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A comparative study on the applicability of ultracapacitor models for electric vehicles under different temperatures

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HIGHLIGHTS

- A systematic experimental procedure is established in details.
- A GA based parameter identification method was evaluated.
- Five typical UC models have been compared under different temperatures and SOCs.
- The effectiveness of the modeling method has been evaluated in UC pack modeling.

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ABSTRACT

This paper presents a systematic evaluation for five typical equivalent circuit models (ECMs) of ultracapacitors (UCs) under different ambient temperatures. A comprehensive experimental profile is designed to obtain the test datasets. The genetic algorithm (GA) is employed to identify the model parameters for five UC models under different temperatures and state of charge (SOCs). Three results can be obtained from the systematic analysis. (1) Due to the better model accuracy and robustness, the Thevenin model is preferred for UC cell modeling with the maximum errors less than 8 mV. (2) Compared with the other four UC models, the Thevenin model with one-state hysteresis (Thevenin-hys model) is preferred for UC pack modeling because of its better performance. (3) From the point of view of model accuracy and robustness against different ambient temperatures, if the SOC is less than 0.5, the UCs are not suitable for further application.

1. Introduction

With the development of society, air pollution caused by vehicles has become a negative factor that impacts people's quality of life [1]. To reduce greenhouse gas emissions and improve air quality, electric vehicles (EVs) and plug-in electric vehicles (PHEVs) have gained the attention of many researchers. Energy storage systems (ESSs) with high energy and power density play a significant role in EVs and PHEVs. Ultracapacitors (UCs), which are also known as supercapacitors or electric double-layer capacitors (EDLC), have been widely used in ESSs of EVs [2] or PHEVs [3], [4] because of their high power density, exceedingly long lifetimes, slow degradation and wide operational temperature ranges [5]. Compared with any other conventional capacitor, the capacitance values of the UCs can be up to thousands of farads [6,7]. To construct a suitable UC model of high accuracy and good robustness for electric vehicles, many valuable studies have been carried out. They are generally categorized into three types: electrochemical models, artificial neural network (ANN) models and equivalent circuit models (ECMs).

(1) The electrochemical models employ the partial differential equations (PDEs) with a large number of parameters to mimic the electrochemical characteristics of UCs [8]. Although the electrochemical models has shown high accuracy, it is difficult to be utilized in EVs or PHEVs. The reason is firstly, although some parameters, such as solid-state lithium diffusion coefficient at completely delithiated state and contact resistance can be measured by the instruments [9], other parameters like the electrode thickness, electrode area, active-material volume fraction, active-material-particle radius are difficult to calibrate [10]. Second, because of the high complexity of PDEs and large calculation burden, the electrochemical models are difficult to satisfy the real-time requirements for the real-time controlling purpose [11].

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(2) The second category of models employs ANNs which have been widely used for their attractive characteristic ofease implementation [12]. In Ref. [13], a multi-layer ANN with two hidden layers is used well in UC simulation. Besides, a multi-layer ANN with a single hidden layer trained via BP algorithm is also used for UC modeling in Ref. [14]. In order to further minimize the model accuracy, some effective training methods have been put forward. For instance, the Levenberg-Marquardt method is used to train the ANN model to further improve the precision in Ref. [15]. Moreover, T.D. Dongale [12] established an ANN model based on sigmoid activation function. The results show that the error rates are only 1.24%, 1.03%, 0.87% and 1.28% for different samples. A combination of ECMs and ANN models is implemented in Ref. [16], in which C.H. Wu struck a balance between the physical meanings and nonlinear dynamics of UC. However, this method requires a huge training dataset to obtain better modeling accuracy. Additionally, for cases that have not been considered in the training of neural networks in advance, the modeling accuracy is often poor.

