



Modeling the effect of two-stage fast charging protocol on thermal behavior and charging energy efficiency of lithium-ion batteries

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ARTICLE INFO

Keywords:

Fast charging
Charging protocol
Thermal behavior
Electrochemical thermal model
Charging energy efficiency
Battery thermal management

ABSTRACT

To enable fast charging of lithium ion batteries, extensive attention is needed to reduce the heat generation rate to avoid thermal runaway. This work studies the impact of the fast charging protocol on thermal behavior and energy efficiency of a lithium ion battery cell for 30-minute charging with 80% rated capacity. A two-stage constant current (2SCC) charging protocol with different current level combinations is adopted to mitigate the temperature rise leading to thermal runaway and improve the charging energy efficiency, because different charging current will generate different rates of heat. An electrochemical thermal coupled model is developed to predict the heat generation rate, charging energy rate, and temperature rise with experimental validation. The simulation results indicate that the “high-low” charging protocols of the 2SCC fast charge can achieve a lower overall temperature rise and higher charging energy efficiency than both the “low-high” charging protocols and the standard one-stage constant current (1SCC) charging. Compared to the 1SCC charge, the 2SCC charging protocol can improve the overall charging energy efficiency by 1%. Additionally, the impact of the 2SCC charging protocol on the thermal behavior under different initial cell temperatures and the heat transfer coefficients are discussed.

1. Introduction

Fast charging technology of lithium-ion batteries is critical to the commercial application of electrical vehicles (EV). Traditional charging protocols charge the cell at a low current because the high charging current may cause lithium plating, resulting in accelerated degradation of the battery [1]. Additionally the high current can increase both the heat generation rate and the cell temperature, which is another reason for battery degradation [2]. Developing new, fast charging protocols that can reduce heat generation and preserve battery life is of high interest for the EV market.

The traditional constant current – constant voltage (CCCV) charging protocol widely used in commercial lithium-ion battery chargers [3,4] is not suitable for fast charge due to the charging current profile. The CCCV has two charging stages: the battery is charged at a constant current (CC) in the first stage until the battery voltage reaches the upper limit pre-defined by manufacturers based on the battery chemistry; In the second constant voltage (CV) stage, the voltage is maintained at the upper limit to avoid overcharge until the charging current is decreased to a pre-defined cut-off value. For fast charge under the CCCV protocol,

the constant current at the first stage is set at a high level, resulting in high polarization. However, the high polarization can increase the charging voltage to its upper limit and switch the charging mode to the CV stage. If the charging capacity in the CC stage is low, the second CV stage with a low current level requires more charging time. Furthermore, the high polarization can lead to lithium plating under high state of charge (SOC).

To avoid reaching the voltage limit under high charging current levels, some fast charging protocols have been proposed. By using decayed charging current profiles, those protocols can reduce the charging voltage increase during the fast charging process as compared with the CCCV protocol. For example, a multi-stage constant current (MSCC) charging protocol can reduce the charging time, temperature rise and improve the charging energy efficiency [5]. By using four levels of constant current charging, the battery can be charged with a high current in the initial stage, then with a low current in the last stage, to avoid polarization at the end of charging. Some other charging strategies such as the variant current decay (VCD) method [6], the linear current decay (LCD) method [7], and the CV-CC-CV method [8] have similar working principles to the MSCC.

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Nomenclature		$U_{OCV,cell}$	Open circuit voltage of the electrode (V)
A	Electrode plate area (cm ²)	V_{cell}	Cell volume (m ³)
A_{cell}	Cell surface area (m ²)	<i>Greek letters</i>	
C_{cell}	Nominal capacity (Ah)	α_a	Anodic transfer coefficient
c_p	Heat capacity (J·Kg ⁻¹ K ⁻¹)	α_c	Cathodic transfer coefficient
c_s	Concentration of lithium in the active material particles (mol m ⁻³)	β	Bruggeman porosity exponent
c_l	Electrolyte concentration (mol m ⁻³)	λ	Thermal conductivity (W·m ⁻¹ K ⁻¹)
D_s	Diffusion coefficient of lithium in the active material (m ² s ⁻¹)	ε_s	Active material volume fraction
D_l	Diffusion coefficient of electrolyte (m ² s ⁻¹)	ε_l	Electrolyte volume fraction or porosity
E_{act}	Activation energy (J mol ⁻¹)	\varnothing_s	Solid phase potential (V)
E_{in}	Charging energy (Wh)	\varnothing_l	Electrolyte phase potential (V)
E_{store}	Chemical energy stored in the cell (Wh)	σ_s	Electronic conductivity of solid matrix (S m ⁻¹)
f_{\pm}	Average molar activity coefficient	κ_l	Ionic conductivity of electrolyte (S m ⁻¹)
F	Faraday's constant (C mol ⁻¹)	δ	Thickness of each battery component (μm)
q	Heat generation rate (W m ⁻³)	η	Local surface overpotential (V)
h	Heat transfer coefficient (W·m ⁻² K ⁻¹)	η_{ch}	Charging energy efficiency (%)
j_0	Exchange current density (A m ⁻²)	<i>Subscripts, superscripts and acronyms</i>	
j_{loc}	Local charge transfer current density (A m ⁻²)	0	Initial or equilibrated value
k_0	Reaction rate constant (m ^{2.5} mol ^{-0.5} s ⁻¹)	s	Solid phase
R	Gas constant, 8.314 (J mol ⁻² K ⁻¹)	l	Electrolyte phase
R_0	Radius of electrode particles (μm)	eff	Effective value
S_a	Specific surface area (m ⁻¹)	pos	Positive electrode
t+	Transference number of lithium ions	sep	Separator
T	Temperature (K)	ref	Reference value
U_{eq}	Open circuit potential of the electrode (V)		

