Information Sciences 259 (2014) 359–368

Contents lists available at SciVerse ScienceDirect

Information Sciences

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

Reliability assessment and failure analysis of lithium iron phosphate batteries

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ARTICLE INFO

Article history:
Available online 20 June 2013

Keywords:
Lithium iron phosphate battery
Pattern recognition
Life cycle test
Reliability diagnosis
Cluster analysis
Failure analysis

ABSTRACT

In this paper, we present experimental data on the resistance, capacity, and life cycle of lithium iron phosphate batteries collected by conducting full life cycle testing on one type of lithium iron phosphate battery, and we analyse that data using the data mining method of pattern recognition. We also predict battery reliability using cluster analysis. A strategy for enhancing the reliability of lithium iron phosphate batteries is proposed based on a statistical analysis and study of the macromechanism of product failures. We show in practice that the average life cycle of a battery is increased by 45.5% after adopting a new strategy that we suggest. The strategy is effective for mass-producing reliable lithium iron phosphate batteries and instructive for improving the industry of lithium iron phosphate battery production, as well as the quality of its products.

1. Introduction

Lithium iron phosphate cells, widely used to power electric vehicles, have been recognized for their high safety, relatively longer life cycle, environment friendliness, higher power, and other attractive features [29,11]. At a room temperature of 25 °C, and with a charge–discharge current of 1 C and 100%*DOD* (Depth Of Discharge), the life cycle of tested lithium iron phosphate batteries can in practice achieve more than 2000 cycles [13,8]. A major Li-ion battery manufacturer, Valence, also reported that after 2000 cycles of charge–discharge its cell can maintain more than 80% of its rated capacity. At present, the average life cycle of this type of cell made in China is generally lower than that. Production and engineering application of this kind of battery made in China would face severe tests [27,32].

Analysis of the reliability and failure mode of lithium iron phosphate batteries is essential to ensure the cells quality and safety of use. For this purpose, the paper built a model of battery performance degradation based on charge–discharge characteristics of lithium iron phosphate batteries [9]. The model was applied successfully to predict the residual service life of a hybrid electrical bus. The paper conducted research on predicting the life cycle of lead–acid, NI–MH, and Lithium ion batteries at different temperatures [7]. The papers [14,12] also discuss the influence of work temperature and discharge current on the life cycle of batteries, and an empirical model was built based on the experimental results [14,12]. There is literature that discusses the mechanism of capacity degradation of lithium-ion batteries, according to the charging law of voltage, capacity, and internal resistance in the battery charge–discharge process [15], and there has been literature that discusses the failure mode of lithium ion batteries in small current discharge, using the Kolmogorov–Smirnov Test (K–S) to test goodness of fit on the distribution of lithium-ion battery life, as well as conducting a statistical analysis of lithium batteries storage reliability [17]. However, there has been little work on the reliability of lithium iron phosphate batteries.

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0020-0255/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ins.2013.06.038

In this paper, we use clustering techniques and statistics to assess the reliability and analyse the reasons behind the failure of lithium iron phosphate batteries. Based on life cycle tests on a batch of cell samples taken from a production of batteries, along with collected test data, an objective evaluation of the reliability of the products is conducted. Through macroanalysis of the failure effect and microScanning Electron Microscopy (*SEM*), this paper reports the main reason and mechanism for these failures, works out a strategy for enhancing the reliability of lithium iron phosphate cells, and provides an effective method for mass-producing reliable lithium iron phosphate batteries. We prove in practice that the average life cycle of a battery is increased by 45.5% after the strategy we suggest is adopted. Research related to this paper will be significant for the improvement of the lithium iron phosphate battery industry.

2. Charge–discharge cycle life test

Ninety-six 18650-type lithium iron phosphate batteries were put through the charge–discharge life cycle test, using a lithium iron battery life cycle tester with a rated capacity of 1450 mA h, 3.2 V nominal voltage, in accordance with industry rules. The environmental temperature, while testing with a 100%*DOD* (Depth of Discharge) charge–discharge cycle test, was 20 °C ± 2 °C [24]. Each cycle period automatically monitors and records the voltage, current, capacity, internal resistance, run time, and other parameters of each battery. The battery testing process is shown in Table 1.

Fig. 1 is the charge–discharge cycle curve of a single lithium iron phosphate battery during one time interval, along with the curve of the batterys voltage in each time interval and the curve of the capacities of the batteries in each cycle.

According to the testers record, ninety-six battery samples failed (when the battery capacity is less than 1100 mA h). The cycles are listed in Table 2 in increasing order, equivalent to the full life cycle test. In order to find better performance rules for failing cells, we continued the test when the battery capacity reached the failure scale. When the cycles reach about 2000, the failure capacity and the internal resistance were recorded and compared with the initial parameters. See details in Table 3.

3. Reliability diagnosis of lithium iron phosphate battery cell

3.1. The hypothesis of failure distribution

As reported, most cell failure distributions follow the probability of *Weibull*, normal, exponential, or the like, so we tested the failure data for many kinds of probability distribution. We find the *Weibull* distribution fits the sample data best. The sample data tends to be a straight line on the *Weibull* probability more than on the others, so we can consider that the failure law of lithium ion batteries satisfies the *Weibull* distribution, as shown in Fig. 2. Because $F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right]$, we can obtain $ln\left(ln\frac{1}{1-F(t)}\right) = mlnt - mln\eta$. In Fig. 2, when $Y = lnln\frac{1}{1-F(t)},\ X = lnt$, the curve represents a linear relationship. Therefore, m is the slope of the curve, that is, shape parameter, $-mln\eta$ is the intercept, so $F(t) = 1 - \exp[-(e)^Y]$ marked on the Y scale of the vertical axis.

By comparing the residual squares, we determined the battery life preliminarily to be close to a two-parameter *Weibull* Distribution, with $\beta = 10.202$, $\eta = 894$. Hypothesis testing must be performed on the distribution type to improve the credibility of the estimation.

3.2. χ^2 Test of distribution type

The failure law of the experimental sample estimated according to probability basically follows the *Weibull* distribution. The χ^2 fitness test can be used to verify further the correctness of that conclusion [10,26,20].

Assume that the distribution function of the life cycle of domestic 18650-type lithium iron phosphate battery cells is:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \quad (1)$$

Table 1
Process flow of battery life cycle.

Test object	Process flow
96 lithium iron phosphate batteries (rated capacity: 1450 mA h)	①Halt 30 min ②5 C constant current charge to 3.65 V, and constant voltage charge to 0.1 C ③Halt 30 min ④5 C constant current discharge to 2.0 V ⑤Record the battery capacity ⑥Repeat step ①to ⑤, Until the battery capacity is under 880 mA h