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Optimal pulse-modulated Lithium-ion battery charging: Algorithms and simulation

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ABSTRACT

This paper focuses on the development of optimized pulse charging strategies for Lithium-ion (Li-ion) batteries. Aiming to improve the constant pulse charging in wide use today, we propose for the first time to modulate the current pulses during the charging process to reconcile health protection with charging pace. Toward this end, we use an equivalent circuit model and then formulate the problem of optimal pulse charging with an awareness of both battery health and charging speed. We then propose to resolve it using the linear control theory and obtain two charging methods, which regulate the magnitude and width, respectively, of the current pulses applied during the charging process. The proposed methods promise a two-fold benefit. First, the pulse-modulated charging will offer an effective means to defend the battery against the charging-induced harm to health without much compromise of the charging speed. Second, the methods have low computational cost, thus suitable for embedded battery management systems (BMSs) with constrained computing capabilities. This compares with the many charging techniques in the literature that require time-consuming constrained optimization. A detailed simulation study of the two proposed methods is offered to evaluate their effectiveness. The study endows pulse charging with a formalized design methodology unavailable before and impose a stronger health protection during its execution, which together can potentially translate into the momentum for its real-world application to Li-ion battery-powered systems including consumer electronics devices, electrical vehicles and solar photovoltaic arrays.

1. Introduction

Recent decades have seen a rapidly growing use of Lithium-ion (Li-ion) batteries, which have seen wide penetration in grid, renewable energy facilities and energy-efficient buildings. In these applications, battery management systems (BMSs) play the essential role of monitoring and regulating the operational status of the Li-ion batteries for improved performance, life, and safety [1,2]. A wealth of research of advanced BMS algorithms has thus come in response to this need. Prior, the focus was mainly on the state-of-charge (SoC) and state-of-health (SoH) estimation, aging status monitoring and thermal monitoring [2]. However, what has been less researched is the charging management, despite the consensus that improper charging protocol can cause fast capacity fade and a shortened life due to the fast build-up of internal stress and resistance, crystallization, and other negative effects [1,3–7].

*Literature review.*Charging by a constant current or a constant voltage is a popular industrial practice [8]. Yet, its relatively easy implementation comes at the expense of decrease in the battery cycle life. An improved approach is the constant-current/constant-voltage (CC/CV) charging [2,8]. Initially, a trickle charge (0.1 C or even smaller) is used for depleted cells, which produces a rise of the voltage. Then, a constant current (often between 0.2 C and 1 C) is applied. This stage ends when the voltage rises to a pre-specified level. It then switches to the constant voltage charging mode. The current diminishes in this mode, but the SoC continues to grow. In recent years, pulse charging has gained much interest among practitioners as an alternative beyond CC/CV. Its current profile is composed of pulses over time. Between two consecutive pulses is a short rest period, which allows the electrochemical reactions to stabilize by equalizing throughout the bulk of the electrode before the next charging pulse begins. This brief relaxation can bring multiple benefits to a Li-ion battery, including better charge acceptance, reduced gas reaction, inhibited dendrite growth, slowed capacity fade and faster charging rates [9–12].

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It is observed that these battery charging practices are inadequate for two reasons. First, they are empirical, with little knowledge available as to implementing them in the most optimal manner. For instance, determination of charge regimes for CC and CV modes, despite its importance for the performance of the CC/CV charging, has been mostly dependent on experience [13]. Second, they often operate as an open loop, simply taking energy from the power supply and failing to take into account the battery's history and current condition. These deficiencies limit the opportunity for maximum health protection during charging. To remedy them, a promising solution is to deploy the feedback control, which introduces a controller and closes the loop between the controller and battery. As such, the charging dynamics can be exploited, and the battery's charging profile optimized to enhance the charging process. In this area, optimal control in conjunction with electrochemical or equivalent circuit models has shown promise for optimizing charging protocols [14,3,15–17]. Model predictive control (MPC), which is also optimization-driven, represents another important class of methods with considerable interest because of its capability to handle health-relevant input, state, and temperature constraints. A few studies have been devoted to MPC-based charging in diverse settings [18–20]. In addition, adaptive control is investigated in [21] to craft an energy-efficient fast charging scheme, and sinusoidal charging studied in [22], which applies sinusoidal currents of the frequency minimizing the battery impedance. Optimal control design of charging/discharging of a battery during its operation is studied in [23] in order to maximize the work it can perform over a given duration while maintaining a desired final energy level.

