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Electro-thermal characterization of Lithium Iron Phosphate cell with equivalent circuit modeling

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ABSTRACT

Prediction of the battery performance is important in the development of the electric vehicles battery pack. A battery model that is capable to reproduce *I–V* characteristic, thermal response and predicting the state of charge of the battery will benefit the development of cell and reduce time to market for electric vehicles. In this work, an equivalent circuit model coupled with the thermal model is used to analyze the electrical and thermal behavior of Lithium Iron Phosphate pouch cell under various operating conditions. The battery model is comprised three RC blocks, one series resistor and one voltage source. The parameters of the battery model are extracted from pulse discharge curve under different temperatures. The simulations results of the battery model under constant current discharge and pulse charge and discharge show a good agreement with experimental data. The validated battery model is then extended to investigate the dynamic behavior of the electric vehicle battery pack using UDDS and US06 test cycle. The simulation results show that an active thermal management system is required to prolong the calendar life and ensure safety of the battery pack.

1. Introduction

High capacity lithium-ion battery is an attractive choice for the automotive energy storage system in hybrid electric vehicles (HEVs) and electric vehicles (EVs) battery pack. The success of the EVs greatly depends on the development of the Li-ion battery. The battery used to power the vehicles is exposed to more severe operating conditions than portable electronic gadgets such as extreme operating temperature in the cold and hot environment (−40 °C to 70 °C), and high charge and discharge rate [1]. Besides, Li-ion batteries should operate within 25–40 °C for optimum performance and calendar life [2]. In addition, it is desirable to maintain the temperature variation between battery modules in the battery pack less than 5 °C [2]. Under high temperature, the capacity fading of the cell is more significant and the separator in the cell could melt, causing an internal short circuit and leading to uncontrollable temperature rise (thermal runaway) [3]. On the other hand, lithium plating will occur at temperature below 0 °C, charging and discharging of the cell become impossible. The lithium plating is permanent and cannot be removed with cycling of the cell [3]. Moreover, 10 years of calendar life targeted by the United States Advanced Battery Consortium further imply that significant efforts are needed in the development of the battery thermal management system for automotive applications [4].

Thermal response of the EV battery pack has been an interest to the researchers due to their potential thermal runaway and degradation of the performance under high temperature operating condition [5]. Laboratory and field test are commonly used to characterize the thermal response of the battery pack under the requirement of the transient power response [6–8]. Zolot et al. investigated the performance of the Toyota Prius battery pack under different driving cycle (HWFET, FTP and US06) at various environmental temperatures. The thermal performance of the battery pack at 25 °C is excellent for all the cycle [7]. However, experimental testing of the battery pack always required expensive facility such as high power programmable battery cycler and huge environment chamber to accommodate the battery pack. Moreover, experimental testing does not encourage innovative design and optimization of the battery pack [6]. Therefore, numerical simulation could be used to overcome the drawbacks in the experimental testing of the battery pack. The numerical models used to investigate the thermal response of the battery pack under different driving cycle can be divided into two main categories which is electrochemical–thermal model [5,6,9,10] and electro-thermal model [2,11–15].

Electrochemical models and equivalent circuit models are widely used to model the *I–V* characteristics, state of charge (SOC) and thermal response of Li-ion battery. An electrochemical

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Nomenclature

C	capacitance, F
C_p	specific heat capacity of the battery, J kg^{-1} K^{-1}
C_Q	cell capacity, A h
E	emissivity
E_m	thermodynamic voltage, V
E_0	battery constant voltage, V
h	convective heat transfer coefficient, W m^{-2} K^{-1}
I_m	current, A
λ	conductive heat transfer coefficient
Q	battery capacity, A h
R	internal resistance, Ω
T	surface temperature of battery, K
T_∞	free stream temperature of air, K
t	time, s
τ_n	time constant n for an R–C branch
V	voltage, V
ρ	density of the battery, kg m^{-3}
σ_{sb}	Stefan–Boltzmann constant, W m^{-2} K^{-4}

Subscript

h	hysteresis
batt	battery
OC	open circuit
avg	average
c	charging
d	discharging

model is used to investigate the electrochemistry reactions in the electrodes and electrolyte at high accuracy, but significant computational resource is required to solve the unknown parameters in partial differential equations [5,10,16–19]. In addition, microscopic information of the battery is also needed such as particle size, current collector and electrode thickness, open circuit voltage of the anode and cathode, and electrolyte conductivity. Unfortunately, these parameters are not provided by the manufacturers and required extensive experimental studies [19]. Hence, electrochemical models are inappropriate to be embedded into the microprocessor in the battery pack management system to provide accurate real time results.

