Journal of Power Sources 400 (2018) 305–316

Contents lists available at ScienceDirect

Journal of Power Sources

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

Health conscious fast charging of Li-ion batteries via a single particle model with aging mechanisms

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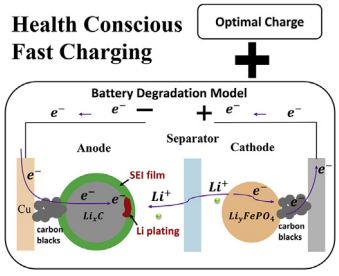
HIGHLIGHTS

- Fast charging achieves the minimum charging time but causes severe capacity fade.
- Health conscious fast charge reduces charge time without sacrificing battery health.
- Health conscious fast charge avoids mainly lithium plating instead of SEI growth.
- High charge rates cause electrolyte depletion which lowers down current capability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Li-ion batteries
Health conscious fast charging
Dynamic programming
Lithium plating
Single particle model
Degradation

ABSTRACT

Battery fast charging is one of the most significant and difficult techniques that affects the acceptance of the electric vehicles. Due to the complex electrochemical reactions, fast recharge could affect the battery functionality and accelerate its aging processes. The accelerated aging process during fast charging can dramatically reduce cell lifetime, impact cell safety, and must be avoided. In this paper, we propose a health conscious fast charging framework with the aim of simultaneously reducing the charge duration and the battery degradation. This paper presents an electrolyte enhanced single particle model with degradation mechanisms. A multi-objective optimal control problem is formulated. Dynamic programming (DP) technique is employed to find the optimal charging strategies. Charging time and battery degradation are traded off and optimized. Strategies for fast charging (minimum time) and health conscious fast charging are examined and compared. Multiple experiments are carried out to compare the charge time and capacity fade between fast charging strategy, traditional CC/CV protocol, and health conscious fast charging strategy. The results demonstrate that the health conscious fast charging strategy is able to significantly reduce the charging time without sacrificing battery health.

1. Introduction

As the most important and most widely used energy storage system, lithium ion battery is essential to the sustainable development of our economy, and plays a crucial role in the transportation electrification and renewable energy. For conventional fuel-driven vehicles, the refueling of gasoline or diesel can be done rapidly at gas stations, with a minimal out-of-service time. However, the battery recharge takes much longer time and also requires meticulous control due to the complex electrochemical dynamics, battery health and safety concerns. In most

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https://doi.org/10.1016/j.jpowsour.2018.08.030
Received 7 May 2018; Received in revised form 22 July 2018; Accepted 9 August 2018
0378-7753/

applications, such as cell phones, laptop, the charging process may last several hours, leading to a long out-of-service time. In electric vehicles with huge amount of battery cells, the charging process may last even longer. The charging method is very crucial. An unsuitable charging method leads to long charging time, and could also compromise the battery longevity. Fast charging helps to reduce out-of-service time and promote the commercialization of EVs. And health conscious charging prolongs the battery life by reducing the harmful side reactions [1–6]. It is thus crucial and also the focus of this article to develop a systematic approach to solve for the health conscious fast charging strategy, and investigate the tradeoffs between charging time and battery degradation.

The traditional charging strategies for lithium ion batteries are constant-current/constant-voltage (CC/CV) [7], pulse current charging, pulse voltage charging [8–10]. Among them, the CC/CV is the most wide-spread method, although its charging performance is still unable to satisfy consumers requirements of fast charging speed and long battery lifespan. Various charging methods are also proposed to improve the charging performance. Such as, multi-stage CC and CV [11,12], neural networks [13], fuzzy logic [14,15], etc. Most of these methods are based on basic knowledge or empirical observations of battery dynamics. However, the best achievable performance determined by the electrochemistry is not approached by those methods.

This paper develops a systematical approach to solve for the optimal charging strategies. The focus of this article is to develop the health conscious fast charging strategy and investigate the tradeoffs between charging time and battery degradation. A degradation model is developed based on the baseline single particle model from the previous work [16]. The degradation model includes the major side reactions (mainly SEI growth and lithium plating) during charging process, and is used for health conscious fast charging optimization. A multi-objective optimal control problem is mathematically formulated. To the best of our knowledge, this is the first time that a single particle model enhanced with degradation mechanisms is used for charging strategy optimization. The fast charging (minimum time) and the health conscious fast charging strategies are examined and compared. Experiments are also carried out to compare the performance between fast charging strategy, traditional CC/CV protocol, and health conscious fast charging strategy. The benefits of health conscious fast charging strategy are demonstrated in experiments. It's also worth noting that due to the curse of dimensionality in dynamic programming and highly nonlinear nature of this problem, multiple techniques, including time to SOC domain conversion, electrolyte dynamics approximation, and static maps for degradation mechanisms, have been used to reduce the computational burden while maintaining the accuracy.

