Research on Battery Balancing Strategies

Li Yuanyuan
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract. While being used as energy storage carriers, batteries usually need to form series-parallel modules to meet the requirements of system voltage and power. Due to the differences of materials, production process and temperature of each battery in the module, there will be unbalanced voltage. If it is not controlled, some batteries will be damaged due to overcharge or over discharge, resulting in the failure of the module or even accidents. This paper first analyzes the development of energy storage batteries, and studies the causes of the imbalance of the battery pack and the significance of its balance. Then several battery equalization methods and their working principles are studied, and the equalization process of a double-layer active equalization system is analyzed in detail, so as to improve the consistency of the batteries and extend their service life. Finally, the comparative analysis results of inductor-based equalization and transformer-based equalization are given.

1. Introduction

1.1. Energy storage background
In the past decade, traditional energy utilization has led to continuous energy crisis and decreasing reserves, and in the meanwhile, causes air pollution, climate warming and other global environmental degradation. Therefore, countries are accelerating their pace of energy transformation [1].

Presently, application of energy storage in China's electricity market mainly includes grid connections for renewable energy, auxiliary services, grid side and user side [2]. In the initial stage of demonstration, the main energy storage equipment includes lithium-ion batteries, lead-acid batteries, and flow batteries. Currently, the energy storage battery has entered a stage of rapid development, with a great market prospect. The application of energy storage is gradually diversified and developed in various fields, such as the smart grid, electric vehicles, and aerospace. These emerging industries will significantly stimulate the demand for energy storage. With the increasing renewable energy and distributed energy access to the grid, the Internet of Energy will focus on energy storage applications.

1.2. Present situation and development trend of energy storage batteries
Currently, electrochemical energy storage batteries are mainly divided into lead-acid batteries, flow batteries, lithium-ion batteries and supercapacitors [3]. In these four categories, lithium-ion batteries and supercapacitors have the most practical prospects.

Lithium-ion batteries are characterized by high energy density, long cycle life, low self-discharge rate, high energy conversion efficiency, and can be charged and discharged at different depths [4]. In recent years, it has been used as the main power source of electric vehicles because it can conduct high-power charge and discharge frequently. However, the main factors limiting the application of lithium-ion battery are safety and cost. At present, its research and development focus is to replace the LiCo$_2$ system with safe and low-cost anode materials, so that it can be better used in large-scale energy storage [5, 6].
Supercapacitors have the advantages of large capacity, high capacity density, high specific power, wide working temperature range, long life and fast charging and discharging. It has broad application prospects in many fields, such as portable equipment, data memory storage system, and emergency backup power supply [7]. In the recent decade, the hybrid supercapacitor is a research hotspot, which combines the advantages of energy density of lithium-ion batteries and power density of double-layer capacitors. With the continuous development of anode and cathode materials and electrolyte, the hybrid supercapacitor has become the most promising solution for the power of electric vehicles in the future [8].

1.3. Current research on the energy management system of energy storage batteries

In the practical application of energy storage batteries, it is essential to have reasonable distribution and management, which requires the energy management system to accurately know the SOC of the battery, complete the reasonable use of the energy inside of the battery, increase the number of battery recycling, and reduce the damage degree of the battery [9, 10].

In recent years, scholars all over the world have carried out a lot of research on the key technologies of battery management system and achieved a series of results. Lin Chengtao proposed an improved Ah counting method by combining Kalman filter with Ah counting to estimate SOC, thus making the battery running in a healthy range [11]. The battery energy management system developed by Guantuo Power and Harbin Institute of Technology can realize accurate data acquisition, transmission, processing, reasonable and standardized charge and discharge control, history data storage and other functions [12]. The Smart Guard system manufactured by Aeroenvironment, an American enterprise, can automatically search the battery with the worst inconsistency, and automatically detect the batteries’ charging depth for charging management [13].

2. Causes of imbalanced energy storage batteries

2.1. Causes of the imbalance in the battery pack

Limited by the characteristics of a single energy storage battery, in practical application, it is usually composed of batteries in series-parallel connection, and the parameters of each battery are not exactly the same. The imbalance between batteries is mainly affected by their internal and external parameters.

The internal reason for the imbalance of the battery pack is the performance difference of each cell. Due to the different materials and production process, even the same type of battery cannot have completely consistent parameters. Under the influence of different application environment and after long-term repeated charging and discharging, the problem of inconsistent characteristics of single battery in series will be more serious.

The external cause of the imbalance of the battery pack is mainly the difference of battery performance caused by the charge and discharge of the battery pack. While charging, the battery with worse performance will first be overcharged, resulting in irreversible damage, which leads to the reduction of the capacity of the whole battery pack system. At the same time, the battery with worse performance is the first to dry up when discharging, which affects the operation of the battery pack as a whole [16]. In addition, the storage environment, temperature, humidity and salt spray will all affect the batteries [14, 15].

