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A comparative analysis and validation for double-filters-based state of charge estimators using battery-in-the-loop approach

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HIGHLIGHTS

- A dual-estimators-based joint estimation framework is set up to estimate SOC.
- The influence of temperature deviation on the SOC accuracy is discussed.
- Four filter-based algorithms have been systematically compared.
- The proposed algorithm is validated by a hardware testing platform.

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ABSTRACT

The state of charge (SOC) estimation is extremely important for the wide commercialization and safe operation of electric vehicle (EV), especially under cold conditions, which is also a critical technology for battery system in EVs used in the 2022 Beijing winter Olympics. Three efforts have been made in this paper: (1) A general joint estimation framework with dual estimators is set up. Based on this frame, a joint algorithm using the recursive least square (RLS) and the adaptive H infinity filter (AHIF) is realized. (2) Four filter-based algorithms have been systematically compared and analyzed at the wide temperature range. The results show that RLS-AHIF algorithm has better performance for SOC estimation even at low temperatures, such as −10 °C, and the SOC error is within 3.5%. (3) A hardware-in-loop validation platform including the battery management system (BMS) and battery test instruments has been built to verify the proposed method. The results from the platform show that the maximum error of SOC is less than 2% at 0 °C and 25 °C. Consequently, the proposed algorithm can achieve the application over a wide temperature range in an actual BMS.

1. Introduction

With most European countries energetically making the timetable for the withdrawal of fuel vehicles, the popularization and large-scale commercial applications of EVs have become an inevitable trend. However, the application of the battery system in all climatic conditions, especially in the cold environment, has been the most significant problem that restricts the EVs' promotion. The BMS, as one of the key electronic control systems in EVs, basically guarantees the reliability and safety of battery pack [1]. The primary functions of BMS are safety management and state estimation. By measuring voltage, current and temperature, the BMS can protect battery from overcharging and over discharging [2,3], To indicates how much electric quantity is left, SOC need to be acquired [4]. Accordingly, the accuracy of SOC estimation is very significant for guaranteeing the safety and reliability operation of the EVs [5,6]. As its unmeasurable feature, the SOC needs to be estimated in real-time during operations [7]. Nowadays, most SOC algorithms can achieve accurate estimation under normal temperature, but the primary problems that accuracy deteriorates under cold conditions are still to be solved.

1.1. Literature review

The methods of SOC estimation include looking-up table method, ampere-hour integral method, model-based estimation methods and the data-driven estimation methods [8]. Although each method has its own advantages, not all of them are compatibly applied to the BMS because of computation, sensor noise, cost, etc.

The looking-up table method is easy to implement and it calculates SOC by the SOC-open circuit voltage (OCV) curve [9,10], which needs

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to be calibrated and stored into the BMS in advance. The estimation accuracy strongly depends on the OCV-SOC curve, which is mainly impacted by the test procedures and the resolution of voltage measurement. Besides, the shape of SOC-OCV curve has a strong influence on estimation. Batteries with flat SOC-OCV curve are not suitable for this method as a subtle error in OCV measurement will bring a large SOC estimation error. In general, this method is combined with the Ampere-hour (A h) integral method to improve the estimation accuracy and robustness. However, the Ah integral method is a non-feedback approach, whose accuracy is cumulatively affected by sensor noise and capacity deviation [11]. The data-driven methods are promising approaches, which are based on the black-box model to accurately describe the strong nonlinear relationship of the input and output variables [12]. Nevertheless, these methods need a large amount of prior history data to train the model, which may be unfit for real-time controllers in vehicle.

The model-based approaches are the research hotspot right now [13,14], which have the characteristics of high calculation precision [15], small computation [16], insensitivity to the initial error and inhibitory effect on measurement noise [17]. The model-based methods usually estimate battery states by all sorts of state observation algorithms. The extended Kalman Filter (EKF) is the most common observer to acquire SOC [18] and it has been directly applied in the BMS [19]. In [20], a hardware-in-the-loop test bench was built to validate the method of EKF. Klee et al. [21] used the actual BMS to systematically compare five model-based methods from six aspects, and the results showed that the model-based methods met the demand of engineering application. But the parameters of these model are constant, which can't satisfy the actual requirements of use. Christian et al. [22] validated the EKF method to estimate SOC at various temperatures based on the offline model parameters in a homemade BMS, but the results are greatly affected by the uncertain measurement noise. Compared with EKF, the H infinity Filter (HIF) is more flexible to deal with the uncertain noise [23] and has been used to achieve the more accurate SOC estimation [24]. Besides, the adaptive algorithms based on battery models are presented to solve the problem that the noise covariance is invariable in traditional filter methods, such as the adaptive extended Kalman Filter (AEKF), adaptive unscented Kalman Filter (AUKF) [25]. It is significantly necessary that these algorithms should be further verified in BMS. However, due to the complexity of hardware system development, there are few relevant literatures that have verified these preeminent algorithms in actual controller systems.

