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Online dynamic equalization adjustment of high-power lithium-ion battery packs based on the state of balance estimation

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HIGHLIGHTS

- A novel concept (SOB, State of Balance) is proposed for the LIB pack equalization.
- Core parameter detection and filtering is analyzed to identify the LIB pack behavior.
- The electrical UKF model is adopted for the online dynamic estimation.
- The equalization target model is built based on the optimum preference.
- Comprehensive imbalance state calculation is implemented for the adjustment.

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ABSTRACT

A novel concept named as state of balance (SOB) is proposed and its online dynamic estimation method is presented for the high-power lithium-ion battery (LIB) packs, based on which the online dynamic equalization adjustment is realized aiming to protect the operation safety of its power supply application. The core parameter detection method based on the specific moving average algorithm is studied because of their identical varying characteristics on the individual cells due to the manufacturing variability and other factors, affecting the performance of the high-power LIB pack. The SOB estimation method is realized with the detailed deduction, in which a dual filter consisting of the Unscented Kalman filter (UKF), equivalent circuit model (ECM) and open circuit voltage (OCV) is used in order to predict the SOB state. It is beneficial for the energy operation and the energy performance state can be evaluated online prior to the adjustment method based on the terminal voltage consistency. The energy equalization is realized that is based on the credibility reasoning together with the equalization model building process. The experiments including the core parameter detection, SOB estimation and equalization adjustment are done and the experimental results are analyzed. The experiment results show that the numerical Coulomb efficiency is bigger than 95%. The cell voltage measurement error is less than 5 mV and the terminal voltage measurement error of the LIB pack is less than 1% FS. The measurement error of the battery discharge and charge maintenance current is less than 1% FS. The SOB estimation error is less than 5% in the laboratory room, the temperature of which is about 25 °C. The equalization charging current is 2 A and the equalization discharging current is 4.4 A, which can realize the real-time energy equalization adjustment among the connected cells in the LIB pack, guaranteeing its safety in the power supply application.

0. Introduction

Lithium ion battery (LIB) has become one of the main power sources along with the development of the new energy industry, which has high energy and power densities, making it to be a competitive choice for the transport energy supply. In the past few years, the LIB packs have risen as the preferred technology for both portable devices and vehicular applications [1–3]. As the voltage of single one LIB cell is also limited, the working range of which is between 3 and 4.15 V, the battery modules and packs are made via serial and parallel combinations of mounts of LIB cells. Then,

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as the internal variations are inevitable in the LIB cells and modules, the quality of all the connected LIB cells is not easy to grasp because of the production difference among them. The working state difference of these connected cells in the LIB pack is due to the material and production process difference in the factory, which has already emerged and becomes more and more obvious along with the its life extension. What's more, they will work differently at various operating environments, such as the environmental temperature and so on. As a result, the inconsistency of its aging performance and other factors will apparent increasingly among the connected cells in the LIB pack. The battery efficiency and life performance will be worse if this phenomenon cannot be ameliorated, resulting in the over-charge and over-discharge phenomenon for a certain cell in the LIB pack, which may cause severely burning fire and other safety issues. Therefore, the battery management system (BMS) is designed and used to monitor the battery usage state, aiming to detect the battery charging and discharging degree and adjust the consistency among the LIB cells. The working condition should be calculated and analyzed considering the usage information in order to ensure the safety operation of the LIB pack. The balance state characterization and management research herein can promote the rapid development of the LIB pack, which can be accessed to the electric vehicle (EV) power, airborne emergency supply, mining and other markets quickly.

The BMS features for the LIB pack consist of data monitoring, working state estimation, thermal management, balance adjustment, communication, and data interpretation and so on. The working state estimation can be done by using the traditional open circuit voltage (OCV), internal resistance (IR), security integration methods, as well as the emerging fuzzy logic algorithm [4], adaptive neuron-fuzzy inference algorithm [5], Kalman filtering (KF) [6] and extended KF (EKF) [7] estimation algorithm, linear model and impedance spectroscopy [8] methods. The equalization management can be divided into dissipative and non-dissipative types according to its energy swapping direction [9–13]. There are mounts of countries that have invested lots of manpower and resources to carry out this extensive research, such as the US, Germany, Japan, South Korea and so on, leading the research direction in this special field [14–18]. The US General Motors, Toyota and other famous car companies have developed the EVs equipped with the BMS which have reached the industrial product level. During the establishment of the specialized EV research projects, there are also some big breakthroughs in the BMS [19–25]. At present, the researches and developments have been done for the BMS from the nation down to the business, attracting great attention instantly.

