Capacity-difference Based Battery Equalization Method

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Abstract
For a battery management systems (BMS), it is a very important task to balance the cells within the battery pack. Without doing that, the lifetime and capacity of them will decrease quickly. Nowadays, many intelligent control strategies shuttle charges by comparing the voltages of cells. However, the terminal voltages of these cells can not accurately reflect the available capacity stored in them, especially in the noise environment. In this paper, we propose an capacity-difference based battery balancing method, in which the transference quantity of charges was looked on as the balancing criterion. Data stream mining (DSM) technique was used to calculate the balancing capacities. A complete shunting topology was used to test the performance of the proposed method. The simulation and experiment results have shown that, comparing with the traditional terminal voltage based balancing strategy, the battery pack with the proposed strategy can increase 3.5% running time.

Keywords: Battery management systems (BMS), state of charge (SOC), data stream mining (DSM)

Nomenclature
Abbreviation
BMS Battery management systems
SOC State of charge
DSM Data stream mining
AC Available capacity
ACD Available capacity difference

1. Introduction
Nowadays, battery balancing technique is becoming the research focus for a BMS, without which, cells in a pack are very easy to be damaged in the long-term repetition of charge/discharge cycles[1-4]. Most of the conventional control strategies for battery equalization are based on cell voltage, the optimization objects of which are to maximize the balancing efficiency and to minimize the balancing time and system cost[5-7]. However, for many Lithium-ion batteries, the OCV-SOC characteristic curves (charge/discharge) in the area of 10%-90% is a flat one. A 10 mV difference is nearly equal 10% SOC in the flat region. The balancing strategy is very easy to be disturbed by noise and measured errors. In the conditions of charge and discharge with constant current, the error will be a slight one. However, when an electric vehicle is running, the charge or discharge process is highly irregular[2]. The noise coming from vibration, connection and measurement will enlarge the error largely. Even if the balancing strategy was not be disturbed by noise and measured errors, terminal voltage should still not be looked on as a criterion for balancing. The reason lies in the inconsistency of the cells.

The other frequently-used battery balancing criterion is SOC. Generally speaking, voltage and current measurements are needed to implement a SOC analysis. Many SOC estimation techniques have been proposed. Unfortunately, most of them are not suited to be used in engineering. For example, some of them require battery disconnection or a long time to rest. Some of them order a large amount of computation resources or memory. In fact, even if these requirements are met, SOC should still not be looked on as a criterion for balancing. The reason lies in the inconsistency of available capacity (AC) of the cell. Generally speaking, the available capacity of a battery is the quantity of electricity that can be delivered at a certain discharge/charge current regime until a predefined discharge/charge criterion appeared. In theory, AC is a suitable criterion for battery cell balancing. However, it is very hard to accurately estimate the AC for cells.

Three kinds of methods were proposed to estimate the AC under variable discharge currents. The first one is to find a constant value K (similar to the K of Peukert equation) which has a certain relationship with AC. The
drawback of this method is that the constant K is largely affected by variable discharge currents and battery ages. It is very hard to obtain a suitable value for constant K. The second method is to find a model that can accurately describe the relationship between the battery terminal voltage and the AC. A lot of efforts have been made to describe the battery terminal voltage, the AC and the discharge current. For example, the Shepherd model is a widely accepted one. However, the applicability of this model is limited to a special temperature range and the model parameters must be calculated from experimental discharge curves with constant currents. It is almost impossible for EV operations to satisfy the requirements. The third method is to implement many experiments under different discharge current regimes that the battery may encounter and then obtain the AC for these discharge current regimes. The shortcoming of this method is that the test condition must is the same as that of the battery used for EV operation. Also, the effect of aging on AC was not been taken into account.

In fact, the battery available capacity was limited by the cells who reach the end-of-charge voltage threshold or low voltage threshold [9]. For a battery pack (cells connected in a string), accurately estimating the absolute values of SOC or AC and balancing cells with them is a hard task to be completed. However, calculating the AC variations for cells and keeping revising them in the charging/discharging circle are easy things to be done. So, in this paper, we introduce a novel online battery balancing method, in which the charge balancing criterion was not the cell voltage, SOC and AC, but the available capacity differences (ACD). Data stream mining technique was used to calculate the ACD among cells. With the obtained ACD information, the cells, the sequence and the quantity of the equalization can be decided automatically by the proposed algorithm. The ACD information was stored in a RAM memory, the power of which was supplied by an independent battery. When the vehicle is in parking, the ACD information will not be lost.