Additionally, the dual-estimator methods are the more promising approaches among model-based methods [8], which can adaptively update the model parameters and state in real time, not disturbed by operating temperature and aging [26]. However, the evident differences of SOC estimation errors obtained by different methods exist [27], as their disparate fundamentals of mathematics. When the ambient temperature changes, the differences may be more apparent. Although the dual estimators are superior, it is also essential to discuss their applicable temperature. Duong et al. [28] employed a highly adaptive estimation algorithm based on the RLS method to estimate the SOC from 10 °C to 40 °C, but the subzero temperature has been omitted. Dong et al. [29] have discussed three dual-filter methods at disparate temperatures, but the input of temperature is not a variate in their algorithms. Yuan et al. [30] also took into account the change of OCV caused by temperatures, but the temperature is not considered in their algorithms. These methods have accomplished the significant exploration. However, how the temperature measurement noise affects the accuracy of SOC estimation need to be deeply explored. Additionally, there is little discussion about the accuracy of different dual-estimator methods over a wide temperature range.

1.2. Contributions of the work

This paper presents a dual-estimators framework including the temperature inputs and aims to discuss the its application accuracy at a wide range of temperature and focuses on the realization of high-precision SOC estimation in real-time onboard controller. This paper therefore attempts to make three contributions in the following.

(1) Considering temperature as one of the input data, a general double-estimators-based framework (RLS-AHIF) is set up. In order to discuss the accuracy of this algorithm, a wide temperature range is used to validate this method. Additionally, we deeply discuss how the SOC accuracy is affected by temperature measurement errors.
(2) We systematically compare four filter-based dual-estimators methods and analyze their calculation errors at the wide temperature range.
(3) In order to validate the proposed framework, we establish a hardware-in-loop validation platform including the real-time BMS controller. The BMS results indicate that the SOC error is less than 2% at different temperatures.

1.3. Organization of this paper

The remainder of the paper is constituted as follows: Section 2 describes the process of modelling and the dual estimators frame for SOC estimation and parameter identification. Section 3 presents the battery test bench and the validation results. Section 4 demonstrates the algorithm validation bench with BMS and the validation results from BMS. And the key conclusions are summarized in Section 5.

2. Modelling and algorithms

Realizing the closed loop estimation based on the battery model and filter-based estimator is a research focus in recent years. With the characteristics of less calculation and high voltage fitting precision, equivalent circuit model (ECM) is normally used in the area of SOC estimation.

2.1. Modelling for lithium-ion batteries

Compared with the existing ECM models, the Thevenin model has been proved to be a better choice for the NMC batteries under normal conditions after considering the calculation complexity, accuracy [24,31]. Thevenin model has been selected to build the model-based SOC estimation in this study, as shown in Fig. 1. The model is composed of a voltage source U_{ocv}, an ohmic impedance R_o, and the polarization impedance (polarization resistance R_D and polarization capacitance

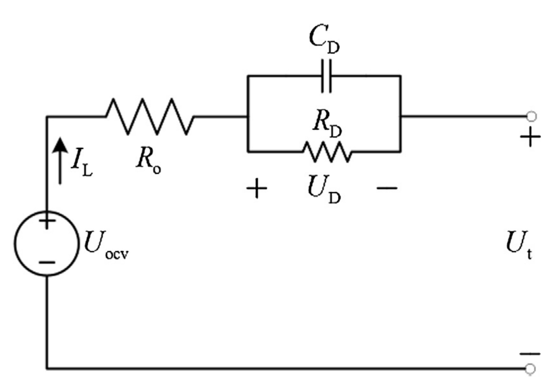

Fig. 1. The Thevenin model.