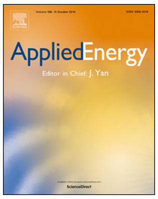
Applied Energy 219 (2018) 256–263

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



A novel echelon internal heating strategy of cold batteries for all-climate electric vehicles application

Shanshan Guo, Rui Xiong*, Kan Wang, Fengchun Sun

National Engineering Laboratory for Electric Vehicles, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- A novel echelon preheating strategy is proposed for all-climate battery.
- A novel electro-thermal coupled model has proposed for calculating battery thermal.
- The proposed method can get high and homogeneous temperature rise rate.
- Results show that the proposed strategy has no apparent damage on battery health.

ARTICLE INFO

Keywords:
All − climate electric vehicles
Lithium-ion battery
Low temperature
Echelon heating strategy
Alternating current

ABSTRACT

Battery preheating at low temperatures is essential to ensure the efficient operation of electric vehicles in all climate conditions. Alternating current heating is proposed as an effective preheating method to improve the poor performance of lithium-ion batteries operated at low temperatures. To describe the dynamic voltage behavior accurately, the Butler-Volmer equation has been employed, and then a novel electro-thermal coupled model has been proposed for accurately calculating the thermal behavior of a battery. To obtain the optimal preheating performance, the electro-thermal coupled model-based available heating current computational method has been developed to obtain the optimal echelon preheating strategy. This method has the potential to balance the heat generation rate and degradation on battery lifetime. Finally, the proposed echelon heating strategy has been verified by battery cells and battery packs. Results show that the battery cell can be heated from the temperature of −20.3 °C to 10.02 °C by 13.7 min with an average temperature-rise 2.21 °C/min. And the battery pack can be heated from −20.84 °C to 10 °C by 12.4 min with an average temperature-rise is 2.47 °C/min.

1. Introduction

Lithium-ion batteries (LiBs) are widely adopted as the power sources of electric vehicles for its high voltage, high energy density, little pollution, low self-discharge, long cycle life and no memory effect [1–3]. However, at subzero temperatures, LiBs are charged or discharged difficultly because of the inactivity of positive/negative materials, the slow viscosity of the electrolyte, and decrease of the electrical conductivity [4,5]. Meantime, the differential concentration of the electrolyte becomes large, and the polarization enhances, the charging is terminated prematurely. More importantly, the diffusion of lithium-ions in the carbon anode is slow and lithium precipitation occurs easily, which may cause short circuit [6,7]. The dramatically decreased performance of LiBs not only results in the substantial loss of both pulse power and usable energy but also makes Li-ion easily deposited, leading to significant reduction of LiBs lifetime, which also stymies the development of new energy vehicles. Meantime, saving resource and protecting environment require electric vehicles to be more efficient and cleaner [8]. Therefore, development of all climate electric vehicles (ACEVs) is the basic strategy to overcome the short mileage problem of electric vehicles used in the Winter Olympics 2022. Moreover, preheating the LiBs to a friendly temperature from the subzero temperatures is an important guarantee to improve the LiBs' poor performance.

1.1. Review of existing preheating methods

Currently, the internal and external heating are the two main

---

* Corresponding author at: Department of Vehicle Engineering, School of Mechanical Engineering, Beijing Institute of Technology, No. 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.
E-mail address: rxiong@bit.edu.cn (R. Xiong).

https://doi.org/10.1016/j.apenergy.2018.03.052
Received 25 January 2018; Received in revised form 28 February 2018; Accepted 18 March 2018

preheating methods for LiBs. Obviously, the external heating method is a strategy that preheats the batteries outside. Reviewed from the published literature, external heating methods are mainly classified as: liquid or gas heating [9,10], heating plate [11], heating pipe [12–14], Peltier heating, and so on [15–18]. Admittedly, the external heating is relatively safe, implemented easily, however, the energy loss is large and heating generation rate is slow, the battery temperature increases unevenly.

Inversely, internal heating as a heating strategy that heat generates from the battery itself has higher heat generation rate, less heat loss, better temperature distribution than the external heating. Many researchers have studied on internal heating, Wang et al. [19,20] proposed a self-heating battery added a piece of nickel-chip between the two tabs. This structure can heat itself rapidly from −20 °C or −30 °C to 0 °C within 20 s or 30 s, consuming only 3.8 percent and 5.5 percent of cell capacity, respectively. Then Yang et al. [21] developed an electrochemical-thermal coupled model to predict the internal characteristics of the same structure batteries and showed the heating time and energy consumption would be greatly affected by the internal temperature gradient. Admittedly, it presents a new way to preheat the batteries more quickly from subzero degree Celsius and consume less energy. However, it depends highly on the certain structure and material of the battery and must be redesigned the existing battery in engineering applications.

