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Control algorithm for a residential photovoltaic system with storage

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HIGHLIGHTS

- A control strategy for a battery system coupled with a PV system is presented.
- With a feed-in limit this strategy does not need a PV production forecast.
- This strategy performs as well as a strategy relying on an exact forecast.
- A relatively small storage size allows peak injection reduction of 50%.

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ABSTRACT

High penetration of photovoltaic (PV) electricity could affect the stability of the low-voltage grid due to over-voltage and transformer overloading at times of peak production. Residential battery storage can smooth out those peaks and hence contribute to grid stability. A feed-in limit allows for the easy setting of a maximum power injection cap and motivates PV owners to increase their self-consumption. A simple control strategy for a residential battery system coupled with a PV system that maximizes self-consumption and minimizes curtailment losses due to a feed-in limit is presented. The algorithm used in this strategy does not require a forecast of insulation conditions. The performance of this algorithm is compared to a second algorithm—a control strategy based on linear optimization using a forecast. Assuming an exact forecast, this second algorithm is very close to the maximum self-consumption and minimum curtailment losses achievable and can be used to benchmark the simple strategy. The results show that the simple strategy performs as well as the second algorithm with exact forecasts and performs significantly better than the second algorithm using real forecasts. Moreover, it is shown that this result is valid for a large range of storage capacities and PV sizes. Furthermore, it is shown that with a time resolution of 15 min for the input data (the resolution of most PV production and load data) self-consumption is overestimated by about 3% and curtailment losses are underestimated by the same amount. Load sensitivity simulations show that different load curve shapes do not fundamentally change the results. Finally, to assess the effect of load aggregation, the case where the strategy is applied separately to 44 households with storage is compared to the case where it is applied to a centralized storage system of the same size as the total storage of the 44 households. The reduction of the curtailment losses with the number of aggregated houses is showed.

1. Introduction

Residential electric energy storage systems coupled with a photovoltaic (PV) installation could contribute to the stability of the low-voltage grid in the case of high PV penetration by absorbing the production power peaks around midday [1–5]. Moreover, such a system increases PV self-consumption, which can provide an economic benefit to the system owner due to lower electricity exchange with the grid and minimized electricity transport losses [6–8]. Economic assessment of such systems optimizing only self-consumption can be found in [9–11]. In Germany, financial incentives for battery storage are available provided that the feed-in power is limited to 50% of the PV system's nominal power [12]. By 2015, more than 12'000 such systems were installed in Germany [13]. As shown by [14], active power curtailment allows for stabilizing the grid voltage. Imposing a feed-in limit is a simple and efficient method to avoid high injection peaks and to hence minimize grid disturbances allowing for higher PV penetration

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Nomenclature

B^+	battery charging energy at time t
B^-	battery discharging energy at time t
B_{loss}	battery losses
B_{cap}	battery capacity
F^+	feed-in tariff
F^-	retail electricity price
FiL	feed-in limit
gf	power exchanged with the grid
L_t	load at time t
L_{tot}	total load energy
MEP	maximum excess PV energy
PV_t	PV production at time t
PV_{cs}	simulated clear sky PV production
PV_{tot}	total PV production
SOC	state of charge of the storage
t	time step
max. sc.	maximization of self-consumption
min. curt. loss.	minimization of curtailment losses
co. opt. w/o forecast	cost minimization without forecast
co. opt. re. forecast	cost minimization with exact forecast using linear optimization
co. opt. re. forecast	cost minimization with real forecast using linear optimization
curt. loss.	curtailment losses
SC	self-consumption
C	cashflow
PV	photovoltaic

[15,16]. However, this limit induces curtailment losses even in the presence of energy storage systems. Therefore, control strategies that minimize those losses and maximize self-consumption are needed. Alternative strategies than a fixed feed-in limit prevent injection peaks are described in [17,18,14].

