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State-of-charge and state-of-health estimation for lithium-ion batteries based on dynamic impedance technique

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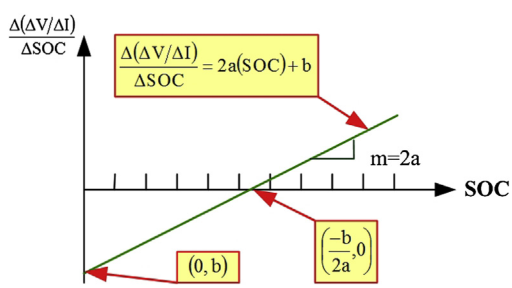
HIGHLIGHTS

- This study proposes dynamic impedance to estimate SOC of Li-ion batteries.
- This study proposes projection method to estimate the SOH of Li-ion batteries.
- We developed a real-time SOC and SOH estimation system, combining a MCU with a BMS.

GRAPHICAL ABSTRACT



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ABSTRACT

This study proposes a dynamic impedance method to estimate the state of charge (SOC) and a projection method to estimate the state of health (SOH) of lithium-ion batteries. We defined changes in voltage over changes in current during charging and discharging processes as the dynamic impedance, which was then used to calculate SOC. The proposed methods do not require initial values, and dynamic impedance provides a more accurate reflection of the electrical characteristics of batteries compared to conventional estimation methods. This approach also enables calculations in real-time. The SOH of batteries degenerates with age, which also alters the characteristics of dynamic impedance. The proposed projection method determines the SOH according to the rate of change in dynamic impedance with respect to the SOC. We also developed a real-time SOC and SOH estimation system, combining a microcontroller and estimation methods with a battery management system (BMS). The BMS retrieves the data required for SOC and SOH estimation and includes various protection mechanisms designed to extend the lifespan of the battery. The hardware structure and the software procedure of the developed system are described in detail. We also present the results of experiments verifying the accuracy and feasibility of the proposed estimation methods.

1. Introduction

Environmental pollution and oil shortages around the world have increased the popularity of electric vehicles [1–5]. Many nations and major automobile manufacturers are thus investing in the research, development, and promotion of electric and hybrid vehicles. However, high costs have prevented these vehicles from securing a significant share of the market. Battery modules account for a substantial proportion of the overall as well as the core component of electric vehicles. The capacity of these components determines the endurance of the vehicle, while characteristics such

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as instantaneous discharge current, maximum continuous discharge current, weight, volume, and energy density determine the vehicle's performance [6–10]. Thus, a high-quality battery module is essential for hybrid and electric vehicles to compete with gasoline vehicles.

At present, the battery modules used in electric cars actually comprise hundreds of cells linked in series and parallel. Despite careful screening, the characteristics of individual cells can change during use, which can result in damage to the overall battery module. To extend the life span of battery modules, most battery modules are now equipped with battery management systems (BMSs) [11–14]. The benefits of these devices generally outweigh the additional costs. The primary function of a BMS is to monitor parameters such as the voltage, current, and temperature of the cells in the battery module as well as its overall functioning as a whole, thereby ensuring the safety of its operation. A full-featured BMS provides protective functions which initiate protective measures in the event of abnormalities, such as abnormal voltages, discharge current, or temperatures.