The BMS technology has developed rapidly in recent years and the related study is in full swing. Many colleges, universities, research institutes and companies have invested mounts of time and money into the BMS research and there are many ways that have entered the practical stage and a new development wave is set off for the LIB pack management [26–43]. However, the BMS technology at this stage is still quite immature as parts of its structure are still not perfect and especially the balance adjustment cannot meet the application requirement. The present balance equilibrium methods are not efficient enough as well as the data acquisition accuracy, working state estimation, security protection, and other aspects of the LIB pack, which need to be improved immediately. The BMS not only has a long way to go upon the development road but also need further research for the safety improvement [44–65]. Aiming to solve this problem, the balance state estimation and equilibrium adjustment strategies based on it are done in the BMS for the high-power LIB packs. In this method, a novel concept named as state of balance (SOB) is proposed, which is different from the previous voltage detection and adjustment methods. The concept SOB is designed for the purpose of the balance state characterization and regulation specifically, in which not only the cell capacity and balance state can be characterized but also the comprehensive balance state characterization for the whole LIB pack. In this method, not only the cell voltage is considered, but also the factors of pack voltage, temperature, maintenance current and IR are taken into the SOB estimation process which is based on the Unscented KF (UKF) algorithm together with the OCV and equivalent circuit model (ECM). Then, the adjustment process is done according to the credibility and optimal preference balance and equalization strategies.

The remainder of this paper is organized as follows. The online parameter detection and filtering method is presented in Section 1. Section 2 describes the SOB estimation method, including the UKF algorithm and the estimation process based on it. Then, the equalization adjustment based on the optimum preference is presented in Section 3. The experimental results are presented and analyzed in Section 4 and the work is concluded in Section 5.

1. Online parameter detection

The sampling approaches have been studied to achieve the cost-effective detection of the core parameters for the LIB pack together with the working state estimation and the health state monitoring. The core parameters for the LIB pack consist of the terminal pack voltage, charging and discharging current, balance adjustment current, cell voltage and temperature, the detection process of which also prevent the occurrence of the over-charge, over-discharge and even reverse polarity phenomena. The voltage and current detection for the LIB pack is critical for the healthy and efficient operation of the high power LIB packs. In the sampling process, the core parameter detection is realized by the real-time monitoring together with the data filtering. The sampling process of the discrete data sequence is done for the core parameter detection and SOB estimation of the LIB packs. It is used to calculate a sliding average of the data sequence, thereby forming a new sequence with the mean value of it. However, there is significant power loss during the equalization process due to the increased IR along with the degraded module appearance, which is also affected by the growth of the cycling charge–discharge maintenance. As a result, the characteristics of the LIB pack, including cell voltage, pack voltage, current and temperature, are detected that are based on the moving average ideology in the real-time detection process.

The specific moving average algorithm can be described as follows. Assuming that there is a sliding and fixed-length window, this virtual window is used for the queue that is moving with the time-series. During the movement, a sampling interval of each movement is defined, in which the front edge of the window admits the new detected data and the rear edge of the window deletes the last data. Thus, there is always a fixed number of the latest data in the filtering window. Then, the new sequence can be obtained through the arithmetic average for the moving average calculation of as shown in Eq. (1).

$$P_{new}[n] = \frac{1}{N}\sum_{k=0}^{N-1} P_{old}[n-k] \quad (1)$$

Wherein, the parameter P is used to indicate the sampling data sequence for the core parameters of the LIB pack. The parameter P_{new} indicates the new data sequence used the moving average process, and the parameter P_{old} indicates the old data sequence before a new data detection. The parameter n indicates the new sampling data number to be processed in time, and the parameter N indicates the window width which is also the valid data of the total length for the calculation sequence. The sliding average frequency response to the model is shown in Eq. (2).