Reliability Engineering and System Safety 134 (2015) 169–177

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

A reliability-based design concept for lithium-ion battery pack in electric vehicles

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ARTICLE INFO

Article history:
Received 28 October 2013
Received in revised form
3 September 2014
Accepted 7 October 2014
Available online 29 October 2014

Keywords:
Multi-state systems
Reliability
Universal generating function
State of health
Battery pack
Electric vehicle

ABSTRACT

Battery technology is an enabling technology for electric vehicles (EVs), and improving its safety and reliability while reducing its cost will benefit its application to EVs. In this paper, a method on the design and analysis of lithium-ion (Li-ion) battery pack from the reliability perspective is presented. The analysis is based on the degradation of the battery pack, which is related to the cells configuration in the battery pack and the state of health (SoH) of all the Li-ion cells in the pack. Universal Generating Function (UGF) technique is used for reliability analysis. As adding new battery cells to the battery pack in the production process can improve its reliability but it also increases cost, tradeoff between the number of the redundant battery cells, the configuration of the redundant cells and their reliability is investigated in this work.

1. Introduction

In view of the fossil fuel depletion and the emission of greenhouse gases (GHG) with the fossil fuel, and the fact that transportation is a major source of GHG emission and usage of the fossil fuel, research and development of electric vehicles (EVs) are blooming significantly. With EVs, their energy sources can be renewable clean energy sources through the recharging of Li-ion battery packs from these clean energy sources, and no GHG emission occurs with EVs.

These EVs are driven by electric motors instead of internal combustion engines. These motors are powered by the Li-ion battery packs in the vehicles. Li-ion batteries are used because they have the highest energy and power densities, and their life time is sufficiently longer [1]. In fact, it is because of the Li-ion battery technology that enables EVs to be a realistic product that we see in the market today worldwide [2].

While EVs are now commercial products, there are three main challenges that are being researched into, namely the limited driving range, long batteries charging time and high cost of the battery pack [2]. All these challenges are closely link to the applications of the Li-ion battery pack in EVs. The high cost of the pack in turn is related to the reliability of the pack because if the pack has low charge/discharge cycle life time, the replacement frequency of the pack will be high, and this will increase the operating cost of the EVs.

Currently, the battery pack of EV contains more than 100 Li-ion cells, and when one cell becomes aged, other cells will have to carry the load and this can cause other cells to degrade rapidly. On the other hand, due to the safety consideration, one cannot open the pack and replace the aged cells in the pack. Thus, when a few cells get aged, the entire pack will have to be replaced and sent to the workshop, and this increases the operating cost of EVs significantly and unnecessary.

The above-mentioned situations will happen even with the use of reliable cells, and thus to reduce the unnecessary replacement of the pack and to prolong the life span of the pack, redundant cells are designed in the pack [3].

Several works reported the reliability analysis of battery packs, and they can be divided into the following categories of focus. The references quoted below are the typical papers selected for each category.

1.1. Thermal management of battery pack to improve pack reliability

The temperature in battery pack is an important factor which affects the safety and reliability of the cells when the vehicle is

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http://dx.doi.org/10.1016/j.ress.2014.10.010
0951-8320/

running. Using thermal management in BMS (battery management system) can improve the reliability of the battery pack. In this category of research works, the heat generation model, the methods of cooling and air flow in the battery packs are investigated [4–7].

1.2. Cell redundancy and configuration to improve pack reliability

In order to improve the reliability of the battery packs, different configurations of cells and the use of cell redundancy, coupled with appropriate designs of DC/DC converters are proposed [8–10]. However, no quantitative relationship between the pack reliability and redundant cells configuration is discussed.

1.3. Prognostic and health management for battery packs

Since there are inevitable differences in the cells, a cell in battery packs could become overcharged and/or over-discharged. This could in turn reduce the lifetime of the packs. Generally speaking, the health state of an individual degraded cell is difficult to detect in a battery pack. To ensure safe driving, the battery packs are routinely replaced even though they do not exhibit any problems, but this will increase the maintenance cost for the drivers. Prognostic and health monitoring (PHM) technology is thus proposed to monitor the battery pack in the EVs. It can monitor the battery pack states during their operations, and extend their useful lives correspondingly [11].

In order to improve the reliability and safety of a battery pack, one simple and direct method is to add redundant cells to the battery pack, but two associated questions should be investigated. First, the configuration of the redundant cells in the battery pack; Second, the number of redundant cells for cost effectiveness. In this work, a design concept is developed to answer these two questions quantitatively.

