GRID-RELIEVING EFFECTS OF PV BATTERY ENERGY STORAGE SYSTEMS WITH OPTIMIZED OPERATION STRATEGIES

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GRID-RELIEVING EFFECTS OF PV BATTERY ENERGY STORAGE SYSTEMS WITH OPTIMIZED OPERATION STRATEGIES

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ABSTRACT: The German distribution grids are facing a rising number of installations of private photovoltaic (PV) systems. Simultaneously, the number of installations of PV panels in combination with battery energy storage systems (PV BESS) is increasing. With appropriate operation strategies that consider grid limitations PV BESS have the potential to provide grid relief and thus reduce overall system cost. The effect of solar power generation units on the low voltage grid depends on the amount of installed generators, but also on the operation strategy of connected storage systems. The implemented operation strategy of the BESS determines the extent to which grid-relief can be achieved with storage systems.

A model of a distribution network based on field data is combined with the model of a PV BESS. The combined tool is used for power flow analysis. With this model of the whole distribution system, different penetration rates for PV systems as well as for PV BESS are simulated and the resulting influence on the grid is examined. Results show that a grid-oriented operation strategy can gain significant relief of the low voltage grid and therefore reduce otherwise necessary grid reinforcements in the near future. At the same time, these operation strategies do not lead to a significant decrease of the overall energy throughput of the PV BESS over the total lifetime of the system. This means the economics of such a system are only slightly influenced by the application of a grid-relieving strategy.

Keywords: Battery Storage and Control, Grid Integration, Grid Stability, Storage, Strategy

1 INTRODUCTION

The German power grid is facing a continuously rising number of photovoltaic power plants and therefore a growing share of fluctuating electricity production. This trend is expected to continue, due to goals set for the share of electricity from renewable energy sources by the federal government and falling prices of PV systems. The predominant share of the installed capacity of photovoltaic power systems is connected to the medium voltage distribution grid or the low voltage grid [1]. The fluctuating feed-in of the PV power plants leads to a reassessment of the capabilities of the grid and possibly to grid reinforcements

On the other hand, the number of battery energy storage systems (BESS) steadily increases, with 35,000 installed PV BESS in Germany by January 2016 [2]. The operation of these storage systems can heavily influence the effect that fluctuating PV power feed-in has on the low voltage grid. Numerous papers investigated the additional benefit of using more sophisticated operation strategies than the simple self-consumption maximization strategy which charges the battery as soon as negative residual load occurs, i.e. the production of the PV system surpasses the electrical consumption of the household. These strategies aim to reduce the maximum PV power feed-in to gain grid relief.

Moshövel et al. analyze the possible grid relief from reduced PV power feed-in by the use of different operation strategies for PV BESS [3]. They figure out that the implementation of forecast-based operation strategies offers increased grid relief over strategies to maximize self-consumption. To reduce PV power feed-in without a notable decrease of solar generated energy, they deploy two different forecast strategies, perfect forecast and persistence forecast.

Weniger et al. investigate forecast-based operation strategies as well. They introduce different strategies and compare their benefit [4].

Angenendt et al. show that forecast-based operation strategies, which limit the maximum state of charge of the PV BESS can enhance the battery lifetime and therefore decrease the levelized cost of electricity [5].

This paper investigates the influence of PV systems on the low voltage grid and how the installation of BESS with respective operation strategies changes how the grid is affected. The influence is determined by means of simulations, using a model of an existing urban low voltage grid with the simulated operation of a DC-coupled PV BESS based on [6].

The decentralized feed-in from photovoltaics can result in power flows from the low voltage grid to the superimposed transmission network in times of high solar production. For now, this does not drastically influence the low voltage grid, but this might change in the near future. With an ongoing trend of new installations for PV in the residential sector, the occurrence of situations in which the low voltage transformer will reach its capacity limit may increase. Especially low voltage grids with relatively long power cables and a high number of connected PV systems might reach the line’s capacity limits in terms of power transfer capability and thermal stress.

The level of energy autarky that can be achieved by increasing the self-consumption of electricity from PV may interfere with a grid-relieving operation of the BESS. The trade-off between a maximization of self-consumption of solar energy and minimization of stress on the low voltage grid results from the non-concurrency of solar power generation and power consumption within a household. The ideal dimensioning of the rated PV power, the electrical storage capacity of the BESS, its rated power, and the power consumption of the household has been part of extensive research [7]. The next step is to ensure a grid-relieving effect of the BESS while simultaneously achieving a high rate of self-consumption by means of an operation strategy of the BESS that incorporates both aspects at the same time.

