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A model predictive control based peak shaving application of battery for a household with photovoltaic system in a rural distribution grid

Deepranjan Dongol *, Thomas Feldmann, Michael Schmidt, Elmar Bollin

Institute of Energy Systems Technology (INES), Offenburg University of Applied Sciences, Offenburg, Baden-Württemberg, Germany

HIGHLIGHTS

- Use of MPC for a single electricity price scenario.
- Peak shaving in the PV feed-in and the load demand.
- Maximum utilization of the self-produced electricity.
- Mixed Integer Quadratic Programming formulation of the optimal control problem.
- MPC implementation scheme in the laboratory.
- Preliminary experiments using the MPC.

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ABSTRACT

In rural low voltage grid networks, the use of battery in the households with a grid connected Photovoltaic (PV) system is a popular solution to shave the peak PV feed-in to the grid. For a single electricity price scenario, the existing forecast based control approaches together with a decision based control layer uses weather and load forecast data for the on–off schedule of the battery operation. These approaches do bring cost benefit from the battery usage. In this paper, the focus is to develop a Model Predictive Control (MPC) to maximize the use of the battery and shave the peaks in the PV feed-in and the load demand. The solution of the MPC allows to keep the PV feed-in and the grid consumption profile as low and as smooth as possible. The paper presents the mathematical formulation of the optimal control problem along with the cost benefit analysis . The MPC implementation scheme in the laboratory and experiment results have also been presented. The results show that the MPC is able to track the deviation in the weather forecast and operate the battery by solving the optimal control problem to handle this deviation.

1. Introduction

A Photovoltaic (PV) system installed in a household allows the use of renewable energy at a local level. A distribution grid with a distributed number of such households can be considered to be an equivalent large PV plant with an aggregated load demand. Households with PV installations are typically under 10 kWp and comprise about 15% of the total installed PV power in Germany [1]. This poses a challenge to the distribution grid due to the mismatch in the power generation and the load demand. As distribution grids are resistive, the reverse power flows from the households to the grid leads to an increase in the voltage at the end of the distribution line. This situation can damage any installed electrical equipment in the grid such as the distribution transformer that have a specified nominal rating to deliver the power from the distribution grid to the households. According to the VDE-AR-N 4105 grid standard in Germany, for the defined nominal voltage of V_n, the permissible voltage rise at the coupling point of the end of the distribution line , V_{cp}, should follow the restriction $V_{cp} \leq 1.03 \cdot V_n$ [2]. The regulation in Germany suggests the feed-in from the households with PV installations to be restricted to 70% of the installed peak PV power capacity [3]. Control strategies such as active power curtailment [4,5] and reactive power control [6,7] are available to meet this feed-in limit. However, this leads to a loss of useful energy. As such, a storage unit such as a battery is used to store the surplus PV energy and use it to meet the load demand.

Conventional operation of the PV battery, without the predictive control strategy, often leads to the battery being quickly charged and is unable to store any surplus PV energy during the peak power generation. As the battery technology is expensive, increasing the size of the battery is not a cost effective solution. Likewise, the battery is discharged as soon as there is a load demand and is unavailable to shave the peak load demand during

* Corresponding author.
E-mail address: deepranjan.dongol@hs-offenburg.de (D. Dongol).

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the morning hours of the next day. The peak shaving strategy presented in [8] for a decentralized battery system in a residential network triggers the battery charging signal for each unit when the PV feed-in is higher than the threshold feed-in power defined. The threshold feed-in power limit is calculated from the sensitivity analysis of the voltage with respect to PV feed-in in the distribution grid. The authors in [9] have also presented the use of a battery to store PV energy when the PV feed-in limit is exceeded. The battery has been used as a buffer.

Battery storage also offers the opportunity to participate in Demand Side Management (DSM) to reduce the peak load demand in the grid. In order to achieve the goals of DSM, the electricity price is varied with the load demand which allows the scheduled operation of the battery at the prosumer side and reduces the mismatch between the power generation and the load demand. However, this would require the participation of the energy market and the involvement of grid operators which is often not feasible and practical for the rural distribution grids.

In this work, the challenge is to design a MPC for an individual household with a PV battery system connected to a rural distribution grid in a single electricity price scenario. The goals of the MPC are to shave the peaks in the PV energy and the peak load demand and maximize the use of the battery. The MPC would allow each individual household prosumer to conduct its own DSM autonomously and help postpone the need for varying the electricity price. This localized approach would be economically beneficial to the household by maximizing the use of self-produced electricity. At the same time, shaving peaks in the PV feed-in and the load demand would benefit the distribution grid by relieving it from the voltage stress.