Several control strategies that allow for the efficient shaving of injection peaks and the maximization of self-consumption at the same time have been proposed in the literature. Solutions based on exact (or perfect) forecasts are presented in [19,20]. However, forecast inaccuracies induce non-negligible changes in the performance of the systems [21–23]. To circumvent those issues, strategies that do not need forecasts were developed. Zeh et al. [22] proposed a feed-in damping strategy, in which the battery is charged using a nearly constant power defined by the battery capacity divided by the time until sunset. This approach gives better results than a feed-in chopping strategy which starts to charge only when a daily maximum feed-in power calculated with a forecast is reached. Moshövel et al. [23] used a persistence forecast strategy based on the optimal state of charge of the previous day. This approach resulted in a self-consumption value 4.4% lower compared to the one with a perfect forecast.

In this paper, in contrast to our previous work [24,19,20], a new control strategy that does not need forecast data and is valid only in the presence of a feed-in limit is developed. The novelty of the solution presented here compared to, e.g. [22,23] is that clear sky production data is used, which can be easily simulated. This data allows for a more precise control strategy allowing for self-consumption close to its maximum value and a reduction of the curtailment losses.

The system under consideration and the corresponding simulation program that was developed is described. In addition to the control algorithm that does not need forecast data, a control strategy that maximizes financial cash flow due to electricity exchange with the grid is introduced and discussed. This second algorithm requires production and consumption forecasts. It is used to benchmark the first algorithm. Both strategies are evaluated in the frame of a feed-in limit and for the second algorithm using a real or an exact (perfect) forecast as a function of the battery capacity, the PV sizing and the value of the feed-in limit.

Most load profiles and PV production data are available with a resolution of 15 min. The time resolution of the input data affects the simulation results such as self-consumption share and the assessment of the effects on the grid [25,26]. Therefore, the effect of the input data resolution (5 s to 30 min) on the self-consumption and loss due to the feed-in limit using the algorithm that does not need forecast data is evaluated. The effect of this time resolution and of its optimal choice is discussed.

To assess the sensitivity of the results as a function of the load curve shape, the same algorithm is applied to 44 different real loads of households recorded in a small Swiss town. Finally, using those 44 loads, we quantify the gain in peak shaving and self-consumption by aggregating loads.

2. Methods

2.1. System configuration

There are two main system configurations for a PV system coupled with a battery: the DC-link configuration, in which the battery is connected before the DC/AC converter, and the AC-link configuration, in which the battery is connected through a bidirectional AC/DC inverter directly to the AC home grid [27,6] (see Fig. 1). The choice of configuration does not significantly change self-consumption simulation results, and the DC-link configuration is used here. Like in the study by Magnor et al. [28], an energy-flow model is applied in this work. Note also that, within this study, power flow from the grid to the battery is not allowed.

The efficiency values as a function of input power of the DC-DC converter and the DC-AC inverter are calculated according to typical curves of commercially available systems [29]. If not stated differently, the converter and inverter nominal power is equal to the DC nominal power of the PV installation. The temperature and voltage dependence of the inverter efficiency are neglected; its efficiency depends only on the input power. A simple battery model with a fixed round-trip efficiency of 90% is used, which is representative of standard Li-ion batteries. The choice of a Li-ion battery is motivated by the potentially lower cycle cost in the long term due to a higher cycle number and lifetime [30].

The battery storage capacity is defined as the effective capacity. For example, a battery with 10 kW h storage capacity and a minimal recommended state of charge of 20% has an effective capacity of 8 kW h.

2.2. Description of the control algorithms

In this work, two control algorithms that optimize financial balance (*cost minimization*) with regard to electricity exchange with the grid (buying or selling electricity, cash flow) are studied. In the presence of a feed-in limit, this objective is equivalent to first minimizing the losses due to feed-in power curtailment and then enhancing self-consumption (as long as the feed-in tariff $\geqslant 0$ and $<$ electricity price). The two control algorithms are: