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A new combined control algorithm for PV-CHP hybrid systems

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HIGHLIGHTS

- A new combined control algorithm for PV-CHP hybrid systems is proposed.
- The control combines a model predictive control and a rule-based control.
- The combined control is able to correct setpoints for incorrect PV and load forecast.
- The computational load is reduced with only a small increase of operational cost.
- The control can be adapted as energy management system for microgrids.

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ABSTRACT

Due to the 2012 change in the renewable energy act the feed-in tariffs, and therefore the number of newly installed photovoltaic systems decreased dramatically in Germany. Particularly in the residential sector as the biggest market new business ideas for photovoltaic systems were developed. Hence a photovoltaic and combined heat-and-power system, which provides not only electricity but also heat. This complex system requires flexible control strategies. A new combined control algorithm is proposed that in contrast to the standard strategies can operate even under incorrect weather and load forecasts without creating discomfort. Furthermore is it applicable for cloud-based solutions. In this paper a high-level model predictive control based on a mixed integer linear programming problem is combined with an additional low-level, rule-based controller. The low-level control compares the set-points of the optimization with the actual values and corrects the set-points according to each system component until the next optimization takes place. The results show that a hybrid system can be successfully controlled by a combined control approach. In case of a cloud-based application the need for an optimization can be reduced by a factor of four without diminishing comfort or facing much higher operational costs. It has also been shown that the combined control algorithm can be used as an energy management of microgrids.

1. Introduction

According to the German Environment Agency in 2015 more than 1.5 Million installed Photovoltaic (PV)-systems were able to cover 7.5% of the net electricity consumption in Germany. On sunny summer days, in particular at weekends, more than 50% of the net electricity consumption is provided. Many of these systems are installed in residential areas in single and multi-family homes, which are responsible for about 25% of the electrical energy consumption in Germany. Since the feed-in tariffs for PV-energy have decreased, the demand for new business cases for PV-systems has risen. As energy costs rise yearly and feed-in is less attractive, self-consumption and PV-battery systems have become more appealing to consumers living in single- and multi-family homes e.g. [1–4]. If thermal demand is taken into account, a higher level of self-sufficiency can be achieved. According to the Federal Environment Agency in Germany more than 80% of the energy consumed in German households is thermal energy required for space heating and warm water, while 40% of the thermal energy is produced by gas heating devices. Retrofit solutions are under study to increase the energy performance in residential buildings using combined heat and power plants (CHP) and heat pumps [5]. However a combination of a PV-battery system with a gas powered CHP could be

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Nomenclature, acronyms and abbreviations

PV	photovoltaic
CHP	combined heat and power plant (gas driven combustion engine)
batt	battery
TES	thermal energy storage
grid	electrical grid
dhw	drinking hot water
sh	space heating
exp	export
imp	import
MPC	model predictive control
MILP	mixed integer linear programming
sd	self-discharge
sc	self-consumption
dis	discharging
char	charging
el	electrical
th	thermal
prod	production/produced
OPEX	operational costs
KPI	key performance indicators
EMS	energy management system

the step towards a higher level of efficiency, lower energy costs and new business cases.

The combination of PV and CHP plants in a system including thermal and electrical loads and storages (in the following also called PV-CHP hybrid system) has mainly two different applications. In one application the CHP plants are combined together with PV systems and other renewable energy sources to cover the loads in microgrids. A second application is the use in buildings. This application is in the focus of this paper using a single family home in Germany as case study.

In both applications the combination of PV and CHP plant poses great challenges to control strategies. The concept of microgrids dates back at least to 1998 [6] resulting in almost 20 years of research in planning and controlling hybrid systems in microgrid application. Since the control concepts are often feasible for both applications methods and experiences from microgrids are used as a starting point for the new control strategy for buildings.

Control strategies can also be part of planning processes, which take different aspects into account. These include factors such as finding the optimal location for installation, or optimizing the system designs and component sizes while deriving operational schedules. An overview [7] and recent studies on planing tools [8], new optimizing algorithms [9–11], component and battery sizing [12,13], and even so called multi-microgrids including heat grids [14] show the importance of microgrids also in context of PV and CHP hybrid systems. The focus of this paper is developing a control algorithm uncertainties taking uncertainties into account. Planing and sizing are not considered in this paper and have been dealt with elsewhere.

Hybrid systems in microgrids can have several control objectives e.g. voltage and frequency control, reactive power management, or an overall energy management strategy [15,16]. In buildings the main objective is energy management. Optimization strategies can help to find an operating strategy so that the PV-CHP hybrid system performs economically while meeting costumer demands for electricity and heat. Optimization methods in microgrids with hybrid energy systems are summarized in [17] with a focus on metaheuristic optimization methods. The uncertainties of load and generation in buildings and microgrids can be better addressed by a model predictive control (MPC). MPC is an optimization control strategy where an optimization problem is formulated and solved at discrete time steps. The control problem is solved over a certain pre-defined horizon using the current state of the system as initial input. But only the control action for the next time step is implemented to the system components. The process is then repeated for the next time step. The model predictive control method has been used in research on PV- and wind systems in numerous publications lately [18]. If only the first step of an MPC is done and time-schedules are calculated the process is known as receding horizon optimization. This method has been used for hybrid systems [19,20], revealing that the length of the prediction horizon can influence the result significantly. A longer prediction horizon leads to higher computational times while a shorter horizon length can lead to uncertainties in the results. In [21] a multi-objective optimization method for a CHP microgrid has been developed. The objectives of minimum costs and minimum emission have been combined. But the effect of uncertainties has not been studied.

For a PV-CHP hybrid system in a building Houwing et al. have shown in [22] the economic advantages of using a model predictive control algorithm. The authors calculated operational costs for an optimized control and compared them with a conventional, rule-based control for the winter period. They found that there is a substantial benefit even when there are no feed-in tariffs available. In [23] it has been showed by analysing five locations in Spain that the primary energy consumption can be reduced when using a hybrid system. However, when it comes to life cycle costs they found that a conventional system (electrical grid plus natural gas boiler) is still superior. Another life cycle analysis was done in [24]. Compared to a conventional electricity supply from the grid and heat from a natural gas boiler, an overall significant improvement of all environmental impacts compared to the conventional energy supply, ranging from 35% for depletion of fossil fuels to 100% for terrestrial ecotoxicity has been found. In [25] Brandoni et al. determined the sizing of the components of a hybrid system. They discovered that, in contrast to solar technologies, the size of micro-CHP units is heavily influenced by several factors and parameters, such as the investment costs, energy loads and tariffs. Outcomes suggest that a hybrid system can reduce the primary energy consumption of households more than single PV technologies, but its size must be properly determined for given costs and conditions. Balcombe et al. derived in [26] PV-CHP hybrid systems in 30 different household types factors such as self-sufficiency-proportion, grid demand profiles and economic costs for the consumers. They found that such systems are on the one hand increasing the self-sufficiency-proportion and improve the grid demand profiles in terms of ramp-ups, on the other hand, however, the system is only beneficial for high energy demand (>4300 kWh/yr).

The MPC method has also been used for combined cooling heat and power (CCHP) systems showing that the use of such a system can increase energy efficiency and decrease operational costs. A so-called hybrid MPC method has been used in [27] and defined in references therein. According to the authors a hybrid MPC method is needed when system variables are discrete (micro CHPs can only be turned on and off). The authors used the method to maximize the self-sufficiency for small-size buildings using PV and thermal solar panels. The MPC used in the following would also fall in the hybrid MPC category, but again the word *hybrid* has a completely

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