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Lithium-ion battery cell-level control using constrained model predictive control and equivalent circuit models

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HIGHLIGHTS

- All-electric vehicle market acceptance limited by inadequate range and high cost.
- Cell-level MPC achieves improved performance goals while enforcing constraints.
- MPC with lithium-ion equivalent circuit model solves constrained charge problem.
- MPC demonstrates stable performance for a wide range of tuning parameters.
- Results suggest next step MPC implementation using electrochemical model.

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ABSTRACT

This paper introduces a novel application of model predictive control (MPC) to cell-level charging of a lithium-ion battery utilizing an equivalent circuit model of battery dynamics. The approach employs a modified form of the MPC algorithm that caters for direct feed-though signals in order to model near-instantaneous battery ohmic resistance. The implementation utilizes a 2nd-order equivalent circuit discrete-time state-space model based on actual cell parameters; the control methodology is used to compute a fast charging profile that respects input, output, and state constraints. Results show that MPC is well-suited to the dynamics of the battery control problem and further suggest significant performance improvements might be achieved by extending the result to electrochemical models.

1. Introduction

A major obstacle to widespread use of electric vehicles remains the high cost and limited range associated with on-board energy storage systems (ESS). Market acceptance is further hindered by a lack of the high performance energy management systems (EMS) needed to supply the high power and energy demands presented by drivetrain electrification [1–3]. Consequently, most commercial offerings are based on hybrid energy storage systems (HESS), which aim to exploit the advantages of different ESS solutions while minimizing their respective drawbacks. All-electric vehicles (EVs) must overcome current range and cost limitations in order to gain appreciable market acceptance.

Electric vehicle energy storage is accomplished by devices that accumulate energy electrochemically to perform useful work at a later time. Examples include batteries, fuel cells, capacitors, and super (ultra) capacitors. The present work will address electrochemical storage using lithium ion batteries.

The term battery is often used to describe both a single battery *cell* and a multi-cell battery *pack*. Battery cells are defined as the smallest individual electrochemical unit, and deliver a voltage dependent on a specific cell chemistry. Battery packs are assembled from groups of cells organized into modules in series and parallel configurations. A battery pack's operation and safety is managed by a battery management system (BMS) consisting of sensor and control circuitry.

It is well known that lithium ion battery performance (and indeed safe operation) can be significantly affected by the choice of charging strategy employed to replenish the battery. The ability to bring a battery to a specified state-of-charge in the shortest time possible is intrinsically limited by internal

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electrochemical processes. Additionally, exceeding certain current rates and cell voltages can cause irreversible damage and capacity loss that will ultimately degrade long-term performance. The most widely used charging profile for lithium-ion batteries is constant-current constant-voltage (CCCV). In this scheme, the battery is first charged at a constant current level until a specified voltage limit is reached, after which the voltage limit is held constant while the current is proportionately reduced. Although CCCV is relatively easy to apply, it is often based on conservative voltage limits and thus may not take full advantage of the true operating range of the battery.

Alternative charging strategies have begun to appear in the literature with some of the most promising motivated by control theory. Recent work by Hu et al. [4] devises a multi-objective optimization problem to trade-off minimization of charge time with energy loss by utilizing a linear quadratic regulator (LQR) problem formulation and a simple equivalent circuit model. Bashash et al. [5] utilize multiple objectives to obtain vehicle charge pattern optimization between energy cost and battery longevity, while other approaches have included fuzzy logic [6] and consecutive orthogonal arrays [7], to name a few.

Most battery management control strategies address system (pack)-level control in order to achieve system level performance objectives (e.g., cell balancing). Surprisingly little has been done at the cell-level to improve overall battery performance and extend lifetime. One approach seemingly well-suited to this task is model predictive control (MPC), which is gaining popularity throughout industry [8]. In Ref. [9] the authors propose a nonlinear model predictive control approach to minimize the charging time of a lithium ion battery based on a complex underlying electrochemical model. Employing a 'look-ahead' strategy, MPC can foresee dynamic changes before they happen and efficiently compute stepwise-optimal input control to achieve a quadratic performance objective. More importantly however, MPC is able to conform to hard constraints imposed on designated problem variables. This feature makes MPC particularly appealing for the battery control problem, where respecting certain voltage and current limits can be shown to influence both instantaneous and long-term cell performance [10].

