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State of charge modeling of lithium-ion batteries using dual exponential functions

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HIGHLIGHTS

- The math model based on characteristics of equivalent circuits of batteries is built.
- The developed model well describes the discharging behaviors of $LiFePO_4$ batteries.
- The impact of storage time and cycle number on discharging behaviors is predicted.
- The accuracy of this model is very high; most RMSE is between 0.002 and 0.5.
- The proposed model can be used to distinguish batteries under various conditions.

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ABSTRACT

A mathematical model is developed by fitting the discharging curve of $LiFePO_4$ batteries and used to investigate the relationship between the state of charge and the closed-circuit voltage. The proposed mathematical model consists of dual exponential terms and a constant term which can fit the characteristics of dual equivalent RC circuits closely, representing a $LiFePO_4$ battery. One exponential term presents the stable discharging behavior and the other one presents the unstable discharging behavior and the constant term presents the cut-off voltage.

1. Introduction

The $LiFePO_4$ battery is a kind of secondary battery that is widely used as energy sources for a variety of devices, such as 3C products, electric vehicles and smart grid applications [1]. The advantages of the $LiFePO_4$ battery are safety, higher energy conversion efficiency and longer lifetime. It is capable of being cycled over 2000 times, which is 5 times higher than a lead-acid battery [1]. In general, the battery is regarded as a current source during the discharging phase, where the output voltage of a battery is stable. However, due to the electrochemical reaction, material aging and undesirable operation environment, the capacity decays rapidly after certain cycle numbers. Therefore, developing a method to detect battery capacity must consider many factors such as storage time, cycle number, self-discharge, internal resistance and ambient temperature, etc. Therefore, it is very important to monitor the state of charge (SoC) of a battery life under different conditions. Various battery models have been developed to capture the characteristics of batteries such as the electrochemical model [2,3], the analytical model [5–9], the stochastic model [4,8] and the electrical circuit model [4,9–12]. A decent model should be able to simulate the actual charging or discharging behaviors and then analyze the lifetime of a battery.

The electrical circuit model is used to analyze the battery status in this work because it is more intuitive and easier for simulating the discharging behavior of the battery. The modified Thevenin circuit model includes an open-circuit voltage source (a capacitor

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and a self-discharge resistor, shown in the dotted line rectangle), a series resistor (R_{series}) and a pair of resistor-capacitor (RC) circuits as shown in Fig. 1 [4]. RC circuits are used to investigate both the quick and slow responses of the closed circuit voltage (CCV).

When a battery is connected to a load, an instantaneous voltage drop is caused by the current flowing through the equivalent resistance (including the battery's internal resistance) of the circuit. Therefore, CCV is the difference between the open circuit voltage (OCV) and the voltage across the equivalent series resistor. The capacitors in the RC circuit begin charging and the voltages across the resistors increase, leading to the reduction of CCV. When the battery is disconnected from a load, there is no current and then the voltage is zero across the series resistor. The capacitors in the RC circuits are discharged by the parallel resistors and the voltages across the RC circuits decrease. Therefore, the measured voltage gradually recovers from a CCV level to an OCV level.

This proposed model, composed of dual exponential terms and a constant term, is used to collect parameters by fitting the discharging voltage and the SoC of $LiFePO_4$ batteries. It is also able to model both the storage time and cycle number to evaluate the quality and the aging of the batteries under different conditions. Measured results are compared with modeled results under different conditions to validate this model.

2. Mathematical models

2.1. Experimental modeling procedure

The capacity of the tested $LiFePO_4$ battery is 15 Ah and the working voltage is 3.2 V. The cut-off discharging voltage is set at 2.0 V and the upper bound of the charge voltage is set at 3.65 V. The measured $LiFePO_4$ batteries can be classified into three types, namely new, stored, and used batteries. A new battery is defined as a battery that has not been used. A stored battery is defined as a battery that has been stored for a certain period of time without being charged and discharged. These batteries are stored in the indoor storage at room temperature of about 25 °C in average. The temperature difference of the indoor storage between summer and winter in Taiwan is small. A used battery is defined as a battery that has been cycled 300 times over a period of 1, 2, or 3 years.

