Expert Systems with Applications 38 (2011) 15183–15193

Contents lists available at ScienceDirect

Expert Systems with Applications

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

State-of-health estimator based-on extension theory with a learning mechanism for lead-acid batteries

Kuei-Hsiang Chao *, Jing-Wei Chen

Department of Electrical Engineering, National Chin-Yi University of Technology, Taiwan

ARTICLE INFO

Keywords:
Lead-acid batteries
Extension matter-element model
State-of-health (SOH) estimator
Coup de fouet voltage
Programmable system-on-chip microcontroller

ABSTRACT

The main objective of this paper is to design and implement an improved intelligent state-of-health (SOH) estimator for estimating the useful life of lead-acid batteries. Laboratory studies were carried out to measure and record the distributed range of characteristic values in each SOH cycle for the battery subject to cycles of charging and discharging experiments. The measured coup de fouet voltage, internal resistance, and transient current are used as characteristics to develop an intelligent SOH evaluation algorithm. This method is based on the extension matter-element model that has been modified in this research by adding a learning mechanism for evaluation SOH of batteries. The proposed algorithm is relatively simple so that it can be easily implemented with a programmable system-on-chip (PSOC) microcontroller achieve rapid evaluation of battery SOH with precision by using a concise hardware circuit.

1. Introduction

For most normal lead-acid batteries, state-of-health (SOH) is determined by measuring the usable capacity of a fully-charged lead-acid battery. In past literature, besides direct use of the Coulometric measurement method, there are lead-acid battery SOH estimation approaches (Robinson, 1996), as characterized in terminal voltage, internal resistance, operating temperature, and the voltage phase angle, which is measured after AC current input to batteries. However, these characteristic values generally vary with battery aging, thus exacerbating SOH estimation. Recently, many expert scholars suggest analysis of the coup de fouet voltage derived at the initial discharge period of a fully-charged lead-acid battery, and thus the SOH of a lead-acid battery could be estimated from its trough value, plateau voltage, or occurring time (Bose & Laman, 2000). Compared with other characteristics, the tendency of coup de fouet plateau voltage versus battery usable capacity is the most linear, thus, using this characteristic to estimate SOH of battery life can achieve accuracy to some extent. There have been many studies on the coup de fouet voltage of a lead-acid battery (Anbuky & Pascoe, 2000; Pascoe & Anbuky, 2005), such as Prof. Pascoe et al., which reported that lead-acid battery coup de fouet voltage can definitely reveal the current SOH of a battery. However, experts failed to determine a definite interpretation of such phenomenon until 2006, when Prof. Delaille et al. (Delaille, Perrin, Huet, & Hernout, 2006) reported that this was primarily a transient phenomenon arising from redox reaction between a sulfuric acid electrolyte (H_2SO_4) in a positive electrode container and a lead sulfide ($PbSO_4$) on a positive electrode plate, in a battery unit. This phenomenon is not restricted to occur in a fully-charged lead-acid battery at the time of discharge moment. In fact, when maintaining and stabilizing a lead-acid battery electrolyte for a period of time, both charging and discharge behaviors would induce such coup de fouet phenomenon (Delaille et al., 2006). When measuring the coup de fouet voltage of a lead-acid battery, the charging/discharging state must be controlled for achieving the measurement condition with one accord. Therefore, it remains difficult to determine the battery SOH simply from the coup de fouet voltage of a lead-acid battery.

In order to improve the lead-acid battery SOH estimation accuracy, many studies have employed intelligent algorithms to estimate the lead-acid battery life state, such as the neural network (Kim et al., 2009; Valdez et al., 2006), fuzzy (Shen et al., 2002; Spath, Jossen, Doring, & Garche, 1997; Wang, Wang, Lee, & Tseng, 1995) and neuro-fuzzy (Jang, 1996; Lin & Lee, 1999; Oh, Pedrycz, & Park, 2006; Pascoe & Anbuky, 2001) algorithms, and combined multiple characteristics representing the lead-acid battery SOH to study the relationship between each characteristics and data of each battery SOH, thereby improving recognition accuracy. Nonetheless, data distribution of lead-acid battery SOH representative characteristics, often appear nonlinear to battery usable capacity throughout the battery service life. Therefore, to estimate the battery SOH from a change of battery usable capacity during the entire lead-acid battery service life, besides considering the battery SOH characteristics, additional testing methods must be imposed in order to improve SOH estimation accuracy.

* Corresponding author. Tel.: +886 4 2392 4505x7272; fax: +886 4 2392 2156.
E-mail addresses: chaokh@ncut.edu.tw, chaokh0706@yahoo.com.tw (K.-H. Chao).

0957-4174/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2011.05.084

Therefore, this study conducts multiple lead-acid battery charging/discharging tests to propose a modified recognition structure based on extension theory (Cai, 1983), so that battery SOH recognition can be more accurate. Input characteristics for the proposed estimation approach include coup de fouet plateau voltage of lead-acid battery, internal resistance under lead-acid battery floating charge, and the ratio of these two characteristics (i.e., coup de fouet voltage plateau value/battery internal resistance, called transient current). By computing the correlation degree of these three characteristics with lead-acid battery usable capacity, this study can improve the estimation accuracy of the lead-acid battery life. It also references a recognition system based a neural network training mechanism from previous literature, takes absolute mean error between training data and recognition results for adjustment basis to expand/reduce the classic field of extension matter-element model, and further modify recognition results to meet the objective of the training data, and achieve the optimum estimation accuracy.