1.1. Literature study

Several research works have been carried out to develop control strategies for a scheduled operation of the battery. The literature study was carried out to understand the existing research works on the predictive control strategies and cover the aspects of control approaches and the optimization problem formulations used by the researchers for this type of system.

In [10], the authors have presented a forecast based control strategy for the peak shaving application of battery in a PV battery system. In this approach, the battery SOC is provided as a set point for the charging or the discharging operation of the battery. The SOC set point is obtained by comparing the predicted PV power and the load demand with the available SOC in the battery over the defined time horizon and tuning it based on the current SOC of the battery. The battery is charged or discharged based on this battery SOC set point. A very similar forecast based control strategy has been used to dynamically set the PV feed-in limit using the battery [11]. In both [10,11], the forecast based control strategies do not include an optimization problem but rather provide battery SOC set points to the local real time controller by using a decision based control (if then else) to operate the battery based on the forecast data.

The peak shaving strategy using the battery presented in [12] uses a model based predictive control approach. The economic operation of the battery is obtained by solving an optimization problem based on the varying price of electricity. The control strategy has two layers. The supervisory layer is the model based predictive control layer that provides the optimal values for the operation of the battery by solving the optimization problem at every 15 min time interval satisfying the operation constraints. The second layer is the decision based control layer (Fast Feedback Control Loop (FFCL) as mentioned by the authors) which handles any deviation between the measurement and the prediction during this interval in real time. The battery operation for peak shaving in [4] uses similar approach as in [12], with an optimization layer and a decision based correction function defined in the real time controller which corrects the measurement-prediction deviation. In both [4] and [12], the battery is used as a buffer to store excess or to provide the lacking energy. In [12] the author has mentioned that using the battery as a buffer is a compromise with the optimal operation of the battery in order to deal with the model mismatch.

Researchers have used the principle of Model predictive Control (MPC) at the supervisory layer for the optimal operation of battery in renewable energy systems as in [13–16]. In these research works, the MPC has been used for the purpose of energy management strategy to offer an economic operation of the system components in a varying electricity price scenario. The economic operation of the system leads to a Linear Programming (LP) problem. The logical condition arising in the problem formulation such as the need to switch on–off of the system components or to avoid the concurrent charging and discharging of the storage unit, introduces binary variables that changes the LP problem to a Mixed Integer Linear programming (MILP) problem. Other objectives for the use of MILP based MPC problems might include a power commitment reference trajectory , such as in [17], for a PV power plant with battery storage where the battery operation is optimized to meet the required load demand. Some researchers have also used a quadratic degradation function of the storage components in the objective function for a hybrid storage system based micro grid with a battery and a hydrogen storage as in [18]. This degradation cost allows the optimization to decide on the optimal use of the hybrid storage components. This leads to a MPC based on a Mixed Integer Quadratic Programming (MIQP) problem. However, solving a MILP or a MIQP problems is not a big challenge as the constraints are linear which guarantees the convexity of the problem and can be efficiently solved using commercially available solvers such as IBM-CPLEX [19].

In the literatures discussed so far, a linear discrete model of the battery has been used to estimate the SOC of the battery in the optimal control problem formulation. But a battery is a nonlinear system. When a nonlinear model of the battery is used to represent the battery ageing or the relation between the SOC and the battery terminal voltage, nonlinear constraints appear in the optimal control problem. The problem becomes Mixed Integer Non-Linear Programming (MINLP) which is stochastic as the variables in the models are interdependent. The only way to solve this problem is using the Dynamic Programming (DP) method as presented in [20–22]. DP is a stochastic approach to solving an optimization problem and requires very detailed information on the battery parameters which is often only possible through rigorous battery experiment. Also, the complexity to solve the problem does not make it suitable for real-time applications, although it could be used in a supervisory layer.

1.2. Scope of the work

In this work, the MPC has been designed and implemented only as the supervisory layer. The correction function or the decision based control during the time interval , as implemented in [4,12], has not used in the experiment as its application is trivial. In our work, the goal of the experiment is to capture the ability of the MPC as a supervisor layer to deal with the forecast uncertainties without compromising the optimal operation of the battery. The focus of this work is more towards the MPC problem formulation.

The MPC has been designed for a single electricity price scenario , with the feed-in tariff of 0.13 €/kWh and the grid electricity price of 0.31 €/kWh, in accordance with the regulation in Germany [10]. The cost of using the battery has been considered to be cheaper than using the grid electricity. The difference between the MPC designed in this work and other forecast based control strategies and the optimization problems for a grid connected PV battery system are as follows: