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Optimal charging of valve-regulated lead-acid batteries based on model predictive control

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HIGHLIGHTS

- A new model predictive controller for VRLA battery charging is developed.
- Convexity of the battery charging optimization problem is proved.
- Recursive feasibility and stability of the battery charging problem is proved.
- The developed VRLA battery charging algorithm is experimentally verified.

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ABSTRACT

In this paper an algorithm for optimal charging of a valve-regulated lead-acid (VRLA) battery stack based on model predictive control (MPC) is proposed. The main objective of the proposed algorithm is to charge the battery stack as fast as possible without violating the constraints on the charge current, the battery voltage and the battery temperature. In addition, a constraint on the maximum allowed voltage of every battery in the battery stack is added in order to minimize degradation of the individual batteries during charging. The convexity of the VRLA battery charging optimization problem is proven, which makes the control algorithm suitable for efficient on-line implementation via solving a quadratically constrained quadratic program (QCQP). The recursive feasibility and stability of the proposed control strategy is ensured. The proposed algorithm is validated both through simulation tests and on the experimental setup.

1. Introduction

Valve-regulated lead-acid (VRLA) batteries are used in a wide-range of applications from stand-by power supplies to automotive applications due to their low-cost and high reliability [1,2]. Their main role in standby applications is to provide energy in the case of power failure. When the power is restored, the battery should be charged as quickly as possible in order to prepare itself for the next power failure [3,4]. This type of batteries is used in other emerging applications like microgrids, where they are combined with various renewable energy sources [5,6]. In such cases it proves beneficial to charge the battery as quickly as possible in order to increase gains in optimization of microgrid energy flows. Furthermore, VRLA batteries with a low internal resistance are used in electric and hybrid electric vehicles where they need to be charged as quickly as possible as well [7–9]. However, fast charging typically comes at the cost of a reduced battery lifetime, which is another important aspect in all the aforementioned applications, since it directly influences the total operating cost of the system due to the fact that battery needs to be replaced periodically [6].

The lifetime of a lead-acid battery is often considered to be a function of materials and design parameters such as grid alloy and thickness, electrolyte composition and strength, as well as the ratio between the quantity of materials constituting the positive and negative electrodes. Besides that, charge and discharge conditions such as rate and depth also have a large impact on lead-acid battery lifetime [10].

There are a few standard charging methods that have been used over the past several decades, regardless of the significant development in technologies from flooded to VRLA batteries [11–13]. Among them the constant-current (CC), constant-voltage (CV) and constant-current constant-voltage (CCCV) charge methods

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are considered as the standard charge methods, where the CCCV method is the most commonly used among them [4,14].

A fast charging can be achieved by using high charge rates and/or high voltage threshold limits [15,8]. However, in most cases, a fast charging has negative influence on aging factors (water loss, grid corrosion and sulfation of the negative electrode) [4]. Furthermore, when fast charging of VRLA batteries is not adequately controlled, significant damage may occur, ultimately resulting in a reduced battery life. Recharge control strategies which minimize the battery life degradation can be achieved by putting constraints on the battery states such as charge current, the battery voltage, the state-of-charge and the battery temperature which are typically provided by the battery manufacturer [3,16–18]. However, such constraints are rather conservative as they are provided for the complete lifetime of the battery and are typically assumed within the CCCV charging method [19].

In the past 10 years the community recognized the need for advanced control algorithms for battery charging and the battery protection in applications where the battery is used as an energy storage, such as model predictive control (MPC), due to its ability of satisfying battery constraints. At every sampling instant, a finite-horizon optimal control problem is being solved. The current state of the system and a plant model is being used to find an optimal control sequence which results in an optimal behavior of the system which satisfies constraints on control input and states over the finite-horizon. The first control signal in the optimal control sequence is applied to the plant and the whole procedure is repeated in a receding horizon manner [20,21]. In that way, new developments in the battery modeling and a new knowledge about the influence of the particular battery constraints on the battery lifetime can be exploited in a control design phase in a systematic way.

