Journal of Power Sources 386 (2018) 10–20

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

# A reliability design method for a lithium-ion battery pack considering the thermal disequilibrium in electric vehicles

Quan Xia, Zili Wang, Yi Ren*, Bo Sun, Dezhen Yang, Qiang Feng

*School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China*

## HIGHLIGHTS

- A novel reliability design method for lithium-ion battery pack is proposed.
- Relationships of multi-physics, degradation and reliability models are constructed.
- The temperature distribution and reliability of different battery pack are analyzed.
- The effect of temperature inconsistency on the cell redundancy strategy is analyzed.
- An optimal redundancy strategy of a battery pack is obtained in this paper.

## ARTICLE INFO

*Keywords:*
Thermal disequilibrium
Battery pack
Reliability
Multi-physics
Redundancy strategy
Electric vehicle

## ABSTRACT

With the rapid development of lithium-ion battery technology in the electric vehicle (EV) industry, the lifetime of the battery cell increases substantially; however, the reliability of the battery pack is still inadequate. Because of the complexity of the battery pack, a reliability design method for a lithium-ion battery pack considering the thermal disequilibrium is proposed in this paper based on cell redundancy. Based on this method, a three-dimensional electric-thermal-flow-coupled model, a stochastic degradation model of cells under field dynamic conditions and a multi-state system reliability model of a battery pack are established. The relationships between the multi-physics coupling model, the degradation model and the system reliability model are first constructed to analyze the reliability of the battery pack and followed by analysis examples with different redundancy strategies. By comparing the reliability of battery packs of different redundant cell numbers and configurations, several conclusions for the redundancy strategy are obtained. More notably, the reliability does not monotonically increase with the number of redundant cells for the thermal disequilibrium effects. In this work, the reliability of a $6 \times 5$ parallel-series configuration is the optimal system structure. In addition, the effect of the cell arrangement and cooling conditions are investigated.

## 1. Introduction

With the deepening of the global energy crisis, the depletion of oil resources and the increased risk of air pollution and global warming, governments and auto companies generally recognize that energy conservation and emission reductions are the main directions of future automotive technology development. Developing electric vehicles (EVs) will be the best approach to solve these two technical difficulties. Currently, lithium-ion batteries, with their high voltage, large specific energy, portable nature, low self-discharge rate, and relatively long life [1], have been widely used in EVs and other energy storage systems [2]. In the future, hybrid electric vehicles (HEVs) and pure battery electric vehicles (BEVs) will likely replace transportation vehicles that use liquid fuels; however, the major challenge is the performance and cost of batteries [3,4]. For EVs, as a commodity, there are three main problems: the limited driving range, long battery charging time and high cost of the battery pack [5]; the reliability of the EV battery pack is one of the primary factors influencing these problems.

To solve these problems, scholars have performed research to improve the reliability of the power battery pack. According to a literature review, there are two main approaches to improving the reliability. One approach is devoted to basic research on lithium-ion cells, such as the development of new materials and material modifications [6,7], which include related research in materials and chemistry and are not listed here. This approach can improve the reliability of a battery pack system by improving the reliability of cells; however, it is limited by the

* Corresponding author.
*E-mail address:* renyi@buaa.edu.cn (Y. Ren).

https://doi.org/10.1016/j.jpowsour.2018.03.036
Received 19 November 2017; Received in revised form 11 February 2018; Accepted 13 March 2018

reliability of the battery cell, which is at the limit of current science and technology. The other approach is to improve the reliability of a battery pack system from the perspective of the system design, including thermal management [8,9], structural redundancy [10], fault diagnosis and health management [11], and battery management system engineering [12]. Among them, the redundancy design is one of the most important methods, i.e., adding redundant battery cells and applying an appropriate redundancy strategy. The use of cell redundancy coupled with appropriate designs of the equalization circuit can effectively improve the reliability of a lithium-ion power battery pack, prolong the life of EVs, and reduce the operating costs caused by the replacement of the battery pack [13].

In fact, adding redundant cells is a simple and direct method to improve the reliability of a battery pack. However, there are still several problems to be solved:

1) Temperature inconsistency: Because of the irregularity and complexity of the structure, the environment of each cell in a battery pack must be different, resulting in an inconsistent temperature distribution during operation. Studies have shown that temperature is one of the important factors affecting battery degradation [14,15].
2) The redundancy strategy (redundancy number, configuration, etc.) requires a more complex structure of the battery pack, which in turn affects the temperature inconsistency.
3) In EVs, the arrangement, cooling conditions and other battery usage and management methods will also affect the degree of the temperature inconsistency.