2.2. Significance of battery balancing

In the application of energy storage batteries, multiple batteries are often connected in series and parallel to provide higher voltage and capacity. Different batteries have different internal resistance and self-discharge rate. Some batteries in the series battery pack will be charged or discharged earlier than other batteries, resulting in the decrease of available capacity and service life of the battery pack [17]. Lithium-ion batteries have high requirements for charge and discharge. When there is a condition including overcharge, over discharge, over-current and short circuit, the pressure and heat of the battery increase sharply, which is possible to create sparks, combustion and even explosion. Therefore,
in the process of charging and discharging, accurate voltage and current management can give full play to the maximum performance of the battery pack. Using battery equalization technology, electronic components can be real-time monitored and automatically balanced to achieve intelligent charging and discharging, so as to protect the battery and prolong its service life [18]. To sum up, in order to improve the operation safety of energy storage system, the design of active equalization circuit has great practical significance.

3. Research of active equalization controlling strategies

Fig.1 shows a double-layer active equalization circuit based on multi-input transformation, including the microcontroller, bottom equalization unit, top equalization unit and switching relay. The microcontroller is connected with and controls the energy balance of a plurality of balancing battery packs, wherein each pack comprises two battery modules, and each module comprises a plurality of battery cells in series. Each two adjacent battery cells share a bottom equalization unit. Each two battery modules share a switching relay and a top equalization unit.

3.1. Analysis of inductor-based equalization circuit

In the bottom balancing control system, assuming U1 has higher voltage than U2 and balancing U1 and U2, the analysis of equalization process is shown in Fig. 2.
At 0-\(t_1\), switch S1 is closed and S2 is open. Battery \(U_1\) charges inductor \(L\) through Loop 1. \(i_L\) increases linearly from 0,

\[
i_L = \frac{U_1}{L} t
\]  

(1)

At \(t_1\)-\(t_2\), the switches S1 and S2 are disconnected, the inductor \(L\) charges the battery \(U_2\) through Loop 2, and \(i_L\) decreases linearly, is shown in Fig.3.

\[
i_L = \frac{U_1-U_2}{L} t
\]  

(2)

Fig.4 is a diagram of transformer-based equalization. The primary side of the transformer is connected to both sides of the battery pack, and the secondary side is connected to each battery cell. In

3.2. Analysis of transformer-based equalization circuit

The transformer-based equalization circuit is selected for the top equalization. According to the flow direction of energy between the battery cell and the battery pack in the equalization process, the transformer-based equalization can be divided into three structures of pack-to-cell, cell-to-pack and bidirectional.
the figure, (a) is the process from pack to cell. The energy of battery pack is stored in the transformer through the power switch, and then transferred from the transformer to the battery cell when the switch is off. (b) is the process from cell to pack. When the energy of battery cell is high, the power switch is closed, and its energy is stored in the transformer, and then transferred from the transformer to the battery pack when the switch is off. (c) is a bidirectional process, and the direction of energy transfer is adjusted according to the actual situation.

The transformer-based equalization process can be simplified as the basic principle of flyback transformer shown in Fig.5. Its primary side is connected to the power supply through the power switch, and the secondary side is connected to the capacitor through the diode D, which limits the energy flow direction.

When the power switch is on, the current pass through the primary side of the transformer, which stores the energy of the power supply in the inductor of the primary side.

$$i_{L1} = \frac{U_1}{L_1} t \quad (3)$$

When the power switch is off, the inductor current on the primary side decreases, and the reverse electromotive force is generated, that is, the input end of the transformer is negative above and positive at bottom while the output end is the opposite. The diode D is on, and the energy of the transformer winding is transmitted to the capacitor.

$$i_{L2} = \frac{U_1 N_2}{N_1 L_2} t \quad (4)$$

| Number of devices | Complexity | Energy transfer | Protection difficulty | Equalization speed |
|-------------------|------------|----------------|----------------------|-------------------|
| Inductor-based equalization | Few | Easy | High | Simple | Slow |
| Transformer-based equalization | More | Complex | Medium | Hard | Fast |

In this paper, the top equalization control system is composed of the transformer-based equalization as shown in Fig.4 (b). Assuming that the voltage of a battery module is too high, the analysis of equalization process is shown in Fig.6.
At 0-\(t_1\), the power switch is closed, the battery cell charges the transformer through Loop 1, and \(i_{T1}\) increases linearly from 0,

\[
  i_{T1} = \frac{u_1}{L_1} t
\]

At \(t_1 - t_2\), the power switch is off, the transformer charges the battery cell through Loop 2, and \(i_{T2}\) decreases linearly, as shown in Fig.7.