Equivalent circuit model which is a simplification of electrochemical model utilized electrical circuit elements such as voltage sources, resistor and capacitor to represent the *I–V* characteristics of the battery [14,15,20–29]. The equivalent circuit model used Thevenin equivalents, impedances or run time based model to represent the characteristics of the cell [15]. In the Thevenin models, the open circuit voltage is assumed constant and a network of resistors and capacitors is used to track the response of the cell to the transient loads [1,14,15,21,22]. The accuracy of the predictions depends on the number of parallel resistive–capacitive networks. There are numerous resistive–capacitive (RC) network available in the literature such as first order RC [22,23], second order RC [1,24,25] and third order RC [15,26] models. Hysteresis behaviors are often added in the model to improve the prediction. Among these models, most of them are developed based on isothermal conditions and the parameters are constant over a wide range of temperature, limiting their use in on-board battery management system [14,27,28]. On the other hand, impedance based model employed an AC-equivalent impedance model in the frequency domain through impedance spectroscopy. A complex equivalent network (Zac) is utilized to fit the impedance spectra [21]. This type of model cannot predict the response of the cell and is only working for a fixed SOC and temperature setting [29]. The runtime based electrical model used discrete or continuous time implementations in the SPICE simulator to determine the variable in the complex electric circuit network. There are several disadvantages associated with the runtime based electrical model when predicting the current varying load conditions [21]. Among these electrical models, Thevenin model with its reasonable accuracy in predicting the SOC and *I–V* characteristics and temperature is more suitable to be implemented into the vehicle power control system and battery testing.

Hysteresis of open circuit voltage of a battery is a commonly found in Nickel–Metal Hydride (NiMH) and Li-ion cell [30–33]. In Li-ion battery, the hysteresis effect on Lithium Iron Phosphate is more significant than cobalt, nickel or manganese based battery [31–33]. In cobalt, nickel and manganese based Li-ion battery, due to the high gradient in the specific of SOC to open circuit voltage (OCV) relation, the impact of hysteresis on the cell's OCV is negligible. On the other hand, the OCV of the Lithium Iron Phosphate cell shows a plateau voltage over a wide range of SOC. The relationship between OCV and SOC during charging and discharging is path dependent and leads to distortion in OCV to SOC static mapping [33]. The hysteresis will cause unreliable OCV reconstruction in the battery management system that using model-based state estimation approach. However, the hysteresis phenomenon could be reduced by increasing relaxation duration before the OCV of the cell is taken.

In the present work, an equivalent circuit model is used to predict the *I–V* and thermal characteristics of 10 A h Lithium Iron Phosphate pouch cell under constant-current discharge and pulse charge–discharge cycle. The simulation results are validated with the experimental data. The equivalent circuit model is then extended to the whole battery pack to investigate the thermal response of the converted EV battery pack under Urban Dynamometer Driving Schedule (UDDS) and US06 Supplemental Federal Test Procedure (SFTP) test cycles. Through simulations, the electrical and thermal behavior of the cell can be predicted and applied in the EVs power control system and battery thermal management system design.

2. Mathematical models

2.1. Number of RC branches in the equivalent circuit model

Number of RC branches in the equivalent circuit is an important factor determines the accuracy of the prediction and complexity of the model. In this study, the number of RC branches used in the modeling was determined using the transient response of the cell voltage during the relaxation phase when the pulse current was removed. The experimental data are fitted with exponential equations according to the procedures as described in [35,36] and the results are shown in Fig. 1. The R-squared value for one RC branch, two RC branches and three RC branches are 0.957, 0.9919 and 0.9963 respectively. From the fitting results, it is shown that one RC branch and two RC branches did not produce a satisfactory match to the experimental data. Although one RC branch and two RC branches are simple, it could not reproduce the experimental results with a sufficient accuracy. Thus, three RC branches with the highest R-squared value were selected for this study as a compromise between the accuracy and the complexity.