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A Novel Lithium-ion Battery Balancing Strategy Based on Global Best-First and Integrated Imbalance Calculation

Liping Shang[1], *Shunli Wang* [1*], *Zhanfeng Li*[2], *Hu Deng*[1], *Youliang Ma*[2], *Jianwei Wang*[1]

[1]School of Information Engineering & Robot Technology Used for Special Environment Key Laboratory of Sichuan Province, Southwest University of Science and Technology, Mianyang 621010, China
[2]School of Manufacturing Science and Engineering, Southwest University of Science and Technology, Mianyang 621010, China
[*]E-mail: wangshunli@swust.edu.cn

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Lithium-ion battery is the development trend in the airborne and automotive applications, but there are constraint technical security risk issues. The spontaneous combustion and other safety hazards of the lithium-ion battery are mainly caused by the imbalance of monomers in the lithium-ion battery packs. In order to solve the imbalance problems in the lithium-ion battery monomers that exist during the charging and discharging process, a novel lithium-ion battery balancing strategy is proposed based on the global best-first balancing strategy and integrated imbalance calculation analytical methodology. This strategy analyzes the variation of the cell voltage and capacity of the lithium-ion battery which are two key characteristic factors for the balancing adjustment. The integration effect degrees of these two core factors are determined for seeking the optimal balancing path to achieve the active equalization of the lithium-ion battery under charging, discharging and shelving conditions. The experimental results show that, the integrated imbalance degree of remaining capacity and terminal voltage of the battery monomer is no greater than 8% and the real-time active equalization goals of the lithium-ion battery under different operating conditions are achieved through the equalization adjustment system (EAS) design and implementation, providing security protection for the lithium-ion battery application.

Keywords: Lithium-ion battery, balancing strategy, global best-first, integrated imbalance, EAS, active equalization

1. INTRODUCTION

Lithium-ion battery has the large energy density, high stability and other advantages, compared with the lead-acid, nickel-cadmium and other type batteries. But both the terminal voltage and the capacity of the independent lithium-ion battery monomers are very small, unable to meet the airborne, automotive and other industrial application needs. As a result, the cascaded group mode application of the lithium-ion battery is the development trend of the battery energy supply under various conditions.

However, due to the small material differences among the monomers which could not be eliminated in the production process, the prone cell voltage and capacity imbalance phenomenon of the lithium-ion battery can be seen frequently, triggering spontaneous combustion and other security issues which seriously hamper the promoting use of lithium-ion battery.

In order to solve the core technology problem that is blocking the lithium-ion battery development, researchers have launched much related technological research, such as the multiphase interleaved converter study for lithium battery active balancing made by Mestrallet et al [1], the on-line adaptive battery impedance parameter and state estimation considering physical principles in reduced order equivalent circuit battery models study made by Fleischer et al [2], the study of a modular balancing bridge for series connected voltage sources made by Ewanchuk et al [3], as well as other exploring studies on solving the imbalance problems [4-15]. Meanwhile, for the key factors, namely, the State of Charge (SOC) of the single monomer and its Terminal Voltage (TV), against lithium balancing, Shang [16], Sun [17], Fan [18], and other researchers [19-29] have conducted much extensive applied research and analyses method study. However, they are still lacking of effective solutions to the comprehensive evaluation and equilibrium path decision-making for both of these two core factors. To solve this problem, a lithium-ion battery balancing strategy method based on the global best-first balancing strategy is conducted, which achieves the active proportional-plus-floating control based on the lithium-ion battery pack charging the under-voltage imbalance monomers and the over-voltage monomers fly-back discharging lithium-ion battery pack cogitation.

2. GLOBAL BEST-FIRST BALANCING STRATEGY

Lithium-ion battery is classified as lithium cobalt oxide, lithium manganese oxide, lithium iron phosphate and other types depending on the anode materials, among which the lithium cobalt oxide has been used in the trial promotion application in the airborne and other domains due to its high energy density, security and other advantages. The monomer terminal voltage and capacity balancing and other security or reliability troubleshooting methodological analyses of the lithium-ion battery monomers play an important positive role in its promotional application.

2.1. The cause analysis of the monomer imbalance

Lithium-ion battery provides power for the outside load in the discharging process, during which its two electrodes are connected to the load to form a closed loop. Because of the potential difference between these two electrodes, the electrons travel from the cathode toward the anode, meanwhile, in the internal lithium-ion battery, the lithium ions travel from the negative electrode to the positive electrode through the electrolyte and separator, until the positive electrode lithium rich state or negative electrode lithium poor state saturation appears. For example, the anode, negative, and overall lithium-ion battery reaction chemical equations of the lithium cobalt oxide in the charging and discharging process are indicated in equation 1, 2 and 3 respectively.

$$LiCoO_2 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}CoO_2 + xLi + xe^- \quad (1)$$

$$xLi + xe^- + 6C \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_xC_6 \quad (2)$$

$$LiCoO_2 + 6C \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}CoO_2 + Li_xC_6 \quad (3)$$

The lithium-ion battery achieves the electric power storage and power supply application target by the chemical energy and electrical energy transformation in the charging and discharging process shown as above.

In the lithium-ion battery production process, take the lithium cobalt oxide battery for example, due to the monomer materials and presence production process difference that could not be eliminated, the lithium-ion battery has imbalance problems among the monomers during their cascaded group work in the charging and discharging process. And especially after long-term working, the imbalance would gradually become more pronounced.

2.2. Global best balancing strategy

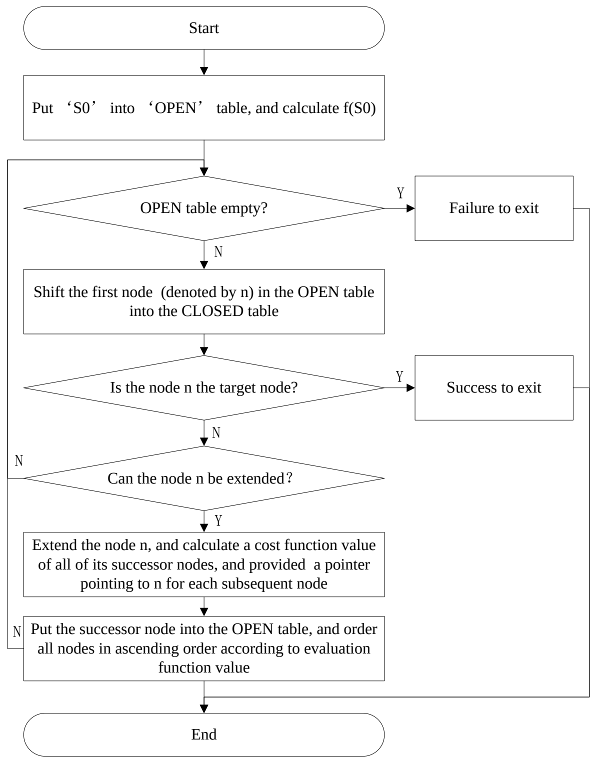

Figure 1. Global best-first search and estimation process

In this paper, a SOC and TV comprehensive evaluation method of the lithium-ion battery monomer is studied, and the target imbalance monomer together with its imbalance degree is determined based on the heuristic global best-first balancing strategy. The basic idea is based on the valuation function f (x) which is used as the detection standard. And it is closely related to the issue features when determining the next expansion node.

In the imbalance monomer selection and its imbalance degree evaluation process, one node is selected with the smallest value of function valuation f (x) among all the nodes in the OPEN table as the next node to be examined in order to implement the selected OPEN table which contains all the nodes to achieve the overall best-first balancing path determination target. It realizes the largest integrated imbalance monomer establishment among all the monomers by the metric imbalance value calculation. The basic process is shown in Figure 1.

2.3. Comprehensive imbalance calculation

Considering these two major elements that affect the equilibrium state of the lithium-ion battery, namely, the single monomer SOC and TV, the lithium-ion battery monomer imbalance reasoning and computing network is built, as shown in Figure 2.