\[
  i_{T2} = \frac{u_1 N_2}{N_1 L_2} t
\]

3.3. Comprehensive comparative analysis of two equalization methods

Comparing the two equalization methods, the main components of the inductor-based equalization circuit are switches and inductors, while in the transformer-based equalization circuit, transformers are also used besides switches, which are bulkier. The inductor-based equalization transfers energy in the form of current, which can realize energy transfer even if the voltage difference between batteries is small. So, it has higher energy transfer ability and faster equalization speed. The transformer-based equalization transfers energy through the counter EMF between the transformer coils, which has low energy transfer ability and slow equalization speed. The inductor-based equalization has high transferring energy and low switching frequency, which makes the control easier, while the transformer-based equalization has high switching frequency and poor current control ability, so it’s more complex to be controlled. It has large coil leakage inductance and the transformer loss; thus, the security of equalization circuit is poor.

The comprehensive comparison of various parameters of the two equalization methods are shown in Table 1.
4. Conclusion
This paper summarizes the development of energy storage batteries and the research of battery energy management system under the global energy storage background. It analyzes the causes of imbalance of energy storage batteries and the research significance of battery balance control. The advantages and disadvantages of passive equalization and active equalization are analyzed, and the characteristics of three active equalization circuits are studied. Finally, taking a double-layer active equalization system based on inductor-based equalization and transformer-based equalization as an example, this paper analyzes the working process and principle of the energy storage system, and the advantages and disadvantages of these two methods are compared and summarized.

References
[1] Zhang Jingwen. The Future Decade is a Period of Rapid Development for Energy Storage [J]. Energy, 2018, 000(011):P.146-147.
[2] Sun Yushu, Yang Min, Shi Changli, et al. Analysis of Application Status and Development Trend of Energy Storage [J]. High Voltage Engineering, 2020, 46(1).
[3] Jiang Kai, Li Haomiao, Li Wei, et al. On Several Battery Technologies for Power Grids [J]. Automation of Electric Power Systems, 2013(1):47-53.
[4] Yan Jinding. Current Status and Development Analysis of Lithium-ion Batteries [J]. Acta Aeronautica ET Astronautica Sinica, 2014, 35(010):2767-2775.
[5] Spagnol P, Rossi S, Savaresi S M. Kalman Filter SoC estimation for Li-Ion batteries[C].IEEE International Conference on Control Applications. IEEE, 2011:587-592.
[6] Li-ion Battery Management System in a Fuel Cell Vehicle[J]. Computer and Communications, 2004.
[7] ZHANG Xiong, SUN XianZhong, MA YanWei. Research of supercapacitors with high energy density [J].entia Sinica Chimica, 2014, 44(7):1081-1096.
[8] Chen Xuedan, Chen Shuoyi, Qiao Zhijun, et al. Application of Supercapacitors [J]. Energy Storage Science and Technology, 2016, 5(006):800-806.
[9] Moreno J, Ortuzar M E, Dixon J W. Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks[J]. IEEE Transactions on Industrial Electronics, 2006,53(2):614-623.
[10] Lee J, Nam O, Cho B H. Li-ion battery SOC estimation method based on the reduced order extended Kalman filtering[J].Journal of Power Sources,2007,174(1):9-15.
[11] Lin Chengtao, Chen Quanshi, Wang Junping, et al. Improved Ah counting method for state of charge estimation of electric vehicle batteries [J]. JOURNAL OF TSINGHUA UNIVERSITY (SCIENCE AND TECHNOLOGY), 2006,46(2):247-251.
[12] Yi Jun. Research and Design of LiFePO4 Battery Pack Management System [D]. Southwest Jiaotong University, 2014
[13] Wu Xianchun. Research on Energy Management of the Hybrid Power Supply System [D]. Southwest Jiaotong University, 2013
[14] Asumadu J A, Haque M , Vogel H , et al. Precision Battery Management System[C]// IEEE Instrumentation and Measurement Technology Conference. IEEE, 2006.
[15] Park K H , Kim C H , Cho H K , et al. Design Considerations of a Lithium Ion Battery Management System (BMS) for the STSAT-3 Satellite[J]. Journal of Power Electronics, 2010, 10(2):210-217.
[16] Jiang Weidong. Research on the Dynamic Equivalence Technology of LiFePO4 Battery Pack [D]. 2015
[17] Pengcheng W , Zhigang C . Research on High Precision Lithium Battery Management System[J]. IOP Conference Series: Earth and Environmental ence, 2019, 371(5):052038 (5pp).
[18] Zheng X , Liu X , He Y , et al. Active Vehicle Battery Equalization Scheme in the Condition of Constant-Voltage/Current Charging and Discharging[J]. IEEE Transactions on Vehicular Technology, 2017