The coupling effects of the abovementioned problems and factors lead to the inconsistent degradation of cells in a battery pack. However, in the existing research of battery redundancy [13,16,17], it is usually assumed that the degradations of cells are identical; this assumption ignores the temperature inconsistency. In fact, the life of the battery pack is often determined by the most degraded cell because of the 'Buckets effect'. Thus, the degree of temperature inconsistency determines the degree of the degradation inconsistency, which in turn affects the life, reliability and redundancy control of the battery pack system. The integration of temperature inconsistency and the redundancy structure of a battery pack is the focus of this paper.

To study the temperature inconsistency, the temperature field of a battery pack should be studied. According to a literature review, there are two methods to study the temperature field of a battery pack: experiment and simulation. Based on the thermal behaviors, some experiments were conducted on types of batteries. The experimental schemes mainly focused on battery charging and discharging [18,19], thermal abuse [20], thermal runaway [21,22], forced cooling [23], phase change materials [24] and other thermal management aspects. At present, the advanced modern electrochemical analysis methods and testing instruments can elucidate the mechanisms of battery materials for battery performance; thus, the material properties can be summarized, and the performance and reliability of a battery pack can be evaluated by experimental methods. However, there are several limitations that make it difficult to control a single variable and to simultaneously take into account both multi-scale and multi-physics factors. Moreover, the reliability design of a battery pack via experiments is costly and time-consuming. Conversely, numerical simulations can be a good approach to overcome the above shortcomings [25].

Currently, with the development of numerical simulation analysis technology and related hardware and software, multi-physics simulation is a promising method. It is known that lithium-ion battery packs are complex electrochemical network systems that contain a variety of electrochemical reactions, mass transfer, charge transfer, heat transfer, and material variations. Therefore, multi-physics coupling analyses have important guidance for the reliability analysis and optimization design of lithium-ion battery packs.

The multi-physics field of lithium-ion battery packs mainly includes electric, chemical, thermal, and flow fields. Since the 1990s, some scholars began to study the thermal behavior of lithium-ion batteries. The two-dimensional thermal model and three-dimensional thermal model were used to study the temperature field of square lithium polymers and square lithium-ion batteries for EVs by Lawrence National Laboratory, University of Berkeley, USA [26,27]. Based on the first principle, a one-dimensional thermoelectric coupling model was established by Gu et al. combining the heat energy equation with the multiphase electrochemical model using the heat production equation and the temperature dependence of materials, they studied the mechanism of thermal runaway [28]. Chen et al. combined the Bernardi equation and basic heat transfer equations to describe the thermal characteristics of lithium-ion batteries. They simplified the heat generation conditions and discussed the heat dissipation process under different convection coefficients [29]. Kumaresan et al. established a thermal model of a soft package lithium-ion battery, and its performance under different cooling conditions and discharge rate were studied [30]. In recent years, with the development of multi-physics analysis technology, research on the multi-physics coupling of lithium ion batteries has been performed by scholars [31–36]. Models that describe the battery are being proposed and perfected gradually, including the pseudo-two-dimensional (P2D) electrochemical model, the three-dimensional (3D) thermal model, and the equivalent circuit model.

For lithium-ion battery packs, coupled sub-models are often used to describe their electrothermal characterization. For example, coupling the electrochemical, three-dimensional thermal and equivalent circuit sub-models of each sub-module, the surface temperature of cells and the entire battery pack were estimated by Sun et al. [34]. Lee et al. defined the winding structure using three sub-models and studied the temperature field of the cylindrical wound large capacity lithium-ion battery [35]. A design methodology using virtual prototyping techniques based on CFD simulations is proposed to analyze the temperature distribution and valuate the thermal management of lithium-ion battery pack by Cicconi et al. [37]. An algorithm for a multi-objective optimization design of a lithium-ion battery pack was proposed by Palma-Behnke et al. based on the multi-physics coupling simulation method [38]. Thus, the method of multi-physics simulation is definitely an accurate scientific method for the thermal analysis of a battery pack. However, to our knowledge, there is still no system reliability model and analysis of a battery pack based on multi-physics simulation.

Consequently, to analyze the thermal disequilibrium, the multi-physics coupling simulation method is used to study the temperature distribution and temperature inconsistency of a battery pack in this paper. By establishing the relationship between the multi-physics coupling model, the degradation model and the system reliability model of battery pack, a reliability design method of lithium-ion battery packs considering the thermal disequilibrium based on cell redundancy is proposed. The paper is organized in five sections. The general framework of the reliability design method is shown in Section 2. The models of the lithium-ion battery pack are established in Section 3, including the multi-physics coupling model, the battery degradation model and the system reliability model. The reliability of a battery pack with different redundancy strategies is calculated and analyzed in Section 4 and followed by the simulation and analysis of the influences of the arrangement and cooling condition. Finally, conclusions and future work are presented in Section 5.

## 2. The framework for the reliability design method of lithium-ion battery packs

In this section, the general framework of the reliability design method for lithium-ion battery packs is described. The framework contains the following four steps, as shown in Fig. 1.