2. Complete Shunting Topology

Figure 1. Complete shunting topology

Many bidirectional non-dissipative balancing topologies have been proposed to deal with the problem of cell imbalance. Most of them use expensive or bulky power switches, diodes, capacitors and inductors to build control circuits. The control units usually manage many high-frequency and well-timed pulse width modulation control signals. The balancing strategies of them are very complex. However, the purpose of this paper is to introduce a data-stream-mining based method for estimating the ACD information and to show how to balance battery cells with the obtained information. So, in this paper, we select a simple topology (complete shunting topology) to illustrating the usage of the algorithm. In fact, the proposed balancing strategy can be used in many other topologies. With the complete shunting topology, the battery management system (BMS) needs no extra power to prevent imbalance. It continues to work during both discharge and charge processes. Each individual cell is controlled by two bidirectional switches and can be disconnected from the current path on the control strategy. The main advantages of the topology are the relatively low cost and high efficiency. The strategy offers intrinsic hardness to a cell fault and the BMS layout is considerably space saving. It is easy to be modularized. The main shortcoming is that it can only be used for low power applications.

3. ACD based equalization method

3.1 Extracting ACD Information with Data Stream Mining Algorithm

A data stream is an ordered sequence of instances. Data stream mining is a process of extracting knowledge from rapid or continuous data records[6]. In many applications, the given data stream can be read only once or the time for computing or storage is very short. For example, computer network traffic, phone conversations, ATM transactions, web searches and sensor data. Many concepts used in data stream
mining come from Incremental Learning (IL) and many incremental heuristic search algorithms were used to cope with the structural changes and online learning demands.

In this section, we present our deterministic algorithm to extract ACD information for cells. With the given topology (Complete Shunting topology), two kinds of decision strategies were usually adopted in balancing algorithms: voltage analysis based balancing strategy and SOC analysis based balancing strategy. Voltage analysis based strategy monitors the voltage across each cell with no need for additional processing or acquisition. SOC analysis based strategy requires both current and voltage measurements to estimate the SOC of each cell. Several algorithms for SOC estimation have been proposed and most of them were not suited for this topology. For example, some of them need a great deals of memory or computation resources, some of others requires disconnecting the battery for a long time. Bearing in mind the achievement of the best performance with the simplest algorithm architecture, we select the voltage based balancing strategy for the BMS.

**Definition 1** (Voltage deviation of celln, \( \epsilon_n(t) \)). Let \( V_n(t) \) be the instantaneous voltage of celln, \( V_{ave}(t) \) be the average voltage of cells in a battery pack, the voltage deviation of celln, \( \epsilon_n(t) \), can be expressed like this,
\[
\epsilon_n(t) = V_n(t) - V_{ave}(t)
\]

**Definition 2** (Charged/discharged capacity of battery pack, \( Q(t) \)). Let \( t_0 \) be the starting time of charge/discharge, \( i(t) \) be the instantaneous charge/discharge current of a battery pack, the charged/discharged capacity of battery pack, \( Q(t) \), can be expressed like this,
\[
Q(t) = \int_{t_0}^t i(t) \, dt
\]

**Definition 3** (Charged/discharged capacity of celln, \( Q_n(t) \)). Let \( t_0 \) be the starting time of charge/discharge, \( i_n(t) \) be the instantaneous charge/discharge current of celln, the charged/discharged capacity of celln, \( Q_n(t) \), can be expressed like this,
\[
Q_n(t) = \int_{t_0}^t i_n(t) \, dt
\]

In the balancing process, if the battery cell, celln, was be disconnected from the current path, the instantaneous charge/discharge current of it is zero, \( i_n(t) = 0 \). Otherwise, \( i_n(t) = i(t) \).

**Definition 4** (Capacity difference between pack and celln, \( \Delta Q_n(t) \)). In the balancing process, the dynamic capacity difference between pack and celln, \( \Delta Q_n(t) \), can be expressed like this,
\[
\Delta Q_n(t) = Q(t) - Q_n(t) = \int_{t_0}^t (i(t) - i_n(t)) \, dt
\]

**Definition 5** (Capacity difference between pack and celln in time interval \( \Delta t \), \( \Delta Q_n(tk) \)). Split the whole balancing process into equal time interval, \( \Delta t \). The capacity difference between pack and celln in the \( k \) th time interval \( tk \), \( \Delta Q_n(tk) \), can be expressed like this,
\[
\Delta Q_n(tk) = \int_{\Delta t_{k-1}}^{\Delta t_k} (i(t) - i_n(t)) \, dt
\]

**Definition 6** (Window, windowj). Let the capacity difference, \( \Delta Q_n(tk) \), be a data stream, the incoming stream is conceptually divided into windows. Each window is a completed charging or discharging process, the width of which was decided by the end-of-charging/end-of-discharging voltage threshold. We label the windows with windowj, the value of it is the number of charging or discharging processes.