Very few of the works in literature, however, studied the effect of the charging protocol on battery thermal behavior for fast charge. Since thermal behavior is also important to battery cycle life and safety during fast charging, research toward the development of fast charging protocols that reduce heat generation and temperature rise should also be considered. In addition, the studies on fast charging protocols are all based on empirical approaches or empirical models such as equivalent circuit models (ECM) [9–12]. These methods cannot capture the real dynamics behavior of the battery system during fast charging. To study battery dynamic characteristics, the electrochemical models proposed by Doyle and Newman et al. [13,14] have been employed in recent research [15–18]. The electrochemical model may not be suitable for real-time application, but the results can serve as a benchmark to evaluate and improve existing real-time algorithms for battery fast charging optimization. Nevertheless, few of the previous works use the electrochemical model to study the effect of fast charging protocols on battery electrochemical-thermal behavior.

In this paper, we study the effect of fast charging with a two-stage constant current (2SCC) charging protocol on battery electrochemical and thermal behavior by applying different levels of currents and combinations thereof to a pseudo two-dimensional (P2D) electrochemical-thermal coupled model developed for a 26650 cylindrical lithium iron phosphate (LFP) battery cell. Various charging current levels ranging from 0.6 C-rate and 2.6 C-rate are applied to the fast charging process for 30-minute charging with 80% rated capacity. The temperature rise, heat generation, and charging energy efficiency are compared for different levels of currents and combinations thereof. An optimal fast charging protocol focusing on maximizing the charging energy efficiency is discussed while satisfying the specific maximum temperature constraint. The effects of initial temperature and surface heat transfer coefficient on 2SCC fast charging are discussed. Section 2 describes the electrochemical thermal model development and model validation. Section 3 presents the proposed 2SCC fast charging strategy. Section 4 discusses the effect of various charging current protocols on thermal behavior and charging energy efficiency based on simulation

results.

2. Electrochemical thermal model and model validation

In this section, a baseline electrochemical thermal coupled model for a commercial A123 26650 $LiFePO_4$ graphite cylindrical battery cell is developed and validated using a single stage CC charge protocol under 4 different charge current rates. This model will be used to investigate and compare the effect of the fast charging in single stage and two stages of interest in subsequent sections.

Fig. 1(a) shows the computational domain of the cell unit comprising three main components: a Li_yC_x negative electrode, a separator, and a Li_xFePO_4 positive electrode, where y and x denote the stoichiometry coefficients of the negative and positive electrodes. The electrochemical model is developed according to previous models [13,14,19,20]. This model considers: 1) the charge conservation in the through-plane direction (x); 2) the Li mass conservation in the through-plane direction (x) in the electrolyte phase and in the radius direction (r) of the active particle in the solid phase; 3) the electrochemical kinetics described by Butler-Volmer equation. Fig. 1(b) shows the thermal model developed using a 2D axisymmetric geometry for the cylindrical cell. The energy conservation is adopted as the governing equation of the thermal model. The heat generation rate term is the average heat source generated from the local region of the electrochemical cell. The total heat generation rate consists of reversible heat due to entropy change, the irreversible heat due to local overpotential at the solid-electrolyte interface, and the ohmic heat. The governing equations and model parameters are listed in the appendix section.

Fig. 1(c) depicts how the electrochemical model and the thermal model are coupled: by the average temperature T_{avg} solved in the thermal model and by the average heat generation rate q_{avg} solved in the electrochemical model. The electrochemical thermal coupled model presented in this paper is solved using a commercial finite element software, COMSOL Multiphysics 5.3, employing the electrochemical and the heat transfer modules in the software package.

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