2 OPERATION STRATEGIES OF BATTERY STORAGE SYSTEMS AND GRID INFLUENCE

In recent studies two different kinds of operation strategies have been discussed. Operation strategies to reduce the PV feed-in power to gain grid relief [3], [4] and operation strategies which are used to enhance the battery lifetime in order to enhance the economics of PV BESS [5]. These strategies use forecast-based operation strategies to reduce the average SOC. A higher average SOC leads to higher calendric ageing as described in various publications, e.g. [8]. Therefore, an operating strategy is introduced which stores only the energy demand of the following night in order to reduce the average SOC, resulting in an enhanced battery lifetime and only a moderate reduction of the self-consumption rate. The resulting SOC curve is shown in the following graph.

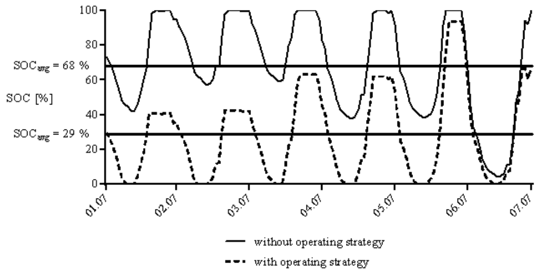

Figure 1: The state of charge of a PV BESS with and without lifetime enhancing operating strategy [5].

A combination of both types of strategy, enhancing battery lifetime while at the same time gaining grid relief, has been discussed in [9].

The presented approach uses the forecast-based lifetime enhancing operation strategy and extends it to take into account relevant network parameters of the low voltage grid. These parameters are the voltage level at the grid connection point, the grid frequency and the reactive power demand, i.e., the power factor cos(φ). The capability of the inverter system to act accordingly is defined in [10]. The principle is to store additional energy above the target SOC chosen by the forecast-based strategy to optimize the battery lifetime in order to support the grid and reduce the local voltage boost, if necessary. This strategy is called grid-oriented.

The relevant factors to determine grid influence of connected households are the voltage level at each grid connection point and the load on each electrical line of the network at any given time. We use the maximum value of the voltage variance ΔU and the maximum utilization of each line in relation to its power transmission capacity over a year as measures, as well as the number of times these two parameters exceed their limit. For the voltage, this means a violation of the $\Delta U \leq 3$ % limit and for the power line utilization the limit is set to 75 % of a line's transmission capacity.

The voltage increase at the end of a line with a high number of connected PV systems can quickly surpass the allowed voltage level of $\Delta U \leq 3$ %, thus resulting in a violation of the ±10 % U (400/230 V) limit [10], [11]. The operation strategy of the BESS is used to avoid a violation of these limits. The effectiveness is determined by power flow analysis.

3 MODELLING AND APPROACH

The presented approach combines a detailed model for households optionally including a PV panel and additional battery storage systems with a model for the low voltage grid and a power flow analysis.

Since not all households in the simulated grid have a PV system or a PV BESS installed, we use a set of varying load profiles to model the cumulative power demand in the analyzed low voltage grid. These load profiles were derived by using profiles for 32 typical domestic appliances and stochastically combining these into a household profile, also taking into account seasonal variations of usage [12]. Figure 2 illustrates the principal set-up of the different model components.

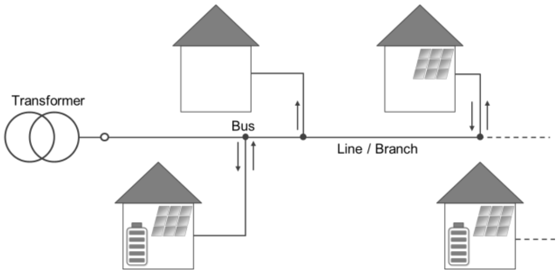

Figure 2: Model components overview – PV BESS and grid model.

The model for a household with a PV BESS is based on [6]. The system layout is shown in Figure 3 and consists of the PV panel, two DC/DC converters, one AC/DC converter, the battery energy storage system, the electrical load of the household and the grid connection. The energy management system (EMS) and the battery management system (BMS) are modelled as separate units as well. Basic operation prevents the BESS from charging from the grid, but only from the PV panel.

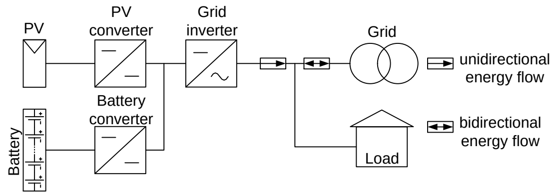

Figure 3: Model of the grid-connected, DC-coupled PV BESS [5], [6].

To determine the influence of PV battery storage systems on the low voltage grid, a quasi-stationary model has been developed to simulate the behavior of the PV BESS, combined with the repeatedly calculated power flow within the grid. The power flow calculation is based on [13] and has been adapted for an iterative simulation of the interlinked power system in combination with the PV BESS model.

The model simulates a large number of different PV battery storage systems which are connected to different busses within the power network and induce a drain of power or a power feed-in at each time step of the simulation. This is used to calculate the resulting power flow within the network topology and, thus, the voltage level at each node or bus in the system. For each time step, the solar production of all PV systems is simulated. This energy is added to the power consumption of each household for every time step, resulting in a residual load of the household. Depending on the existence of a storage unit, additional solar production can then be stored or fed into the grid. On the other hand, remaining positive residual load (thus a surplus of consumption over solar power generated) is either covered from energy stored in the battery system or taken from the grid. The decision, whether energy should be charged into the battery or discharged to cover the load within the household is made by the energy management system (EMS). The decision to charge or discharge the battery also depends on the distinct operation strategy, forecast data, and the actual state of the grid (e.g. frequency and voltage). The power flow calculation is conducted at an adjustable interval to update the voltage level at each node of the grid and to determine the load flow on each line.

The analyzed network is based on an existing urban low voltage grid in Germany. The modelled section has 124 nodes, 113 of which are households, 10 interconnections and the distribution substation. The grid has 128 power cable lines with a total length of 2.25 km. The layout of the grid is shown in Figure 5.

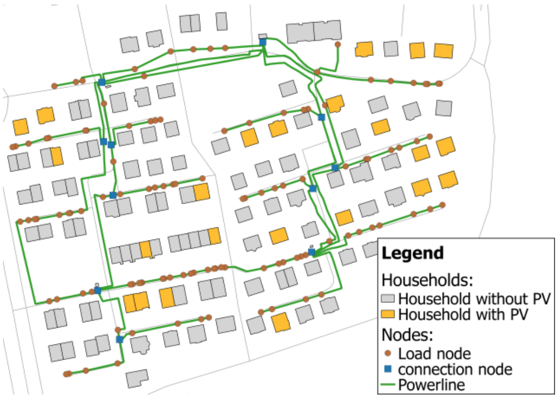

Figure 5: Layout of the modelled low voltage grid.

The results of the power flow analysis during simulation are fed into the EMS of the PV BESS model after each iteration step. The relevant parameters used to determine the grid-relieving operation are the actual voltage at the connection node of the BESS and the grid frequency. The EMS is able to adapt the charging strategy accordingly to reduce the power feed-in of the PV system and additionally, enable a feed-in of reactive power to decrease the voltage boost at line end [10].

4 RESULTS

Based on the aforementioned model different scenarios are analyzed. The results are evaluated based on the week with the highest PV feed-in. During this week the burden on the grid is expected to be the highest.

For the analysis, different scenarios are compared. First, a scenario without PV BESS is compared to scenarios with PV BESS. Different operation strategies for the PV BESS have been implemented. In the base scenario a strategy for maximization of self-consumption is used. This strategy is compared to grid-relieving strategies. The first grid-relieving operation strategy is the persistence forecast. This strategies aims to reduce the cut-off energy while at the same time reducing the PV feed-in peaks. Furthermore, this operation strategy aims to enhance the battery lifetime as well. The second grid-relieving strategy is the grid-oriented operation strategy which also takes into account grid parameters like the node voltage and transmission line utilization in order to reduce the influence of the PV systems on the grid. All three operation strategies are described in Chapter 2.

