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Maximum Available Capacity and Energy Estimation Based on Support Vector Machine Regression for Lithium-ion Battery

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Abstract

The practical application of electric vehicle needs an accurate and robust battery management system to monitor the battery state in real-time. The maximum available capacity (MAC) and maximum available energy (MAE) need to be derived before calculating state of charge and state of energy. However, the estimation of these two parameters is a difficult task due to the complicated and comprehensive influences of temperature, aging level and discharge rate. In this paper a data-driven algorithm, least squares support vector machine, is implemented to estimate the MAC and MAE, and the influences of temperature and degradation are taken into consideration. Meanwhile, a current correction term is proposed to compensate the effect of current rate. The experimental results verify the proposed methods have excellent estimation accuracy for LiFePO4 battery.

Keywords: Battery management system; current correction; least squares support vector machine; maximum available capacity; maximum available energy.

1. Introduction

The increasing pressure from environmental pollution and energy crisis contribute to the hybridization and electrification of vehicle propulsion systems. With the superiority of high specific energy and power, lithium-ion batteries are selected as the main energy storage systems for electric vehicles (EVs). During the whole life-cycle of

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battery, an intelligent battery management system (BMS) is indispensable to online monitor the battery state and prevent the abuse of battery.

The state of charge (SOC) as a crucial index of battery state cannot be calculated directly. The Ampere-hour (Ah) counting is the most widely used method to calculate SOC in real application but it is an open-loop calculation method. The open circuit voltage method is accurate but the battery needs long time to relax, which is unsuitable for real application [1]. Besides, the fuzzy logic [2], artificial neural network (ANN) [3], and support vector machine (SVM) [4, 5] methods have been applied to construct the black-box models for SOC estimation. The similar disadvantages of above mentioned methods are the requirement of extensive experimental data to extract the prior knowledge or train the models. Wang et al. [4] point out that the merit of SVM compared with ANN is the property of condensing information in the training data and providing a sparse representation by using a very small number of data points. The most frequently used algorithm for SOC estimation is the extended Kalman filter method which combines the Ah counting with open circuit voltage correction. This method realizes the closed-loop estimation of SOC, and a variety of the analogous improved algorithms have been proposed [6]. Generally, the remaining driving range is embodied by the SOC of battery pack, and estimated by transmitting the remaining capacity in terms of Ah into driving distance. Some authors have proposed that the state of energy (SOE) serves as an analogue to the *fuel gauge* for EV range prediction better than SOC [7-10]. Mamadou et al. [7, 8] presented a definition of SOE and a method to calculate SOE based on direct power integral which is similar to the Ampere-hour counting method. Liu et al. [9] proposed an improved direct SOE estimation method at dynamic currents and temperatures based on Back Propagation Neural Network. However, it is an open-loop estimation method, and the estimation accuracy of this method may become poor due to the incorrect measurements. Zhang et al. [10] established a joint estimator for SOE and state of power, where the parameters of battery model are estimated dynamically using the recursive least square (RLS) algorithm method. However, it does not take the influences of temperature and discharge rate on MAE into consideration.

The maximum available capacity (MAC) and maximum available energy (MAE) are the amount of charge and energy that can be released from the battery starting from a fully charged state, respectively. These two indispensable parameters can contribute to the SOC and SOE estimation, and also indicate the state of health (SOH) of battery. However, the estimation of MAC and MAE are crucial challenges of battery monitoring due to the comprehensive influences of temperature, aging level and discharge rate. The simplest idea to acquire MAC is accumulating the charges (Q) between two SOC levels and then calculating the value of $Q/\Delta SOC$. It is worth noting that only voltage-based SOC estimation methods are effective for this method. Hausmann et al. [11] employ temperature and current correction terms similar to the Peukert’s law to calculate the remaining available capacity, but the aging factor is not taken into consideration. Zheng et al. [12] and Guo et al. [13] demonstrated that the MAC is related to the variation of constant current charging curves, and can be determined by comparing the measured voltage curve with the parameterized charging voltage curve of the new battery. This method is suitable for the pure electric vehicles with specific charging procedure. In terms of MAE, Barai et al. [14] proposed a method to consider the discharge rate based on the short-term cycling history of battery. Dong et al. [15, 16] derived the empirical expression of MAE with the variables temperature and discharge rate. However, the above methods do not take the influence of aging level into account, and the aging is the vital factor determining the capacity and energy of the battery. Aiming at the existing problem, the data-driven algorithm, namely least squares support vector machine (LS-SVM) was implemented to accurately estimate MAC and MAE. The proposed LS-SVM model is a common resolution for the estimation of MAC and MAE due to their quite similar characteristics. The influences of temperature and degradation are considered by inputting corresponding feature parameters, while the effect of discharge rate is considered by multiplying the current correction term according to the Peukert’s law.

2. Battery parametric model

2.1. Battery model

The SOC has been employed in the figurative sense as a replacement for a fuel gauge used in conventional vehicles. It provides the information of the remaining available capacity of battery, and can be defined as Eq. (1). Similarly, the SOE is generally defined as the ratio of the residual energy to the MAE of battery, and can be