**Definition 7** (Data structure, DS). DS is a set of entries of the form \( (n, \Delta Q_n(t)) \), where \( n \) is an identifier of celln, \( \Delta Q_n(t) \) is an incremental capacity difference between pack and celln until the \( k \) th time interval \( tk \).

**Algorithm:**

(1) Initializing DS. Clean the records in it.
(2) Recording data. For every time interval \( tk \), calculate the incremental capacity differences, \( \Delta Q_n(t) \), and lookup DS to see whether or not an entry for it has exist. If finds, update the entry by incrementing the capacity difference of celln, \( \Delta Q_n(tk) \). Otherwise, creates a new entry \( (n, \Delta Q_n(t)) \) for it.
(3) Does a window boundary arrive? Yes, go (4); No, go (2).
(4) Moving the DS to a special memory DS*. (DS* was used for directing the balancing processes in the proposed control strategy, we can see this in Section 3.2); go (1).

### 3.2 The Proposed Balancing Strategy

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### 3.3 Theory/calculation

In this paper, the ACD information was stored in a memory, the power of which was supplied by an independent battery. So, it can keep available for every charging or discharging cycle. The charge-discharge cycle was divided into two phases. In the first phase, the cell, celln, with the largest/smallest incremental capacity difference, \( \Delta Q_n(t) \), was selected to be disconnected (in the charge/discharge process) until the cell meet the termination condition, \( \Delta Q_n(t) \leq \Delta \) / \( \Delta Q_n(t) \geq -\Delta \). In the second phase, the cell, celln, with the largest/smallest voltage deviation \( \epsilon_n(t) \) was selected to be disconnected (in the
charge/discharge process) until the celln meet the end-of-charge/end-of-discharge voltage threshold. Considering the achievement of simple architecture and good performance, the proposed algorithm and its flowchart were designed like this:

1. Data acquiring. Read in the summary information from DS*, rank the entry (n, $\triangle Q(t)$) with the values of $\triangle Q(t)$.

2. Voltage monitoring. Check the terminal voltages of cells. If the terminate voltage, $V_n$, of a cell, celln, reaches the end-of-charge/end-of-discharge voltage threshold, $V_{High}/V_{Low}$, closes the charge/discharge process. Begins a new window and go (1). Otherwise, go (3).

3a) For a charge process: ① Searches an entry (n, $\triangle Q(t)$) in DS*, the value $\triangle Q(t)$ of which is the largest one; ② Closes the two control switches of celln for a fixed time interval $\triangle t$ to disconnect it from the current path; ③ Updates the shunting electric charge quantity, $\triangle Q(t)$, $\triangle Q(t) = \triangle Q(t) - Q'$. $Q'$ is the charged capacity of battery pack in the time interval $\triangle t$; ④ If all of the $\triangle Q(t)$ in DS* meet the conditions of “$\triangle Q(t) \leq \triangle"$, go (4); Otherwise, go (2).

3b) For a discharge process: ① Searches an entry (n, $\triangle Q(t)$) in DS*, the value $\triangle Q(t)$ of which is the smallest one; ② Closes the two control switches of celln for a fixed time interval $\triangle t$ to disconnect it from the current path; ③ Updates the shunting electric charge quantity, $\triangle Q(t)$, $\triangle Q(t) = \triangle Q(t) - Q'$. $Q'$ is the discharged capacity of battery pack in the time interval $\triangle t$. ④ If all of the $\triangle Q(t)$ in DS* meet the conditions of “$\triangle Q(t) \geq -\triangle"$, go (4); Otherwise, go (2).

4a) For a charge process: ① Select the largest voltage deviation of celln, $e_n(t)$; ② If $e_n(t)$ is greater than a given threshold $\triangle V$, closes the two control switches of celln for a fixed time interval $\triangle t$ to disconnect it from the current path; ③ Go (5).

4b) For a discharge process: ① Select the smallest voltage deviation of celln, $e_n(t)$; ② If $e_n(t)$ is less than a given threshold $\triangle V'$, closes the two control switches of celln for a fixed time interval $\triangle t$ to disconnect it from the current path; ③ Go (5).

