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State of available capacity estimation for lead-acid batteries in electric vehicles using neural network

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Abstract

This paper reviews recent definitions of the state of charge (SOC) that are often used to estimate the battery residual available capacity (BRAC) for lead-acid batteries in electric vehicles (EVs) and identifies their shortcomings. Then, the state of available capacity (SOAC), instead of the SOC, is defined to denote the BRAC in EVs, which refers to the percentage of the battery available capacity (BAC) of the discharge current profile for the EV battery at the fully charged state. Based on the experimentation of different discharge current profiles, including theoretical current profiles and practical current profiles under EV driving cycles, the discharged and regenerative capacity distribution is proposed to describe discharge current profiles for the SOAC estimation. Because of the complexity and nonlinearity of the relationship between the SOAC and the capacity distribution at different temperatures, a neural network (NN) is applied to this SOAC estimation. Comparisons between the estimated SOACs by the NN and the calculated SOACs from the experimental data are used for verification. The results confirm that the proposed approach can provide an accurate and effective estimation of the BRAC for lead-acid batteries in EVs.

Keywords: Capacity indicator; Lead-acid batteries; Electric vehicles; Neural network; State of available capacity

1. Introduction

In a world where environmental protection and energy conservation are growing concerns, the research and development of various technologies in electric vehicles (EVs) is being actively conducted [1,2]. However, the application technology of EV batteries, namely the battery residual available capacity (BRAC) indicator for lead-acid batteries in EVs, cannot keep pace with the development of other EV technologies. The key problem arises from the highly nonlinear characteristics of EV batteries, leading to difficulty in the BRAC estimation and, thus, the driving range estimation for EVs.

Conventionally, the BRAC estimation for the EV battery has been represented by estimation of the battery state of charge (SOC). The purpose of this substitution is to avoid the difficulty in defining the BAC at the fully charged state for various discharge current profiles of the EV battery. There are many papers describing various attempts to estimate the SOC for EVs using different approaches as summarized in Ref. [3]. Nevertheless, the SOC, in fact, is different from the BRAC for the EV battery. Theoretically, the SOC defines the ratio of the remaining active material to the total original active material inside a battery. In this sense, the SOC indicates only the battery state rather than the BRAC on which the EV driving range is dependent. Although the higher the SOC is, the more the BRAC can be exhibited at the same discharge current, they have no explicit quantitative relationship. For example, increasing the battery temperature or lowering the discharge current will cause an increase of the BAC at the same SOC. Fig. 1 shows the effect of discharge current and temperature on the BAC at the fully charged state of one lead-acid battery, where the SOC of the battery at the fully charged state is generally defined as unity.

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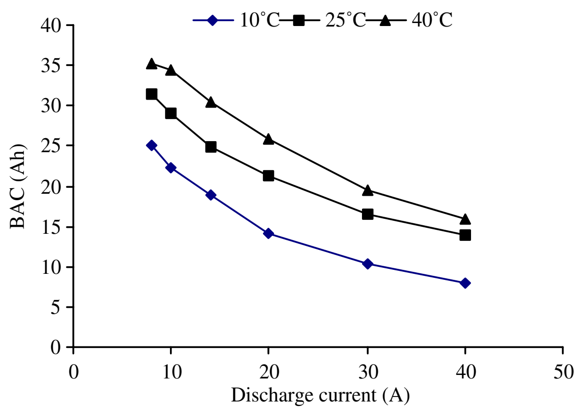

Fig. 1. Effect of discharge current and temperature on the BAC.

On the other hand, some direct estimation methods of BRAC for the EV battery have been explored by using colometric measurement. The idea simply originated from the following basic equation:

$$C_r = C_a - q(t) \tag{1}$$

where C_r denotes the BRAC; C_a is the BAC measured from the discharge test as described in Section 3 and $q(t)$ is the discharged capacity given by

$$q(t) = \int_0^t I_d(t)\mathrm{d}t \tag{2}$$

where $I_d(t)$ is the instantaneous discharge current. Since the BAC for the EV battery generally alters considerably, it has to be assumed as an appropriate value before the BRAC estimation is performed. So far, two methods have been adopted to approximate the value of the BAC at the fully charged state for the EV battery, either based on average discharge current [4,5] or based on a reference discharge current [6,7].