Statement of contributions. The primary contribution of this work lies in the investigation of optimal pulse-modulated charging. In spite of recent advances as surveyed above, control-theory-enabled charging management is still at a nascent stage, requiring more effort in this direction. Among the various open problems, a prominent one is concerned with pulse charging. Although it has gained considerable popularity, there has been no systematic theoretical study about optimal design for pulse width and magnitude modulation to improve charging performance. To fill this gap, we leverage the linear control theory to develop optimal pulse charging solutions capable of balancing battery health protection and charging speed. Two methods will be obtained: the first one, named `PAM-C`, performs optimal pulse amplitude modulation (PAM) throughout the charging process, and the second, named `PWM-C`, optimally modulates the pulse width. In addition to the benefit of enhanced health protection, the proposed methods have a concise formulation and computational efficiency, suitable for real-time embedded BMS platforms. This work is the first one we are aware of that formalizes and optimizes the pulse charging design, with a potential for transforming its practical use in a wide range of battery systems. It will also provide further incentives for the advancement of battery charging technology.

Organization. The rest of the paper is organized as follows. Section 2 introduces an equivalent circuit model oriented toward charging dynamics. Based on this model, optimal pulse charging strategies will be developed and discussed subsequently in Section 3. To demonstrate effectiveness of the design, numerical results are then presented in Section 4. Finally, concluding remarks are gathered in Section 5.

2. Resistance-capacitance model for charging

Throughout the paper, we consider a second-order resistance-capacitance (RC) model proposed by SAFT Batteries, Inc. for high-power Li-ion batteries [24,25]. As shown in Fig. 1, it consists of two capacitors and three resistors. The resistor R_o represents the electrolytic resistance within a battery cell. The double RC circuits in parallel can simulate the migration of the electric charge during the charging (or discharging) processes. Specifically, the $R_s{-}C_s$ circuit accounts for the electrode surface region, which is exposed to the electrode-electrolyte interface; the $R_b{-}C_b$ circuit represents the bulk inner part of the electrode. Seeing a fast-speed transfer of the electric charge, the electrode surface is responsible for the high-frequency behavior during the charging processes and associated with the immediate amount of charge that the battery can absorb. However, it has a rather limited storage capacity. By contrast, the bulk electrode is where the majority of the electric charge is stored in chemical form. Since the diffusion of ions within the electrode proceeds at a relatively slower speed, the $R_b{-}C_b$ circuit makes up the low-frequency part of the charging response. This implies that $R_b > R_s$ and $C_b \gg C_s$. While inductance can be present in a lithium-ion battery circuit, it manifests itself only at charging frequencies larger than 1 kHz [26], which indeed is far outside of the effecting frequency of the pulse charging mechanisms to be presented in this paper. This makes it unnecessary to include an inductive element in this model.

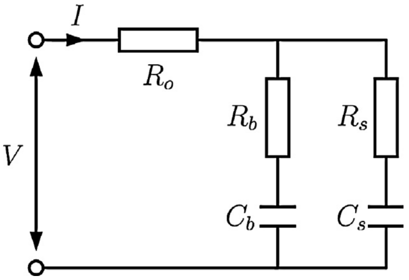

Fig. 1. RC-based equivalent circuit model for battery charging.

Let Q_b and Q_s be the charge stored by C_b and C_s, respectively, and define them as the system state x. That is, $x(t) = \left[Q_b^\top(t)\, Q_s^\top(t)\right]^\top$. The state-space representation of the model is then given by

$$x(t) = Ax(t) + Bu(t), \; y(t) = Cx(t) + Du(t), \tag{1}$$

where $u(t)$ is the charging current, $y(t)$ the terminal voltage, and

$$A = \begin{bmatrix} -\dfrac{1}{C_b(R_b+R_s)} & \dfrac{1}{C_s(R_b+R_s)} \\ \dfrac{1}{C_b(R_b+R_s)} & -\dfrac{1}{C_s(R_b+R_s)} \end{bmatrix}, \; B = \begin{bmatrix} \dfrac{R_s}{R_b+R_s} \\ \dfrac{R_b}{R_b+R_s} \end{bmatrix},$$

$$C = \begin{bmatrix} \dfrac{R_s}{C_b(R_b+R_s)} & \dfrac{R_b}{C_s(R_b+R_s)} \end{bmatrix}, \; D = R_o + \frac{R_b R_s}{R_b+R_s}.$$

Note that $u(t) > 0$ for charging, $u(t) < 0$ for discharging, and $u(t) = 0$ for idling. Derivation of (1) is based on the Kirchhoff's circuit laws and capacitor equation, please see [24] for details. It can be easily verified that this system is controllable, indicating the feasibility of steering the battery's state $x(t)$ to any practically possible point.

The above RC model is linear and straightforward, but it can satisfy the needs in many applications. This is because Li-ion battery systems, e.g., those in electric vehicles, need to limit the minimum and maximum SoC during operation [27,28] for the purposes of safety, life, and a consistent power capability. Within this SoC window, the battery behavior can be approximated as linear. Furthermore, one can draw a linkage between this model and the well-known single particle model (SPM) [29] — the charge transport in the RC model is analogous to the diffusion of ions within a spherical particle representing an electrode. This plain observation can be further expanded to the approximate equivalence between the model in Eq. (1) and the SPM, which is proven in [17].