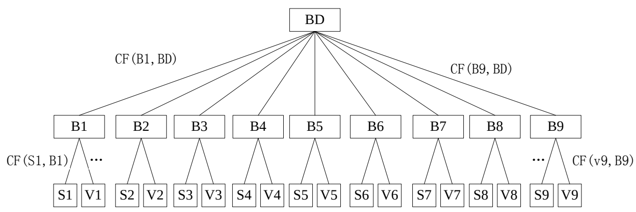

Figure 2. Monomer imbalance inference network

You need to recognize some characteristics of Figure 2, where BD is the overall comprehensive imbalance battery degree which is the representative of the ensemble imbalance, and $Bx(x=1,\cdots 9)$ is the imbalance degree of Battery x which indicates the lithium-ion battery monomer. $Sx(x=1,\cdots 9)$ is the SOC value of the lithium-ion battery monomer that indicates the lithium-ion battery monomer charge state SOC. $Vx(x=1,\cdots 9)$ is the cell terminal voltage (V) of the battery monomer x. $CF(\mathrm{S},\mathrm{B})$ indicates the credibility of the S to B inference rule, namely, the confidence Credibility Factor.

(1) Calculation of the overall imbalance

The decision process is implemented by calculating the overall imbalance degree. The overall imbalance degree is a comprehensive evaluation of the integrated imbalance of the lithium-ion battery, and both the SOC and TV are obtained by calculating the uncertainty inference. The consolidated imbalance degree that influences every monomer calculation process is shown in equation 4.

$$\begin{cases} CFx(\mathrm{BD}) = CF(\mathrm{BD}, \mathrm{B}\,x) \times \max\{0, CF(\mathrm{B}\,x)\} \\ x = 1, 2, \cdots, 9 \end{cases} \quad (4)$$

The integrated imbalance calculation process for all the lithium-ion monomers is shown in the equation 5, which is gained by stepwise superposition of the imbalance influence results.

$$CFmn(\mathrm{BD})=\begin{cases}CFm(\mathrm{BD})+\mathrm{CFn(BD)}-\mathrm{CFm(BD)}\times CFn(\mathrm{BD})\\ \dfrac{CFm(\mathrm{BD})+\mathrm{CFn(BD)}}{1-\min(|CFm(\mathrm{BD})|,|CFn(\mathrm{BD})|)}\\ CFm(\mathrm{BD})+CFn(\mathrm{BD})+\mathrm{CFm(BD)}\times\mathrm{CFn(BD)}\end{cases}\quad(5)$$

The calculation conditions in Equation 5 are arranged as formula 6, corresponding to the order used above sequentially.

$$\begin{cases}CFm(\mathrm{BD})>0,\mathrm{CFn(BD)}>0\\ CFm(\mathrm{BD})\times\mathrm{CFn(BD)}<0\\ CFm(\mathrm{BD})<0,\mathrm{CFn(BD)}<0\end{cases}\quad(6)$$

The lithium-ion battery integrated imbalance degree is obtained by the composite calculation of the imbalance impact of each monomer to determine the operating state of lithium-ion battery and judge its properly working conditions. According to the imbalance degree of the lithium-ion battery, the operating status is gained by the rule that is shown in equation 7, including charging, discharging or shelving status judgment.

$$\begin{cases}charge, CF(\mathrm{BD})>5\%\\ shelve, |CF(\mathrm{BD})|<5\%\\ discharge, CF(\mathrm{BD})<-5\%\end{cases}\quad(7)$$

The protection limit value is obtained according to the imbalance degree after the lithium-ion battery working status is determined in order to prevent excessive imbalance or spontaneous combustion phenomenon resulted by it. The judgment rule is shown in equation 8.

$$\begin{cases}normal, CF(\mathrm{BD})\le 50\%\\ anomaly, CF(\mathrm{BD})>50\%\end{cases}\quad(8)$$

(2) Imbalance degree calculation for individual monomer

The SOC and TV of the lithium-ion battery monomers are two main parameters in its comprehensive imbalance calculation. The comprehensive imbalance state and the imbalance value of the monomers are the main basis in equalization monomer selection and energy transfer direction establishment. The imbalance equilibrium balancing path, balancing speed and balancing direction among monomers are obtained by calculating the monomer comprehensive imbalance value and the global optimum selecting thoughts under imbalance working conditions. The respective monomer imbalance degree calculation is indicated by $CF(Bx)$ which is shown in equation 9.