2. State-of-health characteristics of lead-acid batteries

Coup de fouet voltage is a kind of transient phenomenon, when discharging a fully-charged lead-acid battery, battery terminal voltage would fall instantaneously at initial discharge period, and thereafter restore to normal load voltage. As shown in Fig. 1, the minimal voltage during transient response to coup de fouet voltage is called trough voltage, and after trough voltage appears, battery discharge voltage will restore to discharge voltage in loading; battery terminal voltage at this time is called plateau voltage.

The most significant indicator of lead-acid battery SOH is usable capacity. Based on a knowing of usable capacity, one can further estimate remaining charging/discharging cycles or sustainable floating charge time of a lead-acid battery. According to previous literature, lead-acid battery SOH can be categorized in terms of five characteristics, operating temperature, internal resistance, floating voltage, floating current, and coup de fouet voltage. When choosing lead-acid battery SOH estimation characteristics, the following major factors are taken into account.

2.1. Refrain from prolonged monitoring of equipment

To users, battery SOH does not require real-time estimation, but the use of the Coulometric measurement method or prolonged monitoring of battery operating temperature requires more memory capacity of the estimation system, which benefit neither hardware volume nor cost, and prolonged estimation would impact on battery use.

2.2. Restriction of estimation circuit hardware

As the relationship between lead-acid battery SOH and usable capacity is a nonlinear function, more characteristics are normally required to estimate its usable capacity in order to improve accuracy. However, the more characteristics used, the more complicated the estimation system, the higher the cost, and the more restrictions in application. Therefore, how to use the fewest estimation apparatus to achieve highly accurate SOH estimation remains a critical research topic.

2.3. Adaptiveness of estimation approach

Usable capacity of lead-acid battery can act as a uniform indicator for both battery floating life and recycle life. However, battery floating or recycling uses variable charging/discharging methods, therefore, if estimating SOH using a constant program testing method while satisfying both battery application modes, then the estimation approach would be more widely applied.

Based on the above factors, it is a good choice to select coup de fouet voltage as the major characteristic for estimating lead-acid battery SOH. The reason that coup de fouet voltage failed to estimate lead-acid battery SOH previously is that its variation is little, thus, error factors were too much. In other words, almost any kind of battery application environment factor, such as current floating voltage, previous depth of discharge, charging/discharging current and post-charge waiting time, could all cause measurement errors. In the implementation of a measuring system, a 10 mV scaled meter and a timekeeping device can measure coup de fouet voltage, except that the constant current discharge is difficult on a battery. Considering the influences of various factors on coup de fouet voltage, this study performs 10% and 100% depth discharge on a 12V-13Ah lead-acid battery, respectively, and adopted a 0.1 C current to charge the lead-acid battery, allowing the charge voltage to reach 15.2 V and floating charge, then measured internal battery resistance and floating voltage after 120 min waiting time, followed by a 0.5 C current to discharge the battery for 10 min in order to acquire its coup de fouet voltage data. The general test system structure is shown in Fig. 2, where a programmable system on chip (PSoC) microcontroller is the control kernel of the entire system

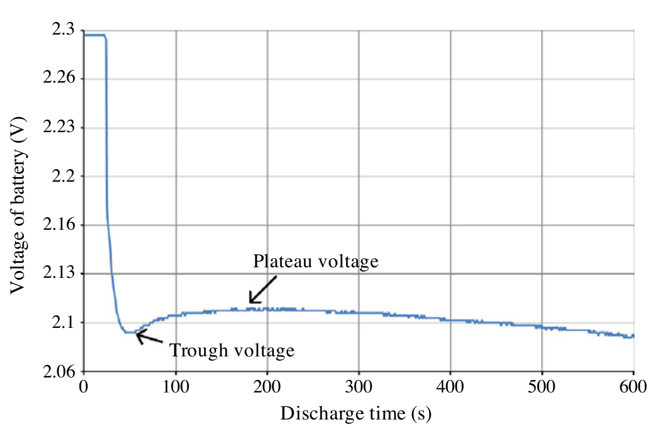

Fig. 1. Test curve of coup de fouet voltage for a lead-acid battery.

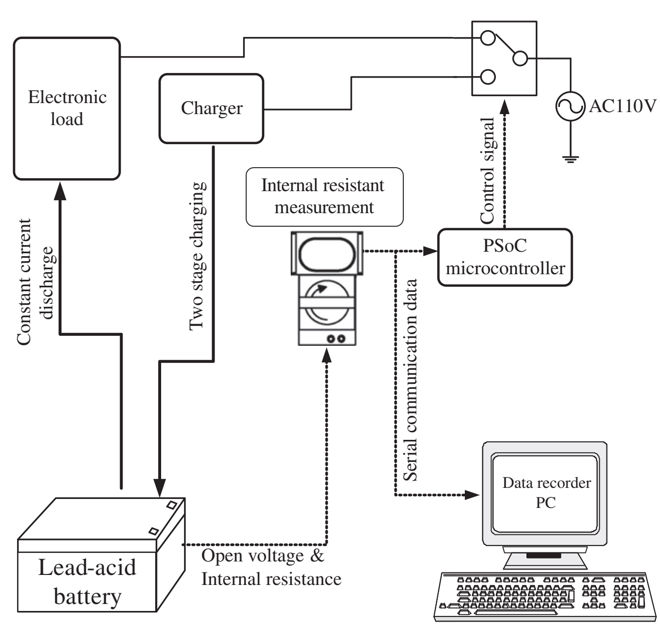

Fig. 2. Scheme of lead-acid battery coup de fouet voltage acquisition system.