MPC has been employed in various applications with a battery used as an energy storage. In such applications the battery constraints have been incorporated in the design phase to prolong the battery lifetime. In [22] MPC has been used for demand planning in microgrids while satisfying all the battery constraints. Authors in [23] have used predictive charge control strategy for stationary photovoltaic system with battery storage to reduce the photovoltaic injection into the grid without enlarging the battery size and prolonging the battery lifetime by minimizing the dwell time at high state-of-charge. In [24] authors proposed a combination of the optimal generation scheduling algorithm and MPC which achieved an efficient protection of the VRLA battery bank from deep discharging and overcharging in a microgrid. Also, the papers [6,25] have presented MPC algorithm used for optimization of different microgrids with flooded and lithium-ion batteries, respectively, while keeping all the battery states under defined constraints.

MPC has also been used for charging of batteries which are connected directly to the charger. To predict the future battery behavior, authors in [26,27] have used an equivalent circuit model. Authors in [28] used a step-response model as an approximation of the electrochemical model of the battery, while authors in [19] used the full electrochemical model. Using the electrochemical model can result in a better performance compared to using an equivalent circuit model. However, an equivalent circuit model enables for using the standard quadratic MPC framework. In [26] an additional temperature model of the battery is used together with an equivalent circuit model which results in a non-linear MPC problem that is solved using a genetic algorithm. Authors in [29] use MPC to prolong the battery lifetime by using a two-dimensional degradation map which describes battery degradation processes as a function of state-of-charge and charging current. The developed battery model is linearized in order to use the quadratic MPC framework. All the aforementioned papers which are considering a battery connected directly to the charger, apart from [26], provided only simulation results.

From the practical implementation standpoint of the MPC, it is crucial to ensure that the associated optimization problem can be efficiently solved and that a solution exists at every time instant. The latter requirement is usually referred to as the recursive feasibility of an MPC problem. Without recursive feasibility guarantees, MPC algorithm can work perfectly for a while and then suddenly stop because a feasible solution does not exist [20,21,30]. This problem is recognized in the case of MPC based battery charging [28], where the constraints are implemented in the form of soft constraints in order to prevent a loss of feasibility. However, by introducing soft constraints, the constraint violation is allowed even for the nominal model. Even if the optimization problem is recursively feasible, MPC does not guarantee stability due to its finite-horizon. The stability has to be ensured in a design phase by using stabilizing constraints or a properly designed cost function [20,21]. The aforementioned papers considering MPC based battery charging are missing stability and/or recursive feasibility guarantees. In addition, the papers that are solving a non-linear MPC problem are missing guarantees that their solution is globally optimal.

To bridge this gap, in this paper we propose a non-linear MPC strategy for charging of VRLA batteries which guarantees adherence to all the constraints that are relevant for safe operation of a battery: the upper threshold voltage level, the maximum battery temperature increase - compared to the ambient temperature, the maximum charge current and the maximum state-of-charge. Furthermore, guarantees on the recursive feasibility and stability are enforced for the nominal model of the battery.

Unlike the existing MPC based charging strategies such as [19,27–29] the proposed method concentrates on charging of VRLA batteries instead of lithium-ion batteries and provides recursive feasibility and stability guarantees. However, the proposed method is not limited solely to charging of VRLA batteries, instead it can be applied for any type of battery represented by an equivalent circuit model. The proposed method is similar to [26,27] in the sense that it uses an equivalent circuit model of the battery. In addition, similar to [26] a temperature model of the battery is included which results in a non-linear MPC problem. However, we adopted a temperature model, presented in [31]. Unlike [19,26,28,29], which also solve a non-linear MPC problem, we prove that our formulation of the non-linear MPC problem is convex and thus we guarantee attaining the global optimum. Furthermore, we formulate the non-linear MPC problem as a convex quadratically constrained quadratic program (QCQP) which can be efficiently solved by the existing solvers.

Since some of the model states are not directly measurable, one may use a full-state observer to alleviate that problem. In this paper we rather resort to converting the model to a non-minimal state space form which uses the plant input and outputs as state variables.

The proposed algorithm is validated on a VRLA battery stack both through simulation tests and experimentally. Due to a different behavior of the individual batteries in the battery stack, additional constraints are added to the MPC problem in order to keep the voltage of every battery below the upper threshold voltage level provided by the manufacturer. This additional constraint will cause the MPC algorithm to decrease the charge current if it is expected that the battery voltage of a single battery will increase above the upper threshold voltage level, which causes a slower charging compared to a standard MPC method, but also prolongs the battery life.

This paper is organized as follows: Section 2 presents the models of a VRLA battery together with the experimental setup. The proposed MPC algorithm is presented in Section 3, while Section 4