$$CFm(Bx)=\begin{cases}CFm1(\mathrm{Bx})+\mathrm{CFm\,2(Bx)}-\mathrm{CFm\,1(Bx)}\times\mathrm{CFm\,2(Bx)}\\ \dfrac{\mathrm{CFm\,1(Bx)}+\mathrm{CFm\,2(Bx)}}{1-\min(|CFm1(\mathrm{Bx})|,|CFm2(\mathrm{Bx})|)}\\ CFm1(\mathrm{Bx})+\mathrm{CFm\,2(Bx)}+\mathrm{CFm\,1(Bx)}\times\mathrm{CFm\,2(Bx)}\end{cases}\quad(9)$$

In equation 9, the variation m ($m=1,2,\cdots,M$) is corresponding to the m monomer, and its calculation conditions are sequentially shown in equation 10.

$$\begin{cases}CFm1(\mathrm{B}x)>0,\mathrm{CF}m2(\mathrm{B}x)>0\\ CFm1(\mathrm{B}x)\times\mathrm{CF}m2(\mathrm{B}x)<0\\ CFm1(\mathrm{B}x)<0,\mathrm{CF}m2(\mathrm{B}x)<0\end{cases}\quad(10)$$

$CFm1(\mathrm{Bx})$ and $\mathrm{CFm\,2(Bx)}$ represent the imbalance degree of the SOC and TV value of each individual monomer. The calculation process is shown in equation 11.

$$\begin{cases} CFm1(\mathrm{B}x) = CF(\mathrm{Bx,Sx}) \times \max\{0, \mathrm{CF(Sx)}\} \\ CFm2(\mathrm{B}x) = CF(\mathrm{Bx,Vx}) \times \max\{0, \mathrm{CF(Vx)}\} \\ \mathrm{x} = 1, 2, \cdots, M \end{cases} \quad (11)$$

In equation 11, $CF(\mathrm{Bx,Sx})$ and $CF(\mathrm{Bx},V\mathrm{x})$ respectively indicate the SOC and TV imbalance degree (weight) of the individual monomer, and its initial value is 1, which will be established by the adjusted weight value between 0 and 1 according to the different experimental validation effect.

(3) Balancing strategy

According to the judgment and establishment to the comprehensive imbalance state on the various working conditions, the comprehensive security restriction is judged in a normal situation. The target monomer for the balancing adjustment is defined according to the global best-first balancing strategy. Finally, how fast the energy transfers is determined according to the absolute value of the imbalance degree ($|\mathrm{CF(Bx)}|$), and the energy transfer direction is determined according to the plus-minus value, as shown in equation 12.

$$\begin{cases} positive-charge, CF(Bx) < 0 \\ flyback, CF(Bx) > 0 \end{cases} \quad (12)$$

The novel balancing strategy proposed by us incorporates the thoughts of other scientists. For example, the multiphase interleaved converter for lithium battery active balancing studied by F. Mestrallet [1] and so on. The innovative any cell(s) to any cell(s) active balancing thought is referred and improved. Based on multiphase converter legs connected to each lithium battery potential, it is able to transfer energy from any cell(s) to any cell(s). Developed by the artificial intelligence knowledge, this new balancing mechanism can achieve good results.

3. BALANCING SYSTEM DESIGN AND IMPLEMENTATION

The voltage and capacity value of the individual Lithium-ion battery monomers are both relatively small, and in most cases, single one monomer is difficult to meet the site condition demand. Therefore, it should be cascaded as battery pack to meet the application condition demands. A certain type basic cascading structure of the lithium-ion battery designed by us is shown in Figure 3.