MPC has shown promise in application to hybrid system performance; for example [11], and [12] demonstrate a fuel cell-UC configuration, and [13] and [14] use a fuel cell-battery set. These works exploit a degree of freedom introduced by a secondary energy source (either battery or ultracapacitor) in order to optimize operation of hydrogen fuel cells; in this case, constraints are imposed to avoid a detrimental oxygen starvation condition. A power flow control solution is presented in Refs. [13] and [14], while control on the current applied is presented in both [11] and [12].

The effectiveness of cell-level control is ultimately limited by the underlying mathematical model of battery cell dynamics. Existing cell-level implementations rely almost exclusively on equivalent circuit models of battery dynamics due to their inherent simplicity and general effectiveness. Related work was accomplished by Moura et al. [15] where the problem of film growth in Li-ion battery packs was addressed via switching. There, the authors propose an unequal charging profile obtained through switches controlled by deterministic dynamic programming (DDP) and DDP-inspired algorithms. Although showing effective reduction in film growth, the approach is computationally demanding.

Previous work by Plett ([16,17]) has shown successful implementation of an Extended Kalman Filter (EKF) to estimate cell SOC using equivalent circuit models. For applications where it is of interest to limit SOC during operation, it is suggested that MPC may be used to optimize selected measures of cell performance while respecting such limits.

To that end, it is of interest to examine what can be achieved applying MPC techniques to the control of a battery cell using an equivalent circuit model. Specifically, this paper examines the potential efficacy of MPC to carefully regulate input current when applied to the problem of "fast charge" of a battery cell. In order to clearly illustrate the behavior of MPC with fundamental battery cell-level dynamics, we confine our treatment to discrete-time equivalent circuit cell models representing linear, time-invariant systems. Extensions to reduced-order physics-based models will follow in a subsequent paper.

This paper is organized as follows. In Section 2 we review the basics of battery cell modeling and develop the expressions defining the equivalent circuit model forming the basis of this study. Section 3 introduces the principles of Model Predictive Control and details the modifications employed to incorporate a direct feed-through term. Section 4 formulates the fast-charge optimization problem and Section 5 presents results.

2. Battery cell modeling formulation

2.1. Electrochemistry basics

Vehicle autonomy and reliable performance depend heavily on accurate knowledge of a battery's internal state. When used together with 'smart' controls, dynamic state information can enable significant improvements in battery life and driving range. However, understanding the fundamental processes driving cell behavior is a critical first step to realizing these gains.

Candidate battery technologies for drivetrain electrification include: lead acid, nickel metal hydride (NiMH), and lithium ion (Li-ion). Li-ion batteries have emerged as the candidate of choice due to their high specific energy, low self-discharge rates and long cycle life. Additionally, lithium-ion cells show no memory effect and the high open circuit voltage characteristic allows them to provide the same power at lower current, or by using a reduced number of cells compared to NiMH and NiCd.

2.2. Lithium-ion battery operation

A battery produces electricity by releasing stored potential energy through an electrochemical process. Typical cells consist of three basic elements: a positive electrode, a negative electrode and and electrolyte material. The two electrodes are usually made of different substances, both of which chemically react with the electrolyte as ionic bonds.[1] A separator material electrically isolates the positive and negative electrodes to avoid self discharge of the cell. Lithium-ion batteries work differently from other electrochemical cells in that they depend on an "intercalation" mechanism rather than a standard redox reaction. Intercalation involves the insertion of lithium ions into the crystalline lattice of the host electrode without altering its crystal structure.

Presently, most commercial Li-ion cells use some form of graphite (C_6) for the negative electrode material; a commonly used material for the positive electrodes is Li_xCoO. However, since this material encounters difficulties in scaling, viable candidate cathode materials also include $Li_xMn_2O_4$ and Li_xFePO_4. Each electrode is in electrical contact with a current collector, which transports the electrons from the solid electrode material to the external circuit.

[1] An ionic bond is a type of chemical bond formed due to the attraction between an atom that has lost one or more electron and an atom that has gained one or more electrons.