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Optimized Charging of Li-Ion Batteries by Using Adaptive Impedance-Based Approach

Abstract: Decreasing the charging time of Lithium-ion (Li-ion) batteries is essential for modern energy applications. However, significant challenges arise in balancing charging speed with safety and longevity. This study investigates the potential of real-time battery impedance measurements for controlled charging in Li-ion batteries. By integrating real-time data into adaptive charging algorithms, charging is optimized for safety, efficiency, and longevity. Experimental validation highlights the feasibility of these methods while identifying challenges such as computational demands and sensitivity to noise.

Keywords: Adaptive charging, Lithium-ion batteries, Electrochemical impedance spectroscopy

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1 Introduction

Fast charging is a critical feature in Li-ion battery applications, particularly in applications like electric vehicles, where long charging times hinder widespread adoption. Conventional fast-charging techniques such as constant-current constant-voltage (CC-CV) charging often operate without real-time insights into the battery's dynamic state, increasing the risk of overcharging, overheating, and accelerated aging [1]. To overcome these limitations, there is a need for advanced charging control that integrate real-time diagnostics to ensure optimal charging performance while preserving battery health.

Impedance measurement has been recognized as a valuable diagnostic tool for assessing the internal state of Li-ion batteries, providing insights into parameters such as state of charge (SOC), state of health (SOH), and thermal conditions. However, traditional impedance measurement techniques, such as electrochemical impedance spectroscopy (EIS), are time-consuming and unsuitable for real-time applications. Recent advancements in rapid impedance measurement methods, including binary broadband perturbation and Fourier analysis, offer the potential to monitor battery impedance in real-time with high accuracy and minimal computational burden [2].

In this study, we investigate the application possibilities of real-time impedance-based methods for controlling fast charging of Li-ion batteries. By exploring the integration of binary broadband perturbation and Fourier techniques into fast charging protocols, this work aims to assess their feasibility and potential benefits.

2 Theory and Methods

Lithium plating in Li-ion batteries is a chemical process that occurs during charging when the intercalation of lithium ions into the electrode material is incomplete, causing metallic lithium to deposit on the electrode's surface. This phenomenon poses a significant risk, especially during fast charging, where high current densities increase the likelihood of plating. If this lithium deposition continues to grow within the solid-electrolyte interphase (SEI) layer, it can penetrate into the electrolyte, resulting in irreversible lithium loss and a subsequent decrease in battery capacity [1].

Lithium plating can be mitigated by employing pulse charging methods [3]. The characteristics of the ripple are defined by its time-domain shape (e.g., square, sinusoidal, triangular), amplitude, and frequency. The ripple frequency has been identified as the most critical factor influencing the performance of pulse charging methods [3]. An optimally selected ripple frequency can reduce charging time, enhance charging efficiency, and minimize battery degradation.

The optimal frequency of the pulse charging ripple, f_{opt}, can be determined by utilizing the internal impedance of the Li-ion battery cell. The frequency f_{opt} corresponds to the point where the imaginary part of the battery impedance, Z_{batt} is zero i.e. where the phase shift of the impedance is 0° [3]. The impedance can be rapidly measured in real time by applying broadband perturbations and Fourier techniques [4].

3 Experiments

Fig. 1 shows the measurement setup applied in the work. A commercial Li-ion battery was charged both by the pulse charging method and conventional CC-CV charging method. The experiments were conducted using a bi-directional switch-mode power supply (Kepco BOP 50-20MG) to inject current into the Li-ion battery cell. Excitation generation and measurements were carried out using a Nidaq USB-6363 measurement card. The cell voltage was measured directly at the battery terminals, while the current was measured using a Tektronix 312A Hall-effect current sensor.

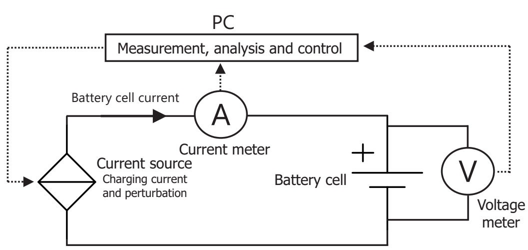

Fig. 1. Schematic of the measurement set-up.

The Li-ion battery cell was first charged from 0 % SOC to 50 % SOC using the CC-CV method with a current of 0.88 A. Then, the battery battery was recharged and charged again by the pulse charging method using a square wave pulse with a 50 % duty cycle. The peak charging current was set to 1.76 A to ensure a similar effective current compared to the CC-CV method. The optimal pulse charging frequency, f_{opt}, was determined through online battery-impedance measurements conducted with a 0.88 A load, with measurements taken at every 10 % SOC increment. The impedance was measured using a wideband technique as described in [4]. The initial pulse charging frequency was determined by measuring the battery impedance at 0 % SOC while the cell was at rest.

In the pulse charging experiment, a total of five different f_{opt} values (416 Hz, 679 Hz, 643 Hz, 802 Hz, and 183 Hz) were used during each stage of the charging intervals (0 %–10 %, 10 %–20 %, 20 %–30 %, 30 %–40 %, 40 %–50 %), respectively. The impedance measured at 30 % SOC, along with the determined f_{opt} is shown in Fig. 2.

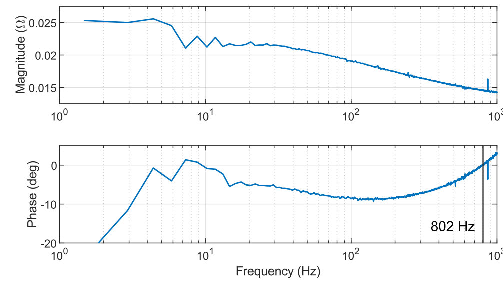

Fig. 2. Battery-impedance measured at 30% SOC presented as a Bode plot. The value of f_{opt} marked at 802 Hz.

No significant differences were observed in the charging times, as the pulse charging method was only 0.6 % faster than the CC-CV charging method. However, the pulse charging method offered other advantages, primarily in reducing battery degradation and improving efficiency. By applying intermittent pulses of current, pulse charging allows for cooling periods that reduce heat generation and thermal stress, mitigating factors such as lithium plating and capacity fade. Additionally, the method enhances Li-ion diffusion within the battery, promoting a more uniform charge distribution and optimizing internal impedance. These features not only contribute to improved battery longevity but also enable safer and potentially faster charging without compromising the battery's health. Studies demonstrated that the use of wideband techniques to obtain battery impedance in real time can significantly improve the efficiency of the pulse charging method by introducing adaptivity to its operation.

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