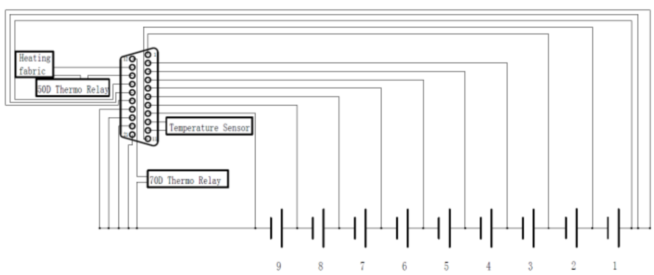

Figure 3. Lithium-ion battery basic cascading structure schematic diagram

The physical meanings of the labels in Figure 3 are shown as followings, the number 1 to 9 indicates the individual battery monomers. Besides, there are still one Heating Fabric, one 50D Thermo Relay, one Temperature Sensor and one 70D Thermo Relay which are shown in the figure 3.

The balancing regulation is achieved according to the lithium-ion battery active global optimal priority equilibrium strategy, and the lithium-ion battery active balancing system is designed, in which the balancing adjustment among these cascaded monomers are realized during the energy supply process. The overall structure of the lithium-ion battery active equalization adjustment system (EAS) is shown in Figure 4, which is designed to realize the active equalization.

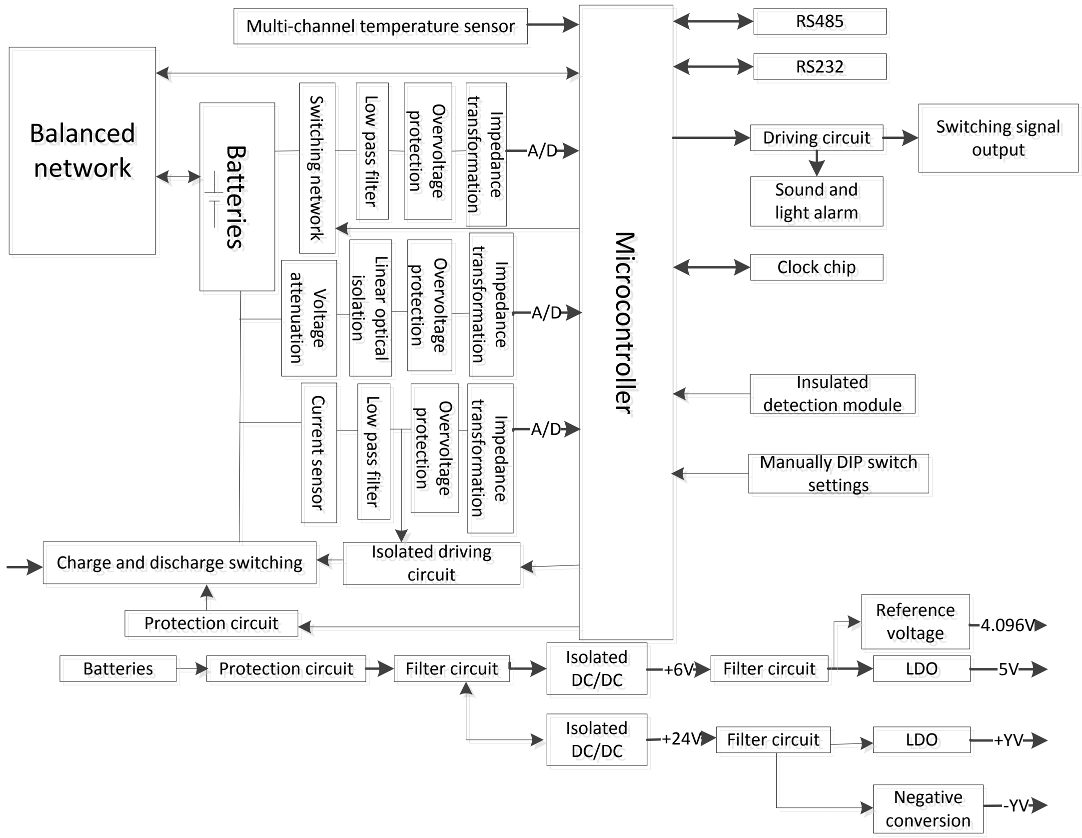

Figure 4. The overall structure diagram of the EAS

The function module diagram of the lithium-ion battery EAS based on the global best-first balancing strategy is shown in Figure 5, in which the EAS is divided into several modules. According to this design thought, the EAS device is realized for balancing the monomers in the lithium-ion battery during its charging, discharging process.