For the case of average discharge current, the SOC $p_{ave}(t)$ is defined as

$$p_{ave}(t) = 1 - q(t)/C_{ave}(t) \tag{3}$$

where $C_{ave}(t)$ is the average BAC corresponding to the average discharge current. The BRAC is estimated by using Eq. (3) without causing an error unless the discharge current varies significantly. This situation seldom occurs in the discharge current profiles of the EV battery. Fig. 2 shows four typical examples of the discharge current profiles for lead-acid batteries in EVs corresponding to the US federal urban driving schedule (FUDS), the US federal highway driving schedule (FHDS), the standard European reference cycle (ECE) and the Japanese mode 10.15

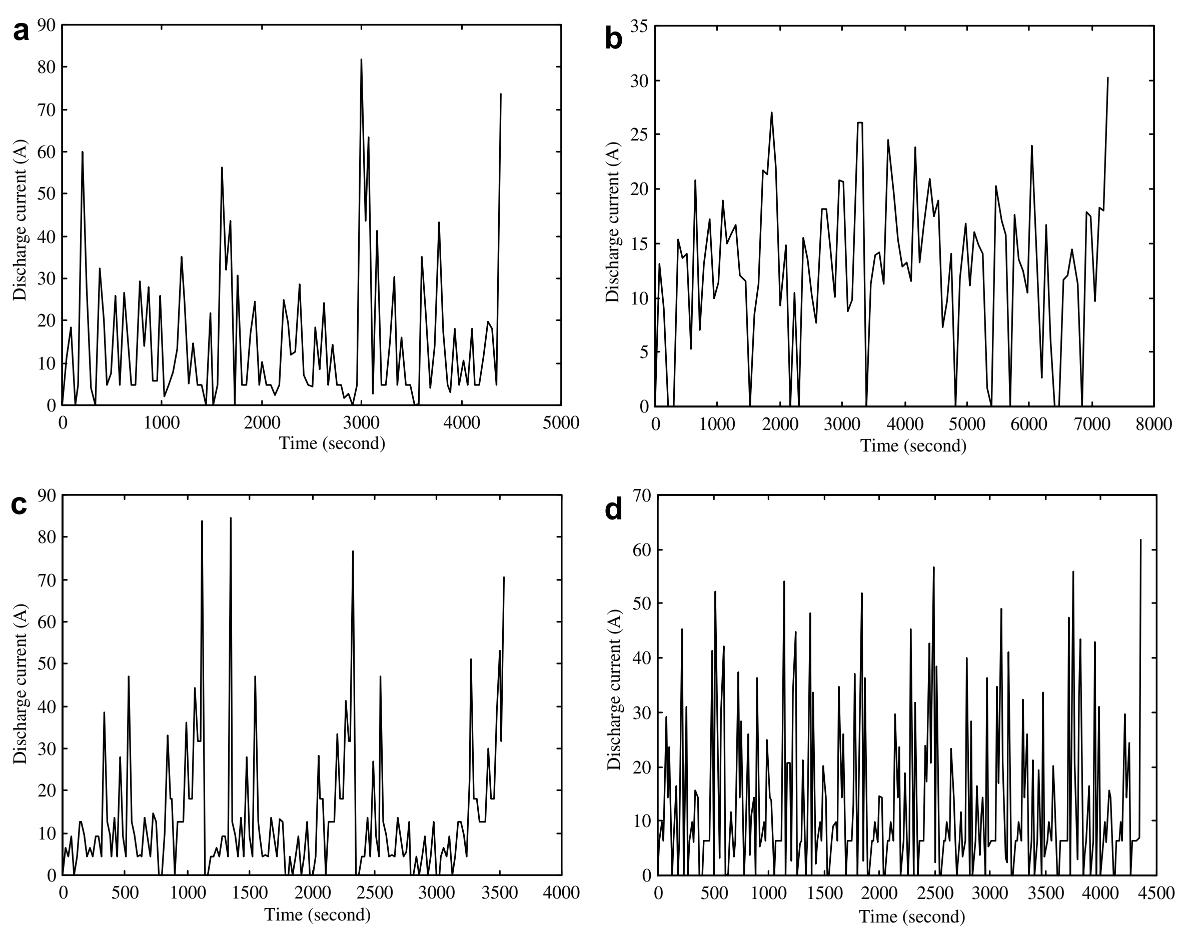

Fig. 2. Discharge current profiles of EV standard driving cycles without regenerative current: (a) FUDS; (b) FHDS; (c) ECE; (d) JM10.15.