The paper is organized as follows. In section 2, the physics-based single particle model with electrolyte dynamics and aging mechanisms is developed and presented. In section 3, a multi-objective optimal control problem is formulated. The health conscious fast charging strategy is derived and compared with fast charging strategy. In section 4, the optimal charging strategies are discussed in details. And the experiment results are provided to compare the performance of fast charging strategy, traditional CC/CV protocol and health conscious fast charging strategy, followed by conclusions in section 5.

2. Electrolyte enhanced single particle model with degradation mechanisms

The battery system considered in this study is a graphite/ LiFePO4 energy cell. The battery electrode consists of a large number of particles. There are approximately 7.5 billion particles in the anode electrode in the 400 mAh cell used in this study. It's almost impossible to simulate all of these particles at the same time. Therefore, the single particle model is used in this work, which assumes that each electrode of a lithium ion cell can be approximated by a single spherical particle whose surface area is scaled to that of the porous electrode. Fig. 1 provides a schematic of the SP model with degradation mechanisms. We first present the electrolyte enhanced single particle model [16], and then add the major side reactions (mainly SEI growth and lithium plating) to the single particle model. The electrolyte enhanced single particle model with degradation mechanisms is used for charging strategy optimization.

2.1. Single particle model with electrolyte dynamics

We begin by presenting the partial differential equations that govern the electrochemical dynamics. The solid phase diffusion equation in spherical particles is simplified by using two-term polynomial approximation [17–19] as follows:

Cathode

$$\frac{dx_{p,avg}}{dt} = \frac{-3J_p}{FR_p c_{p,max}}, J_p = \frac{I_{app}}{S_p} \tag{1}$$

$$x_{p,surf} - x_{p,avg} = \frac{-J_p R_p}{5FD_{s,p} c_{p,max}} \tag{2}$$

Anode:

$$\frac{dx_{n,avg}}{dt} = \frac{-3J_n}{FR_n c_{n,max}}, J_n = \frac{I_{app}}{S_n} \tag{3}$$

$$x_{n,surf} - x_{n,avg} = \frac{-J_n R_n}{5FD_{s,n} c_{n,max}} \tag{4}$$

where $x_{i,avg}$, electrode's SOC, is the ratio of the solid average concentration to the maximum solid concentration $c_{i,max}$ for each electrode. J_i is the current density for each electrode. S_i is the electroactive surface area for each electrode. I_{app} is the applied current. R_i is the particle radius. $x_{i,surf}$ is the ratio of the solid surface concentration to the maximum solid concentration. $D_{s,i}$ is the solid phase diffusion coefficient. F is the Faraday constant.

The Bulter-Volmer kinetic expression is commonly used to predict the rates of lithium intercalation and deintercalation reactions

$$J_i = k_i \left[\exp\left(\frac{\alpha_{a,i} F}{RT}\eta_i\right) - \exp\left(-\frac{\alpha_{c,i} F}{RT}\eta_i\right)\right] \tag{5}$$

where η_i is the over-potential for lithium ion deintercalation/intercalation reactions. $\alpha_{a,i}$ and $\alpha_{c,i}$ are the anodic transfer coefficient and cathodic transfer coefficient respectively. R is the gas constant. T is the temperature. k_i is the reaction rate coefficient.

η_p and η_n can be estimated as [20].

$$\eta_i = \frac{RT}{\alpha_{a,i} F} \ln(\xi_i + \sqrt{\xi_i^2 + 1}) \tag{6}$$

where

$$\xi_i = \frac{J_i}{2k_i} \tag{7}$$

The following equations show the relationship between the electrode potentials and the over-potentials.

$$\eta_p = \phi_p - U_+(x_{p,surf}) \tag{8}$$

$$\eta_n = \phi_n - U_-(x_{n,surf}) \tag{9}$$

where ϕ_i is the electrode potential. U_+ and U_- are the open circuit potentials in Fig. 1.

Finally, the cell voltage is obtained by the following equation:

$$V_{cell} = \phi_p - \phi_n + I_{app} R_{cell} \tag{10}$$

where R_{cell} is the internal resistance.

The electrolyte diffusion dynamics [21] is given as