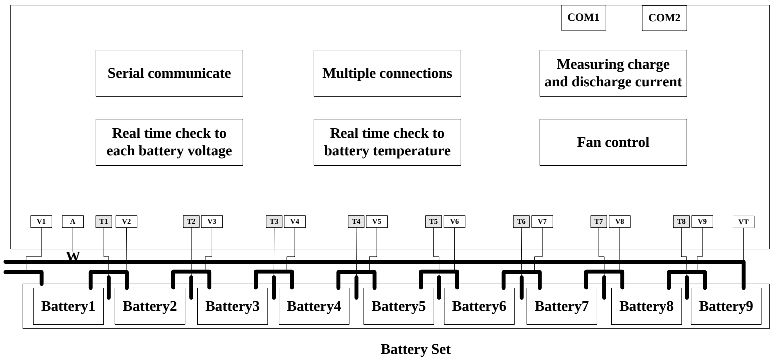

Figure 5. EAS function module diagram

The EAS developed by us has advantages of modularity and standardization, which are Compatible with more modules designed by other researchers. Take the multiphase interleaved converter for lithium battery active balancing designed by F. Mestrallet for example, the converter can be integrated into existing EAS systems. The equalizers designed by other scientists for serially connected lithium-ion battery cells can also be used in the EAS just for one single module.

4. EXPERIMENTAL ANALYSIS

4.1. Capacity variation experiment

Different discharging rate and constant current discharging experiments are done by discharging the lithium-ion battery under different temperature conditions (-20 ℃, -10 ℃, 0 ℃, 10 ℃, 20 ℃, 60 ℃). The total battery discharging amount is recorded, which is emitted by discharging the lithium battery from the full power state to terminal discharging status. The discharging process is stopped by the discharging limits because of reaching the terminal voltage. The experimental results are analyzed by the normalization and other analysis methods.

Experimental results show that different discharging rates have different impacts on the final lithium-ion battery discharging capacity, and it is relatively more pronounced at low temperature conditions.

The lithium-ion battery capacity value have almost no change along with different discharging rates above 0 degree Celsius ambient temperature. However, when the temperature is less than 0 °C, the discharging capacity of the lithium-ion battery significantly reduces as the discharging rate increases. With low temperature conditions, the greater the lithium-ion battery discharging rate is, the less capacity the battery releases. The discharging capacity effect of the experimental results as the temperature changes at 1C discharging rate is shown in Figure 6.

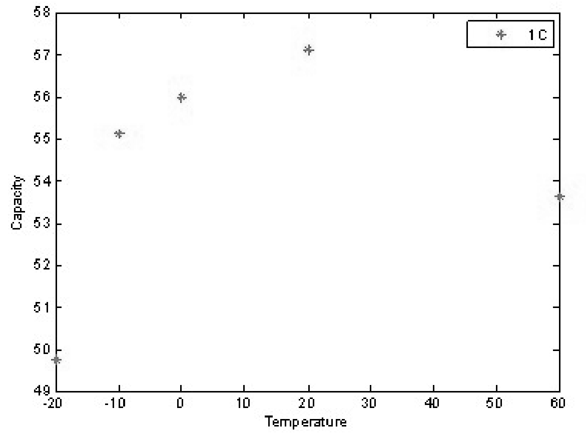

Figure 6. Temperature influence of discharging capacity at 1C discharging rate

By the analysis of the experimental data of Figure 6 about the influence of the temperature to the capacity, we can see that the capacity will grow along the temperature ascension. The Influence of temperature and upper cut-off voltage on the formation of lithium-ion cells are also studied by F. German [12]. In his analysis, especially the part b of Figure 1 in his paper, we can see that the experimental data can comply with the graphite half-cell data but do not comply with the full cell and NMC half-cell data. We have done more experiments and certified our experimental results. As a result, we have participate the heater in our battery and EAS to gain more power supply capacity.

4.2. Voltage variation experiment

During the different discharging rate (9, 12.5, 22.5, 45, 90, 180, 225 A) experiments, the voltage variation regular pattern is obtained in the discharging process under different conditions and normalized by the fitting method to find the overall variation. The normalized discharging voltage characteristic curve under mutative discharging magnification is shown in Figure 7.

