Model Predictive Control with Adaptive Parameters for fast charging Li-Ion Batteries

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Abstract

This project will create a model predictive controller (MPC) fast charging solution for a generic lithium-ion battery. The controller will be used to determine the optimal current input into the battery for fast charging while considering current, terminal voltage, open circuit voltage, and temperature loads that degrade or otherwise harm the battery's state of health. The generic lithium-ion battery will be modeled using a state space representation of an equivalent circuit model (ECM) as a 1 RC Thevenin model. Offline parameter identification of the model will be assumed. This project seeks only to demonstrate the efficacy of MPC controller design after constant parameters have been identified. Both the state space representation of the model as well as the MPC controller will be designed and implemented using MathWorks's Simulink, a powerful industry standard tool for control systems.

Introduction

Motivation & Background

As the share of the vehicles on the road trends towards electrification, charging these electric vehicles remains a prohibitive issue. Refueling an internal combustion engine is quick, and refueling stations are highly accessible. This study seeks to implement theory and technology from the literature of renewable systems control to address the disparity between refueling and recharging times.

Model predictive control as a tool for lithium-ion battery fast charging has shown promising results. The main advantages of MPC over other optimal controllers are the receding prediction and control windows, as well as the involvement of a constrained input in the optimization. This means the controller can account for nonlinearities present in the system, and generally adapt to divergence from predicted states.

Simulink is utilized for the design and simulation of the control system as it is a powerful industry standard tool with lots of modules and community support for control systems as an application. Direct support of state-space modeling, proper visualization of the system & its signals, and a well-developed user interface for designing an MPC controller are all reasons why Simulink was selected as the main tool for the project.

An equivalent circuit model is used for the model of the battery as it is only non-linear in the output, has few parameters which need to be identified, and is necessary for the support of the thermal resistance model of the batteries internal and surface temperatures.

Relevant Literature

In the literature from Hongwen He, we can see the results of many different equivalent circuit models including Rint, RC Thevenin, PNGV, and DP models [1]. The information in this paper from Hongwen HE at the Beijing Institute of Technology details the efficacy of different equivalent circuit models. This is what will be considered for the design of the first module of the project – the equivalent circuit model – that the MPC uses to model the real battery. This is coupled with a state space model of the internal and surface temperatures [3]. In addition to this, an MPC controller such as one outlined in Marcello Torchio [2] will be supplied with current, terminal voltage, and temperature constraints so that degradation of the battery is minimized.

Focus of this Study

This study focuses on demonstrating MPC as an effective mechanism of controlling the state of charge of a generic lithium-ion battery with realistic constraints such as current, terminal voltage, and temperature. Such a strategy could be applied in the fast charging of electric vehicle batteries to reduce the disparity between refueling and recharging times.

Technical Description

The first step in controlling the battery is properly formulating the 1RC state space model described in the literature above. This has been done as follows: note that the state space model does not include temperature at this time.

$$\dot{x} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{CR_1} \end{bmatrix} x + \begin{bmatrix} \frac{1}{Q} \\ \frac{1}{C} \end{bmatrix} u$$

Where

$$x = \begin{bmatrix} z \\ V_c \end{bmatrix}$$

Due to the nature of the MPC controller, the output equation must contain references to all relevant terms including the state variables themselves

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ p_1 + p_2 + \frac{3}{4}p_3 & 0 \\ p_1 + p_2 + \frac{3}{4}p_3 & 1 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ R_o \end{bmatrix} u$$

Where

$$y = \begin{bmatrix} z \\ V_c \\ OCV - p_o + .25p_2 + .25p_3 \\ V_{term} - p_o + .25P_2 + .25P_3 \end{bmatrix}$$

The constant offset of OCV and V_{term} are a result of the linearization around the point

$$x_{eq} = \begin{bmatrix} 0.5 \\ 0 \end{bmatrix}, u_{eq} = 0$$

Where the OCV function itself is modeled using the polynomial

$$OCV\ (z) = p_0 + p_1 z + p_2 z^2 + p_3 z^3$$

Figure 1. is a depiction of the linearization of the OCV function over the relevant domain (0% to 100% state of charge).