4.1 Effects of PV BESS operation strategies on the low voltage grid

A main indicator for the influence of PV systems on the low voltage grid is the effect of voltage boosts at the grid connection point caused by the power feed-in. If the voltage criterion is met, neither a voltage drop caused by the household load nor a voltage boost from feed-in results in a deviation from the standard grid voltage of more than three percent ($\Delta U \leq 3\,\%$) at a house's connection point. The analyzed grid has been designed to ensure this for the case of voltage fluctuations caused by electrical load. Through the impact of PV power feed-in on the other hand this limit can be well surpassed, if a certain amount of additional PV systems is installed. Figure 6 shows the voltage curve at the most critical node during a mid-summer day with a comparison for different installation rates of PV systems. In this scenario, we assume that there are no battery storage systems installed.

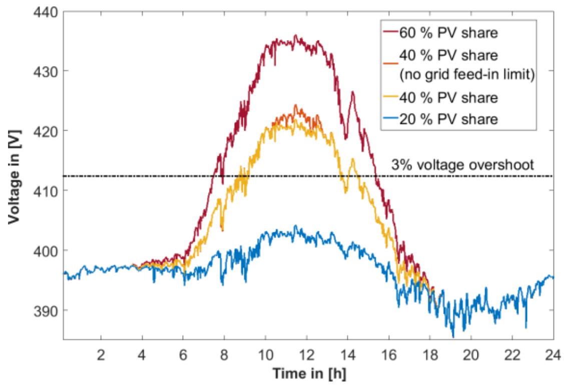

Figure 6: Comparison of node voltage for different share of installed PV systems.

In case of a 40 % share of installed PV systems the grid does already face a voltage increase above the allowed limit. A comparison of the orange and yellow curve shows that this is only slightly dampened by the 70 % limit for the maximum power feed-in by PV systems as it is part of the requirements for systems funded by the EEG. The difference between the voltage curve with and without this limit is almost negligible, as shown by the orange and yellow curves.

We evaluate the effectiveness of a BESS to act grid-relieving by its ability to reduce the voltage overshoot caused by PV feed-in and also by the reduction of stress put on the transmission lines in the grid. We use the 40 % PV share scenario, since it does already show situations in which the set limits are surpassed, but the assumed amount of installed PV systems is not unrealistic in the medium term. Figure 7 depicts the resulting voltage over the course of a day during summer for the same node of the grid as discussed before in Figure 6.

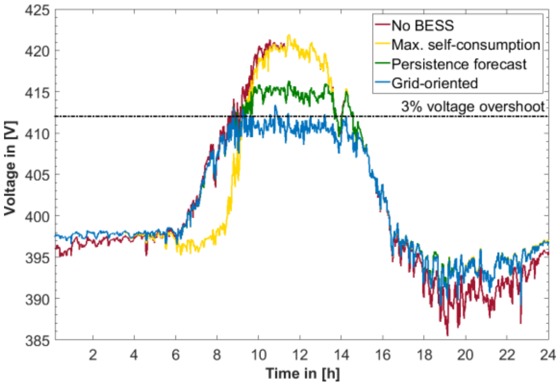

Figure 7: Comparison of node voltage for different PV BESS operation strategies.

It is clearly visible that the simple introduction of battery storage systems in the grid does not necessarily support the grid or help to reduce the occurrence of situations in which the grid is operated outside the allowed conditions. This is indicated by the overlapping yellow and red curves during midday. The battery systems which use a maximization of self-consumption charge as soon as additional power from the PV system is available and therefore become fully charged before the midday peak. Thus, they cannot help to reduce an overburden of the grid caused by massive feed-in from PV. If an operation strategy which uses a delayed charge is applied, like the forecast-based strategy to prolong battery lifetime, the battery is charged during noon, which reduces the power from PV fed into the grid. This strategy is illustrated by the green line in Figure 7. Still, in case of a significant share of households with photovoltaics, this does no longer suffice to ensure a grid operation within the set limits. This is caused by an accumulated voltage boost over the length of a transmission line. This may also cause unevenly distributed restrictions for households connected to the same line. The application of a voltage-based, grid-oriented strategy helps to avoid these instances and can ensure an operation within the allowed system bounds. This strategy, depicted by the blue curve, avoids a voltage overshoot at any node in the low voltage grid by storing additional power from the connected PV systems. Most of the time, the battery will have enough remaining capacity, since it has only been charged to the level necessary to provide for the demand of the following night. Only if the battery is already fully charged and the voltage boost still surpasses the three percent limit, the PV power will be cut off.