For the first question, the effect of cells configuration in the pack on the pack's reliability is generally overlooked. However, the effect can be significant. Let us illustrate the effect with the following idealistic example.

Assuming perfect conversion such that the total power in the battery pack can be converted into the required voltages and currents at a given output power without any loss, Figs. 1–3 show four possible configurations of 10 identical cells in a battery pack.

Assuming every cell has two states, namely the normal and abnormal, and the probability of a cell in the abnormal state is x. Given that the different battery packs are to supply the same power P, the current I through each cell in the 4 different configurations will be the same and equal to $I=(P/10V_0)$, where V_0 is the voltage of a cell. If we assume that the battery packs are charged/discharged for the same number of cycles, and the degradation of the cells are identical, the probability of normal state for the battery packs with different configurations could be calculated as follows, and they are shown in Fig. 4.

$$P_a = 1-\left[1-(1-x)^5\right]^2 \tag{1a}$$

$$P_b = (1-x^2)^5 \tag{1b}$$

$$P_c = 1-\left[1-(1-x)^2\right]^5 \tag{1c}$$

$$P_d = (1-x^5)^2 \tag{1d}$$

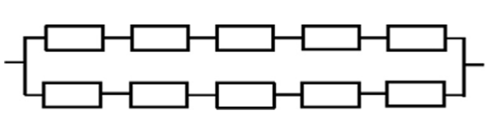

Fig. 1. Structure a.

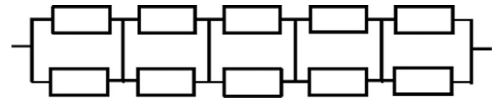

Fig. 2. Structure b.

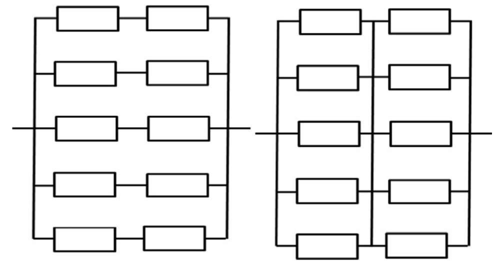

Fig. 3. Structure c (left) and structure d (right).

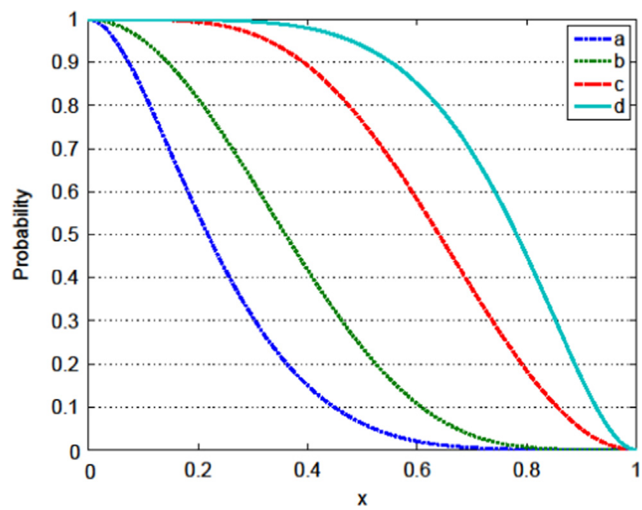

Fig. 4. The probability for different structures.

From the above example, we can see that the reliabilities of the parallel-series structures, i.e. structures b and d are higher than the series-parallel configurations, i.e. structure a and c, with structure d being the best for the reliability. Therefore, if the redundant cell number and cost are not in consideration, adding more parallel branches in battery pack will be preferred, and its reliability can be greatly enhanced [12]. With cost consideration, tradeoff between reliability and the number of the cells is inevitable, and this is the focus of this work.

State of health (SoH) of the cells will be used here for analysis. SoH is defined as a variable which reflects the general health condition of a cell and its ability to deliver specified energy or charge as compared to its fresh state. The knowledge of SoH can be used to recognize ongoing or abrupt degradation of the cells and to prevent possible failure.

There have been many SoH methods in literatures [13–17], and none is considered as standard currently. To illustrate our design concept, any SoH method that models the effects of temperature, charge–discharge cycling and current on cell capacity fading, and its rate capability losses will be good enough for our purpose. In this work, we choose the model proposed in [17], which is also used by others [18,19]. This model is based on the electrochemistry mechanisms of the cells. With this model, a capacity fade prediction that describes the degradation effects from the charge and discharge cycling number, temperature and the discharge rate is possible.

To calculate the reliability of a battery pack using the cell's SoH, multi-state systems (MSS) and universal generating function (UGF)