Batteries have limited storage capacity, and are able to transfer energy only within range of their capacity. A battery that is constantly in an overcharged or deeply discharged state is likely to suffer permanent damage. Estimating the state of charge (SOC) is therefore a crucial issue preventing overcharge and over-discharge [15–18]. The SOC can generally be defined as the ratio between the available capacity and maximum available capacity, usually expressed as a percentage [19]. The SOC cannot be derived directly from measuring battery parameters but rather is estimated using algorithms and measurement data. The existing methods of SOC estimation can be broadly divided into online and offline approaches [20–27]. No input of data is required to initiate online methods; rather, parameters are continuously measured during the estimation process. In contrast, offline methods require manual input into the requisite algorithm, commonly involving look-up tables and discharge tests. Offline methods allow for direct comparisons with the default data and are easy to implement; however, they tend to be less accurate, require more time for estimation, and are easily affected by factors associated with the battery, operating conditions, and the environment. As a result, online approaches are the preferred method of SOC estimation. The most recognized methods include the open circuit voltage method and the Coulomb counting method. The former determines the SOC directly, according to the terminal voltage of the battery, while the latter involves integrating the current in time to calculate the energy entering and leaving the battery. Although these methods are simple and inexpensive, they have definite limitations. For instance, the open circuit voltage method uses the terminal voltage to determine the charge capacity, which requires that the battery remain unused for a long period of time. The batteries of electric vehicles are often in constant use, such that the intervals between use are too short to enable accurate SOC estimation [28,29]. The Coulomb counting method calculates only the energy passing in and out of the battery and thus only the changes in the SOC. Determining the actual SOC requires an accurate initial value. As a result, this approach is generally used in conjunction with the open circuit voltage method; however, discrepancies between the initial value and the actual SOC can lead to errors in subsequent results [30,31]. Thus, an increasing number of researchers have been looking for an SOC estimation approach that is more efficient, more rapid, and more accurate. Theories and technologies from other domains, such as artificial neural networks, fuzzy logic, and the Kalman filter, have been applied to online SOC estimation; however, persistent limitations have thus far prevented their being applied commercially. For example, artificial neural networks can be applied to all types of batteries; however, the algorithm requires a substantial amount of data for training and is slow to converge. Fuzzy logic is also applicable to all types of batteries, but the definitions of its membership functions are extremely subjective and thus unsuitable for large models. Similarly applicable to all types of batteries, the Kalman filter is suitable for dynamic applications such as electric vehicles; however, this algorithm is unduly complex.

Another important parameter of batteries is the state of health (SOH) [32,33]. This represents the extent of aging in the battery and is generally defined as the ratio between the maximum available capacity and the rated capacity, also expressed as a percentage. The calculation of SOH is crucial to understanding the exact aging conditions and maximum available capacity in a battery, as well as a key factor in determining when a battery should be replaced. Conventional techniques include the standard charge and discharge method and the internal resistance method. The former involves discharging the battery to the cut-off voltage using the standard discharge current and then charging the battery to the charge limit voltage using the standard charge current. The ratio between the charge capacity and the rated capacity is then calculated and converted to a percentage which is defined as SOH [34]. In the latter, an unused battery is discharged using a pulse current, during which variations in voltage are recorded. The open circuit voltage, voltage variations, and currents are used to calculate the internal resistance of the battery, which is then used to determine the extent of aging in the battery. Unfortunately, both of these methods have shortcomings. The standard charge and discharge method requires an extremely long period of time to complete measurements, thereby ruling out real-time detection. Furthermore, the measurement process results in the wasteful consumption of a considerable amount of energy and necessitates specialized instruments and equipment that cannot be operated without training. The internal resistance method requires a test component or circuit comprising high resolution equipment to ensure accurate measurement, which makes this method both cumbersome and costly. In addition, the method is applicable only to unused batteries, which again prevents real-time measurement [35,36].

Besides, in order to realize the electrochemical impedance characteristic of the battery, the electrochemical impedance spectroscopy (EIS) was widely applied in several researches [37–40]. The EIS is a nondestructive technique designed to understand the electrochemical impedance characteristic of a battery. Before using this method, an equivalent circuit model is essential. Next, it applies a sinusoidal voltage/current signal to the battery and analyzes the current/voltage response respectively at wide range frequencies [37,40]. And then the electrochemical impedance characteristic of the battery can be determined by some figures, which are plotted by the measured results, for example, Lissajous figure and Nyquist plot [37–40]. However, the used equivalent circuit model must have high accuracy, that is, the equivalent circuit model is complex with a large number of elements. Moreover, EIS cannot be used in the charging or discharging process since it has to apply the various sinusoidal voltage/current signals to the battery and observe the responses. As a result, EIS cannot be used to implement the real-time SOC and SOH estimation function of a battery. Therefore, this study proposed the dynamic impedance method to overcome these mentioned shortcomings.

This study implemented a real-time SOC and SOH estimation system in which BMS is used to capture the electronic characteristics of the battery module. A microcontroller (MCU) serves as the control center of the system to calculate the SOC and SOH of the battery. Chapter 2 details the proposed SOC and SOH estimation methods and Chapter 3 presents the hardware. Chapter 4 describes the software procedures, and Chapter 5 presents experiment results verifying the efficacy of the proposed techniques.