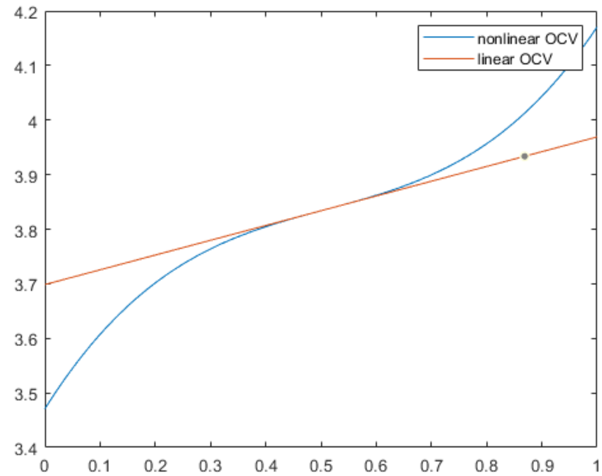

Figure 1. Open-Circuit Voltage linearization

This state space model becomes the plant for the MPC controller, which was designed in Simulink using the MPC Design tool. The four output equations became the *measured outputs* of the system, and the control input became the *manipulated variable*. The MPC controller was also supplied with a reference trajectory for the outputs, however the corresponding weights would be set to zero for all discrepancy with the reference aside from state of charge. Constraints were set in the MPC designer for current and terminal voltage. Here the length of the receding prediction and control horizons could also be set. An example of the results for a charge scenario with 100s long prediction and control horizons where the maximum current was set to 2A, and the maximum terminal voltage was set to 4V is shown in the figures below.

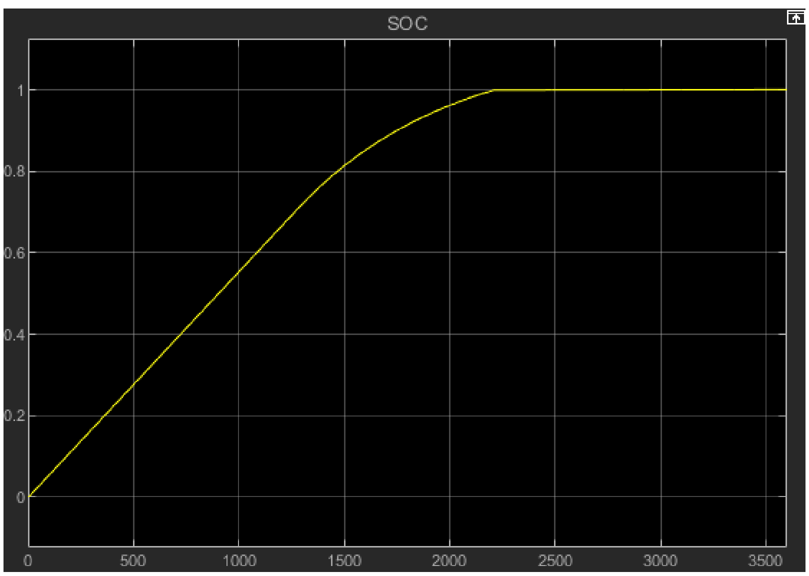

Figure 2. State of Charge from 2A 4V test

In this scenario the controller determines that the optimal result is to maximize current until the terminal voltage starts to restrict the current around 1400 seconds. From this point the controller carefully balances the current supplied with the dissipation until the battery is fully charged.

