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State of charge estimation for pulse discharge of a $LiFePO_4$ battery by a revised Ah counting

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ABSTRACT

Tracing the battery's state of charge (SOC) accurately in real-time is a vital requirement for safe and reliable battery management. This paper proposes a revised Ah counting method for SOC estimation by correlating the available capacity with the amount of dischargeable lithium (Li) in the electrode particles. The revised Ah counting method can capture the dynamic responses of SOC during the pulse discharge operations. The calculated discharge capacities for a $LiPFeO_4$ battery with the revised Ah counting method are in close agreement with the measured values giving the maximum error by 1.1%. The changes in the unavailable Li in a carbon particle are analyzed. The results show that the variation of unavailable capacity is a gradual process during the pulse discharge. The accuracy of the traditional Ah counting and the revised Ah counting for SOC estimation are evaluated with the constant current pulse and the variable current pulses at different environment temperatures. The results indicate that the revised Ah counting method performs better synchronism than that of traditional Ah counting method. The maximum error of the estimated discharge time with the proposed method is less than 3.8% compared to the experimental measurement.

1. Introduction

In recent years, lithium (Li) ion batteries were widely applied in electric vehicles (EVs) and hybrid electric vehicles (HEVs) by virtue of their high-performances (e.g. high voltage platform, high energy density, and long cycle life etc.). The state of charge (SOC) is an important parameter for battery management system (BMS). It is analogous to the level of fuel contained in the tank for the conventional vehicles. Accurate SOC estimation can prevent the battery from over-charging, over-discharging and unpredicted system interruption, thus prolonging the battery lifecycle and allowing efficient battery power management [1]. However, to precisely estimate SOC is a challenge because the charge capacity being drawn from a battery depends on many factors, including the geometry structure of micro-porous electrodes, charge/discharge current, temperature, cycle degradation, cut-off voltage, and service history etc.[2]. Besides, the microscopic constructional parameters such as the material composition and the structure of micro-porous electrodes change with the usage of battery. The SOC is a direct indicator in the driving for EV or HEV applications. Accurate SOC estimation can quantify the available capacity in real-time and guarantee to select a safe and reliable battery operation. Therefore, a precise SOC estimation method that can adapt to the changing operating conditions in EVs or HEVs is urgently required.

There are several SOC estimation methods [3–7], among which the ampere-hours (Ah) counting method is one of the most extensively used on account of its easy implementation [8]. However, Ah counting method suffers from the drawbacks of the accumulated measurement errors and inaccurate determination of initial SOC. Besides, the precision of the Ah counting method is greatly affected by the fluctuations of discharge current and environment temperature [9,10]. The power demand for driving the EVs presents dynamic variations owing to the variety of road conditions. It can cause current fluctuations during the battery discharge. In addition, the Li ion batteries are usually operated at various environment temperatures associated with a great deal of heat generation during discharge [11–13]. These factors lead to the variation of the maximum effective battery capacity, and thus increase the difficulty and deviation of SOC estimation. In the traditional Ah counting, the influences of the operating current and temperature on SOC estimation are generally considered by a coulombic efficiency obtained by fitting abundant experiment data. However, it is difficult to determine the coulombic efficiency accurately because the relationship between the discharge capacity and the operating current or battery temperature is

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Nomenclature

a	specific surface area of electrode particles (m^{-1})
A	unwinding area of the electrode (m^2)
brug	Bruggeman tortuosity exponent
c_0	initial electrolyte concentration in the solution phase (mol m^{-3})
c_s	Li concentration inside the electrode particles (mol m^{-3})
$\bar{c}_s$	the volume-average concentration of Li in the electrode particles (mol m^{-3})
$c_{s,0}$	Li concentration in the electrode particles of the fully charged battery (mol m^{-3})
c_{smax}	maximum Li concentration in the electrode particles (mol m^{-3})
c_{th}	the theoretical specific capacity of the Li ion battery (Ah/kg)
$C_{available}$	the available capacity of the battery in real time (Ah)
$C_{discharged}$	the discharged capacity of the battery in real time (Ah)
D_s	diffusion coefficient of Li in the electrode particles (m^2 s^{-1})
F	Faraday's constant (26.8 Ah mol^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
I	current applied to the battery (A)
L	thickness of the electrode (μm)
l	length of the unwinding electrode (m)
m	the weight of the electrode material that has occurred deintercalation or intercalation (kg)
n^0_s	the molar of the Li that cannot be available in the electrode particles (mol)
N	cycle number of the battery
N_{Li}	the number of moles of the transferred Li from electrode particles (mol)
r_s	the average radius of the electrode particles (μm)
R	gas constant (8.314 J mol^{-1} K^{-1})
R_{SEI}	resistance of the film at solid electrolyte interphase (Ω•m^2)
t	time (s)
t_+	transport number of Li ion in electrolyte
T	the battery temperature (K)
T_{amb}	the ambient temperature (K)
w	width of the unwinding electrode (m)