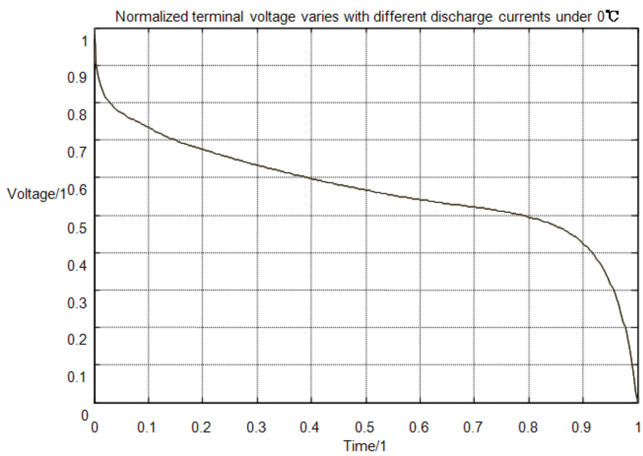

Figure 7. The voltage characteristic curve under different discharging rates

The experimental results are accurate which are proved by comparing with the experimental validation of the multi-D model according to continuous discharging studied by S. Jung [6]. With the comparison the Figure 7 in our manuscript and the Figure 6 in the paper of Multi-dimensional modeling of large-scale lithium-ion batteries, we can see that the voltage changing characteristic is similar in the wake of the discharging time. However, the normalized discharging voltage characteristic studied by us can give more lithium battery characteristics in common for analysis. Only in this way can we realize the EAS more accurately.

During the working mechanism analysis and the basic experimental researches, the comprehensive imbalance degree evaluation methodology based on these two major important parameters (SOC and TV) is explored. The EAS design and implementation target for the lithium-ion battery is achieved, which ultimately realizes the energy equilibrium regulation for the imbalance phenomenon among the lithium-ion battery monomers.

4.3. Balancing adjustment experiment

The real-time detections of the lithium-ion battery parameters are done on the EAS at different equilibrium conditions to realize the active adjustment, which is carried to the processor via the A/D sampling after the immunity dealing process of the circuit jamming noise. The active equalization regulation is done according to the global best-first balancing strategy out of the comprehensive SOC and TV value of the lithium-ion battery. The detection accuracies and the ranges of the parameter specifications are shown in Table 1.

Table 1. Detection accuracies and ranges of the parameters

Para	TV	Temperature	Current	Voltage	SOC
Error	≤0.5%	±1℃	±1A	±5mV	≤5%
Range	0-5V	-30-85℃	0-350A	0-45V	0%-100%

Through the global best-first balancing strategy research, and based on the SOC and TV integrated impact estimation, the online active balancing goal of the lithium-ion battery is achieved by the design and implementation of the active balancing strategy, in which the integrated impact value is referenced. By comparing with the State-of-health monitoring of 18650 4S packs with a single-point impedance diagnostic studied by Love [10], we can see that the EAS designed by us can adapt more lithium-ion battery monomers and the detection accuracy of the core parameters are higher. The EAS can realize the real-time equalization among the individual monomers when the battery is in the discharging or charging state.

Verified by experiments under laboratory balancing regulation on different discharging rate and temperature conditions, this method can achieve the active balancing adjustment among the lithium-ion battery monomers under different working conditions. The EAS realizes the active real-time equalization goal and achieves the monomers balancing regulation for the lithium-ion battery packs, achieving the balancing strategy. The comprehensive imbalance degree of the SOC and TV is no bigger than 8% under different working conditions.

5. CONCLUSION

A novel global best-first active equalization method for the lithium-ion battery is proposed based on the global best-first balancing strategy and comprehensive imbalance calculation, in which the consolidated imbalance estimation of the SOC and TV imbalance degrees are used as the reference values. A lithium-ion battery EAS is developed based on this approach and the balancing strategy for different discharging rate among different monomers. The experiments estimate that this method can achieve the lithium-ion battery active balancing adjustment under different conditions and effectively guarantees the safety of lithium-ion battery monomers, which provides useful indemnification for the reliable energy supply of the lithium-ion battery.

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