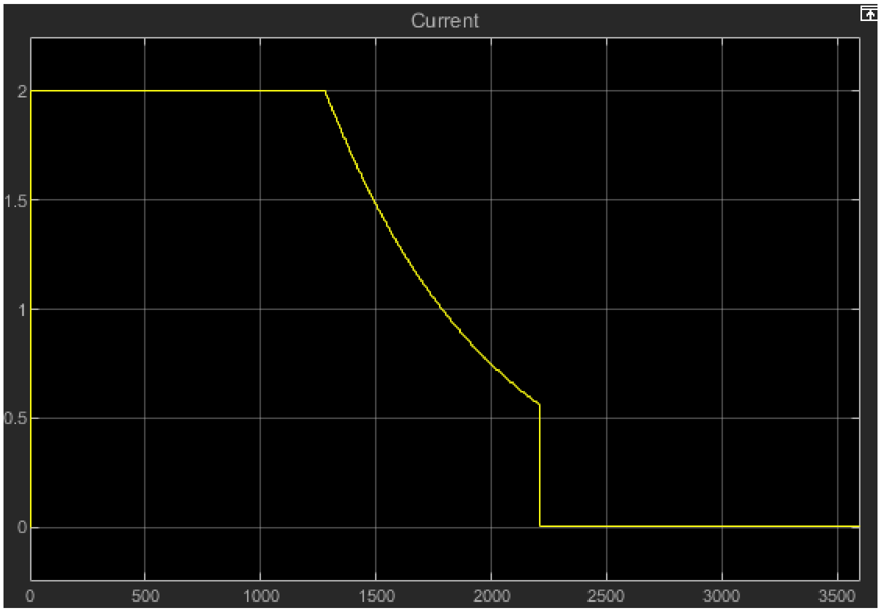

Figure 3. Current from 2A 4V test

This balance is necessary due to the build up of the open circuit voltage,

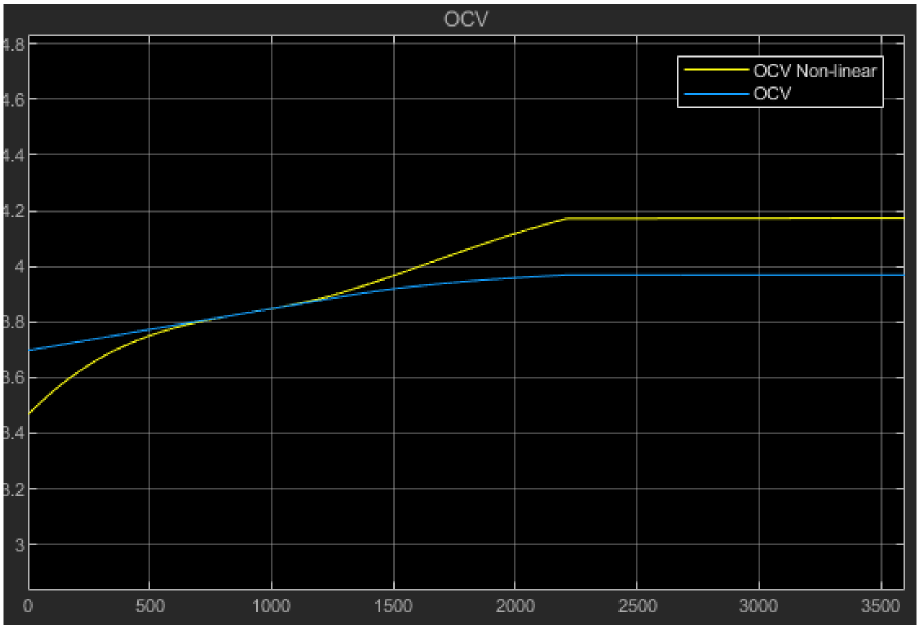

Figure 4. Open-circuit voltage from 2A 4V test

The linear approximation of the open circuit voltage is an under-estimation, which presents issues for the efficacy of the modeling approach which relies only on one linearization step, which will be discussed below.