Greek letters

ε_s	volume fraction of electrode active material
ε_l	volume fraction of electrolyte
ε	emissivity of the battery can
ρ	density (kg m^{-3})

Subscripts

n	negative
p	positive
ref	reference temperature for Arrhenius

nonlinear and complicated. Moreover, the SOC estimated by the traditional Ah counting method cannot capture the transient process as the operating current varies during discharge in the EV applications.

It is known that the capacity of battery depends directly on the amount of deliverable Li from the electrode particles. How much the Li can be intercalated or deintercalated from the electrode particles is strongly related with the Li diffusion coefficient, current density, particle scale, particle shape etc. The Li diffusion coefficient is function of the temperature and physical properties of electrode materials. The SOC is defined as the ratio of the available capacity to the effective total capacity. This paper proposes a revised Ah counting method for SOC estimation based on dynamically computing the deintercalated Li and dischargeable Li from the carbon particles. The method can capture the transient process of SOC. The SOC for a $LiFePO_4$ battery during discharge are estimated by the proposed method at different pulse currents and ambient temperatures. The unavailable Li in a carbon particle during discharge is calculated and analyzed with a constant pulse current. The battery SOC estimated by the revised Ah counting and the traditional Ah counting is compared.

2. Model development

A typical cell configuration of Li ion batteries is composed of the negative electrode, the separator, the positive electrode, and the current collectors. The ionic and electronic transport processes of Li ion batteries during charge or discharge are illustrated in Fig. 1. During discharge, Li ions deintercalate from the negative particles and intercalate into the positive particles. The separator acts as an electronic insulator, forcing the electrons to flow through an external circuit. As shown in Fig. 1, the direction of Li migration during charging is opposite to that of discharge processes.

The structure of electrodes can be regarded as porous materials. The characteristic parameters for porous structure can be described by the fractal geometry theory. The distribution of particle size for porous media follows the principle of statistics. The number of particle size d can be calculated by:

$$N(L \geq d) = \left(\frac{d_{\max}}{d}\right)^{d_f} \quad (1)$$

where d is particle diameter and $d_{\max}$ is the maximum particle diameter. The d_f is fractal dimension within [0,2] and [0,3] for two dimensions and three dimensions, respectively. The density function of particle size is given by [14]:

$$f(d) = d_f d_{\min}^{d_f} d^{-(d_f+1)} \quad (2)$$

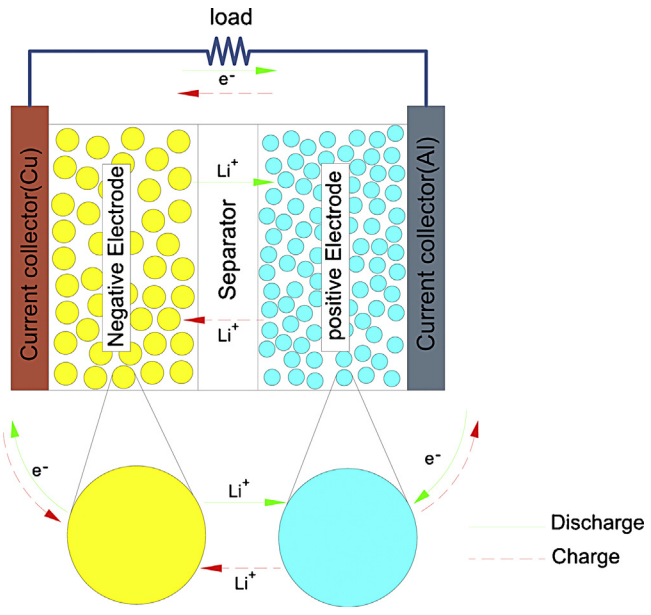

Fig. 1. Schematic of Li ions transport process during charge or discharge.