5. Checking the window boundaries. Does a window boundary arrive? Yes, delete the entries (n, Qn) in DS*, reads in new entries from DS and go (1); No, go (4).

In the procedure, step (1)-(3) were directed by DSM-based strategy. Step (4) was directed by voltage-based balancing strategy.

4. Simulations

Matlab/Simulink is a software for modeling and simulating dynamic systems. In this section, we simulate the complete shunting balancing topology with it. Five lithium-ion batteries with different capacities were used for the simulation and comparison. The nominal voltage, rated capacity, initial SoC, maximum capacity, fully charged voltage, internal resistance were respectively “3.2V, 3.6Ah, 100%, 3.6Ah, 3.72V, 0.0088 Ohms”, “3.2V, 3.4Ah, 100%, 3.4Ah, 3.72V, 0.0094 Ohms”, “3.2V, 4Ah, 100%, 4Ah, 3.72V, 0.008 Ohms”, “3.2V, 3.8Ah, 100%, 3.8Ah, 3.72V, 0.0084 Ohms”, and “3.2V, 2.5Ah, 100%, 2.5Ah, 3.72V, 0.0128 Ohms”. MOSFET switches were used in the simulation, the internal resistance Ron, snubber capacitance were respectively 0.001 Ohms, 100000 Ohms and 250nF. The BMS acquires voltage on each cell, overall pack voltage and charge/discharge current.

4.1 The Summary Information

In order to clearly show the summary information in DS*, we give a sketch to show the obtained process. The micro-changes of the integral current in 10-40 second were presented in Figure 2. For the five cells, the shuttle current of them in 10-40 second were A1, A2, ..., An.

![Figure 2. A section of the summary information (10-40 second).](image)

4.2 The Influences of Noise

To clearly show the noise influences on cells' shunting currents and voltages, in Figure 3, we compared shunting currents of Cell1-Cell5. It can be seen that, when no noise was overlaid on the measured terminate voltages, the "lowest voltage cell..."
rest,” shutting strategy is effective. The cells (Cell1 and Cell2) with high rated capacity (4Ah, 3.8 Ah) keep releasing charges and the cell (Cell5) with lowest rate capacity (2.5Ah) has rests. With this strategy, the battery has a long discharge time. On the contrary, when a random noise [-0.2V ~ 0.2V] was overlaid on the measured terminate voltages, the balancing result of the traditional shutting strategy was not very well. Some inappropriate cells were selected to have a rest. That leads to invalid charge shuttling. It can be clearly seen in Figure 3(a) and Figure 3(b), the shuffling currents and the voltage-changes of Cell1~Cell5 were very irregular. And the discharge time became shorter.

4.3 Strategy Comparisons

To further compare the effects of the traditional terminal voltage based balancing strategy (TV-BS) and data stream mining based balancing strategy (DSM-BS), we shown the shuttling current and SOC of cell1 and cell5 under the two conditions. Nine duty cycles were show. From the microcosmic views, we can find that when random noises were overlaid on the measured terminal voltages, the traditional balancing strategy can not select the proper cell to rest. That leads to an irregular current appeared in Figure 4. One the contrary, as the data mining algorithm can filter most of the noise produced by random-noise-producers, the proposed DSM-BS strategy can effectively make use of the shuttling charges among cells. We can see that, after 7 duty cycles, the SoC of Cell5 in Figure 4 is greater than that of Figure 4. Completing the same 9 duty cycles, the traditional balancing algorithm cost 5950 seconds, that means algorithm (b) is a more effective balancing strategy that algorithm (a).

5. Conclusion

Cell balancing is an important task for battery management system. The lifetime and safety of a battery pack is largely decided by the performance of it. A novel control strategy (data-stream-mining based cell balancing strategy) was presented. The comparative study between it with terminal-voltage based cell balancing strategy was performed. The simulation results have shown that, comparing with the traditional terminal voltage based balancing strategy, the pack with the proposed strategy can increase 3.5% running time. In the proposed algorithm, data stream mining technique was integrated into the balancing process and the historical information was used to direct the balancing process. The algorithm not only can balance the cell’s residual capacities online, but also can report the state of health of them offline or online.

Acknowledgements

We are grateful to the anonymous referees for their invaluable suggestions to improve the paper. This work was supported by Beijing Municipal Education Committee project (KM201811232003), funds for the Research Base of Beijing Municipal Commission of Education under Project (No.PXM2017_014224_000005) and funds for promoting university connotation construction in 2018(Beijing Information Science and Technology University ).
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