(3) The ECMs, which have been extensively studied in a lot of researches, are only composed of resistors, capacitors and voltage sources. Compared to electrochemical models and ANN models, the obvious advantages of UC including simple structure, fewer modeling parameters and lower computation have led to wide application for ESSs [8]. There are a lot of papers focused on the development of ECMs for UC modeling. R.L. Spyker [17] proposed classical equivalent circuit including a capacitor, an equivalent parallel resistance (EPR) and an equivalent series resistance (ESR) to adequately describe UC dynamic characteristics. On the basis of classical equivalent circuit, L. Zubieta [18] developed a novel ECM of the double-layer capacitor for application in power electronics which consists of three resistor-capacitor (RC) branches. The result shows that some improvement is obtained. M. Marracci [7] proposed a double-layer UC model, which is analyzed under different conditions. In Ref. [19], a simple model with two RC branches is utilized to describe the UC behavior, and the proposed model and the recursive equation model are compared. A standard RC model, a two RC branch model and a dynamic model of UCs are presented in Ref. [20], in which the results of three UC cells with capacitances of 650 F, 200 F and 3000 F are compared. C.G. Suo [21] presents an extended model whose novelty lies in transforming the constant resistor into a variable resistor when the current changes. R.A. Dougal [22] created a UC model featuring automatic order selection of complexity and automatic scaling of capacity in a virtual test bed platform, which can automatically select the order or number of stages of the ladder network and accurately reflect other capacitors with different sizes at the same time. Besides, H. Gualous [23] verifies the UC dynamic characteristics based on an impedance model by using an electrochemical impedance spectroscopy (EIS) method. Consequently, in consideration of the modeling accuracy, model complexity and practicability, ECMs are selected in this paper. Although researchers have proposed many models to simulate the performances of UCs, it is difficult to conclude which one is the best. A model with high accuracy but low computational complexity to be applied to EVs or PHEVs has always been the research focus.

On the other hand, temperature, which seriously affects the stability of UC, plays a very important role when the UC is operating. The previous studies focused on the effects of temperature are generally categorized into two kinds: the operating temperature and ambient temperature. There have been a lot of papers focused on the effects of operating temperature on the thermal behavior. The heat conduction equations in one-dimensional, two-dimensional and three-dimensional space have attracted the attention of many researchers [24]. K. Wang [25] uses a three-dimensional model to study the effects of operating conditions and ambience on the thermal behavior of UCs. Y. Parvini [5] presents a validated lumped and thermal model for a cylindrical UC cell. This electric model is a two-state ECM with three parameters to be identified. E. Manla [26] proposes a battery-based model and a capacitor-based model. The model accuracies have been verified based on the comparison results between the measured values and simulated values at various temperatures. A first-order thermal model for electric double layer capacitors is established via lumped capacitance approximation in Ref. [27]. Unfortunately, from the above studies, it can be seen that most papers neglected the effects of ambient temperature.

Considering the previous description, this paper targets two contributions. (1) To select the preferred UC model for real application, five different UC models are compared to find which one is the most suitable for ESS application according to the model accuracy, model complexity and robustness against different ambient temperatures. (2) The proposed modeling method is then applied for UC pack characteristic modeling at different ambient temperatures to further verify its applicability for real applications.

The rest of the paper is organized as follows. In Section 2, an experimental rig is established, and the experimental profile is designed. The parameter identification of five models is completed in Section 3. In Section 4, five UC models are evaluated based on a comparison between the experimental and emulation values. In Section 5, the modeling approach is verified in UC pack modeling. Finally, the conclusions are presented in Section 6.

2. Experimental setup

2.1. Experimental rig

To obtain the charge-discharge characteristics and capacity characteristics under various temperatures, an experimental rig, shown in Fig. 1, is established. The experimental rig consists of an ARBIN BT-5HC test system, RGD-500 thermal chamber, host computer and UC. The ARBIN BT-5HC test system can measure the current, terminal voltage, charge-discharge capacity, charge-discharge energy, record step index, and cycle index. It can also send all of the measured datasets to the host computer via an Ethernet cable. The test system has a current measurement range between −100 A and 100 A and a voltage measurement range between 0 V and 5 V. In addition, it has 16 ports to connect to test-

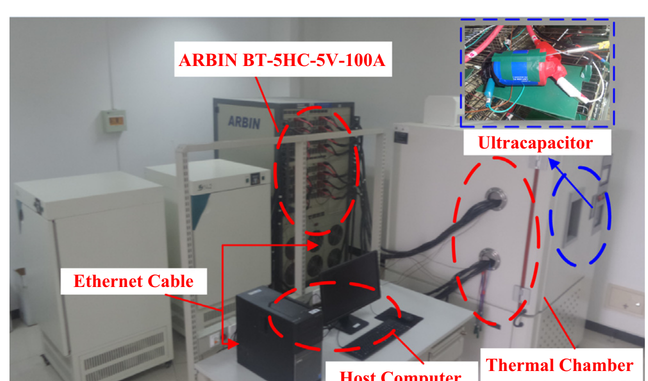

Fig. 1. Configuration of the experimental rig.