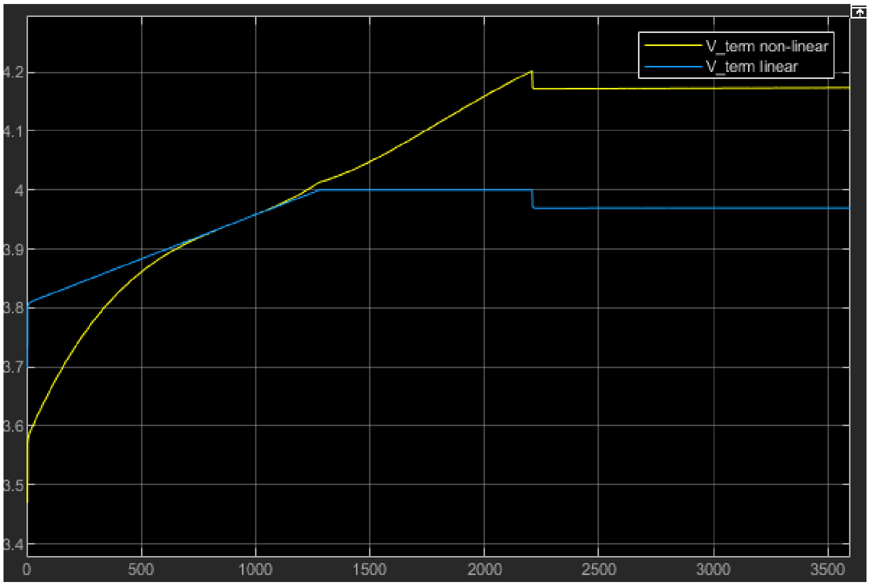

Figure 5. Terminal Voltage from 2A 4V test

The linearized form of terminal voltage is thus maintained at 4V after significant build up of the open-circuit voltage. The improper control of the non-linearized terminal voltage is discussed below, and suggestions to address it are made.

Discussion

Design of the controller has led to multiple conclusions about the approach used. MPC as a technology for actively constraining the input proves effective, adequately limiting the current supplied to the battery for the entirety of the simulation, while also incorporating this constraint into the optimization at every time step. Unfortunately, utilization of state-space modeling significantly hindered the potential advantages of MPC control, such as re-linearization of a non-linear model, something impossible when working with state space. While linearized terminal voltage was adequately constrained, the underestimation of the control response led to improper constraint of the terminal voltage, as terminal voltage growth from control input is highly nonlinear. Utilization of MPC control on a non-linear model could likely account for this issue. Constraint of current – and proper modeling of that constraint – remains a proper advantage of using MPC as opposed to other control methods.

Summary

This project is composed of two Simulink modules necessary to create an MPC controller for lithium-ion battery fast charging. These are the state space model of the battery as well as the MPC controller. MPC was selected as the controller architecture for this system due primarily to its ability to constrain control signals and account for this constraint in the optimization of predicted control scenarios. In this regard the model suffices well, properly constraining current to less than 2A. It is also capable of modeling a linearized terminal voltage. With proper linearization, such as at the midpoint or at the maximum, the issues of over estimation could be mitigated or eliminated. Still, an ideal solution involves MPC control with a non-linear model.

Citations

[1] H. He, R. Xiong, and J. Fan, “Evaluation of lithium-ion battery equivalent circuit models for ... an Experimental Approach,” energies, https://pdfs.semanticscholar.org/989c/bd5ddda33516d42d50b3e251bea236c80ace.pdf (accessed Apr. 5, 2024).

[2] M. Torchio, “Model Predictive Control Strategies for Advanced Battery Management Systems,” University of Pavia, https://iris.unipv.it/retrieve/e1f104fb-9c12-8c6e-e053-1005fe0aa0dd/main.pdf (accessed Apr. 4, 2024).

[3] X. Lin, et al., “A Lumped-parameter electro-thermal model for cylindrical batteries ,” ScienceDirect, https://www.sciencedirect.com/science/article/abs/pii/S0378775314001244 (accessed Apr 4 2024).