In the experiment, each $LiFePO_4$ battery was charged by a DC power source using the constant-current and constant-voltage (CC-CV) method till the charge voltage reached 3.65 V. The batteries were then idle for a few hours to ensure that they were in a steady state. The batteries were discharged through a DC electronic load with a discharging current of 20 A under constant-current mode to simulate the high-current discharging behavior. The measurements were performed and recorded automatically by a computer till the battery voltage was reduced to 2.0 V. The experimental setup flow is shown in Fig. 2.

Take a new battery as an example, the recorded result is shown

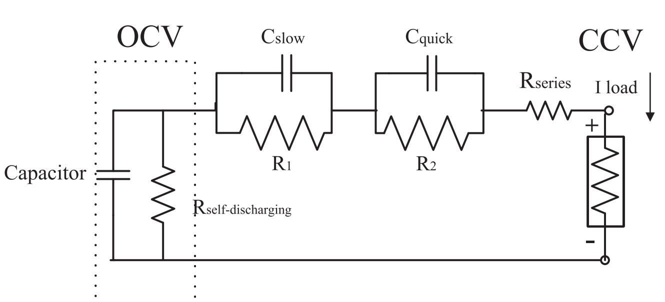

Fig. 1. The electrical circuit model for a $LiFePO_4$ battery.

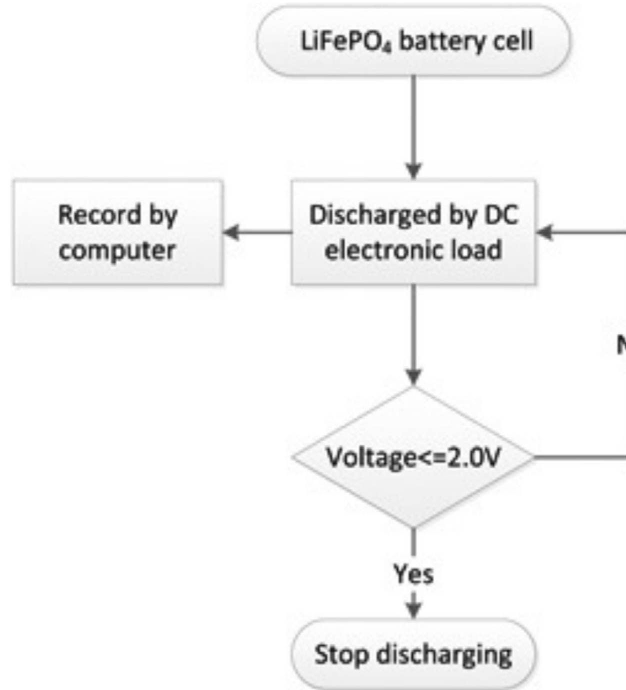

Fig. 2. Experimental setup flowchart.

in Fig. 3 along with an asymptote of the measured curve. It can be seen that the curve has two turning points and the curve can be divided into three portions. The first portion is the voltage before the first turning point. It is mainly determined by the internal resistance of the battery, the wire resistance, and the discharging current value as the battery changes from an open-loop state to a closed-loop state. The voltage in the first portion of the curve can be described using

$$CCV = OCV - I \cdot Req \tag{1}$$

where CCV is the closed circuit voltage, OCV is the open circuit voltage, I is the discharging current, and Req is the equivalent resistance of the battery and the wires. The second portion is

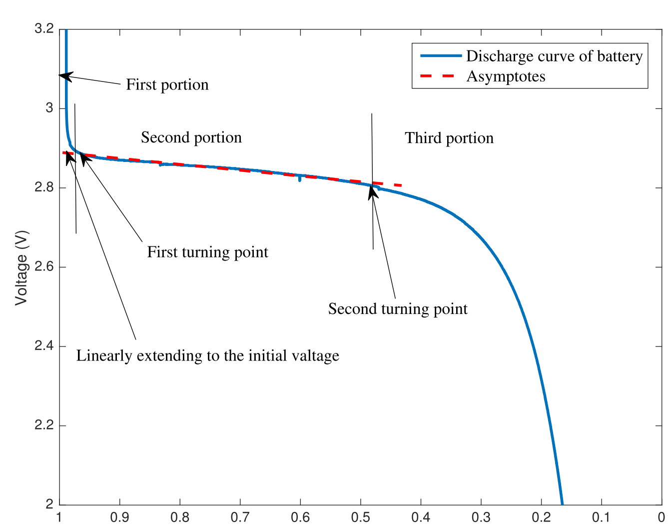

Fig. 3. A discharging curve of a measured battery.