging $V_{D,@LV}$ is achieved by comparing to the minimum voltage at the beginning of charging. Cell voltage difference at the end of charging $V_{D,@HV}$ is similarly achieved by comparing to the minimum voltage at the end of charging. The equalizer is shut off during the charging process so as to accurately record the cell voltages. Equalization is started after FL-EA calculates the equalization currents for each cell using the achieved $V_{D,@LV}$ and $V_{D,@LV}$. FL-EA uses $V_{D,@LV}$ and $V_{D,@LV}$ to fuzzily identify cell capacities and SOCs. In the schematic illustration of Fig. 1, the achieved $V_{D,@LV}$ and $V_{D,@LV}$ are sorted with label “small (S)” and “large (L)”. Cells are subsequently categorized into 4 groups:

a) Low SOC: $V_{D,@LV} = S$ and $V_{D,@HV} = S$. A small voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be fully discharged at the end of discharging; A small voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be uncharged at the end of charging. The whole process reveals that the cell has a low SOC and a normal capacity. The equalizer should charge the cell for equalization. But for DCE, as the equalizer cannot charge cells, the cell should not be discharged by the equalizer to prevent over-equalization.
b) Low capacity: $V_{D,@LV} = S$ and $V_{D,@HV} = L$. A small voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be fully discharged at the end of discharging; A large voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be fully charged at the end of charging. The whole process reveals that the cell has a low capacity and pack capacity is likely to be constrained by the cell. If the cell has the minimum voltage at the beginning of charging and has the maximum voltage at the end of charging, we may infer that the cell approaches the minimum cell capacity and pack capacity also approaches the minimum cell capacity which is DCE theoretical pack capacity. Equalization can be stopped.
c) High capacity: $V_{D,@LV} = L$ and $V_{D,@HV} = S$. A large voltage difference between the cell voltage and the minimum voltage at the beginning of charging indicates that the cell tends to be undischarged at the end of discharging; A small voltage difference between the cell voltage and the minimum voltage at the end of charging indicates that the cell tends to be uncharged at the end of charging. The whole process reveals that the cell has a high capacity and no equalization is needed.