The other internal heating strategy is alternating current (AC) heating, and as one kind of AC heating, the sinusoidal alternating current (SAC) heating strategy, which is verified that the battery has no damage after dozens of heating cycles and recommended as a good way for internal heating [22]. Yan [6] carried out three heating strategies, namely self-internal preheating, convective preheating and pulse preheating, according to the thermal-electrochemical model, and experimentally verified the merits and drawbacks among the capacity loss, heating time and system durability. Experimental verification displayed that AC heating large excitation current amplitude can accelerate heat generation rate [4,23,24]. While the battery may be damaged irreversibly by the high current amplitudes, for which may exceed the safe voltage range and lead to overcharge. Simultaneously, the well-known polarization occurs in the electrochemical reactions, so the polarization voltage should be considered and kept in a reasonable range when selecting the excitation current amplitude in order to ensure the terminal voltage in the safe range [25]. Ruan et al. [22,26] proposed the optimal frequencies during heating processes, which are temperature-adaptive based on the polarization voltage. Nevertheless, the effect of frequency on the temperature rise rate is smaller than that of the current amplitude. Zhu [27,28] compared the sine and rectangular excitations and described the relationship between resistance frequency and current amplitude which can directly show the effects of current frequency and amplitude on the heat generation rate. However, the suitable current amplitude at different temperature is not clear. Moreover, Ge [29] used a three-electrode model cell to measure the Measurement of the electrochemical impedance spectroscopy (EIS) of the positive and negative electrodes and determined the maximum amplitudes of the AC heating current at different frequencies which can prevent lithium deposition. Admittedly, this method serves as a good innovation, while the three electrodes cannot be widely adopted in the engineering application. Therefore, the optimal excitation current amplitude of the AC heating that speeds up the heating time and avoids overvoltage at low temperatures remains unanswered.

1.2. Contributions of this study

Based on the previous research over the AC heating, this study proposed an echelon heating strategy for lithium-ion battery, which has apparent merits as follows: Firstly, using Butler-Volmer equation, the optimal excitation current amplitude the suitable frequency and the optimal variable current amplitude is calculated accurately according to the electro-thermal coupled (ETC) model in order to achieve the maximum heat temperature-rise and reduce the complexity of engineering applications, Secondly, the echelon heating strategy with a short and efficient heating process can heat the single battery and four series of the battery pack from −20.3 °C to 10.02 °C within 13.7 min and 12.4 min, and the average temperature-rise rate is 2.21 °C/min, 2.47 °C/min. Thirdly, the proposed strategy prevents the battery from overcharging without apparent detrimental effect on the battery life. For its short preheating time, no lithium deposition and temperature consistency, the echelon preheating strategy can be taken into account as a potential method to preheating the ACEVs in cold weather.

1.3. Organization of the paper

The paper is structured as follows. The electro-chemical model is displayed in Section 2. The experiments and lab equipment are presented in Section 3. The experimental results and discussions about the proposed heating strategy are described in detail in Section 4, and conclusions are summarized in Section 5.

2. Description of echelon internal heating strategy

2.1. Battery energy conversation equation

For 18,650 batteries, the heat generation rate between internal and surface is quite consistent according to Ref. [4]. Therefore, the battery is considered as a lump and the heat generation rate can be defined by:

$$mc_{\mathrm{p}}\frac{\partial T}{\partial t} = \dot{Q} - \dot{Q}_{\mathrm{n}} \tag{1}$$

where m is the mass of the battery, c_{p} is the specific heat capacity, T is the battery temperature, t is the time, $\dot{Q}$ is the heat generation rate, $\dot{Q}_{\mathrm{n}}$ is the heat loss rate to the outside of the battery, which concludes: heat flux and heat radiation. Ordinarily, heat radiation is ignored. Thus,

$$\dot{Q}_{\mathrm{n}} = hS(T - T_{\mathrm{amb}}) \tag{2}$$

where h is the equivalent heat transfer coefficient, S is the surface area of battery, T_{amb} is the ambient temperature.

2.2. ETC model

Subjected to the SAC excitation, the heat source of the battery is

$$Q = \int_0^{2\pi} u(t)i(t)\cos\theta dt \tag{3}$$

where θ is the phase angle.

The heat generated from the real part of impedance is only taken into account according to Ref. [4]. The heat generation rate during the SAC heating can be governed as:

$$\dot{Q} = \left(\frac{I}{\sqrt{2}}\right)^2 R_{\mathrm{Q}} \tag{4}$$

where I is the input amplitude of the AC. R_{Q} is the real part of the overall impedance.

The ETC model [14] is employed and shown in Fig. 1.

According to the ETC model, R_{Q} can be expressed as:

$$R_{\mathrm{Q}}(T) = R_{\mathrm{i}}(T) + \frac{R_{\mathrm{ct}}(T)}{1 + (2\pi f)^2 R_{\mathrm{ct}}^2(T) C_{\mathrm{dl}}^2} \tag{5}$$

where R_{i} is ohmic resistance, R_{ct} is electrochemical polarization resistance. C_{dl} is the electric double-layer capacitance. According to the Arrhenius equation, the R_{ct} can be described as:

$$R_{\mathrm{ct}}(T) = A\cdot\exp\left(\frac{E_\alpha}{T}\right) \tag{6}$$

where E_α is the activation energy, and A is a pre-exponential constant,