In addition to the voltage level at each node in the grid, the transmission limits of all power lines must be kept within the operating limits. Without any storage units providing grid relief, several lines of the simulated network surpass their allowed boundaries. This is shown in Figure 8. With the implementation of PV BESS with a grid-oriented operation strategy, all connected transmission lines are kept in the operating range. The same applies to the utilization of the technical assets of the distribution substation. If the transformer has been dimensioned to provide the maximum demand of all connected households, then a reasonable share of installed PV systems can lead to the transformer being overburdened during midday peaks. This means not only additional transmission capacities are needed to reinforce the grid, but the transformer has to be exchanged as well, which leads to additional costs without the use of BESS.

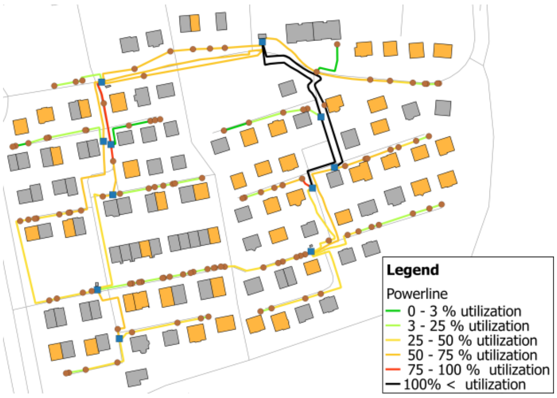

Figure 8: Transmission line utilization at 40 % PV share.

4.2 Influence of grid-reliving operation strategies on the economics of PV BESS

The evaluation of the economics of PV BESS using different operation strategies is done by the application of a detailed battery aging model based on [6].

As shown in the previous section the application of forecast-based operation strategies has a positive influence on the power grid. In this section the influence of the grid-supporting operation on the economy of a PV BESS is analyzed. The total energy throughput of a storage system is a good indicator for its profitability because this value shows how efficiently the BESS is used. The different operation strategies are evaluated using the 40 % PV share scenario.

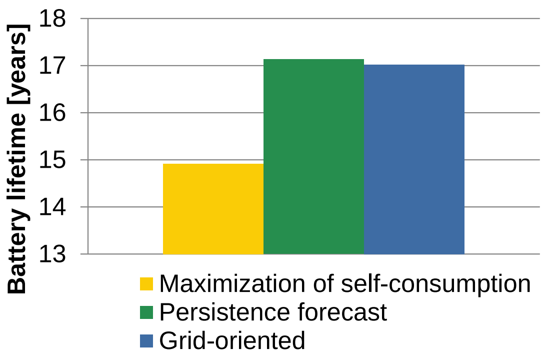

Figure 9: Average lifetime of the PV BESS.

As mentioned in Chapter 4, the persistence forecast operation strategy as well as the grid-oriented operation strategy use forecast-based algorithms to enhance the battery lifetime. The effect of these algorithms is depicted in Figure 9. The average lifetime of the installed PV BESS can be enhanced when the persistence forecast or the grid-oriented operation strategy are used in comparison to the simple maximization of self-consumption. The lifetime of the battery system using the persistence forecast operation strategy is slightly higher compared to the grid-oriented strategy because of the additional energy stored to relieve the grid. This leads to an increased average SOC at certain times a year with the grid-oriented strategy, which leads to slightly higher calendar aging of the battery system. This effect is rather negligible due to the few occurrences over the course of a year. The additional effect of cyclic aging is also insignificant in comparison.

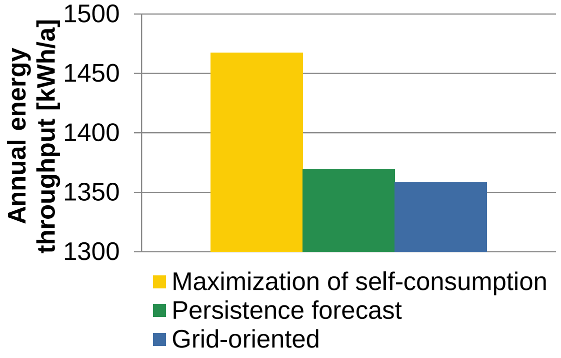

Figure 10: Annual energy throughput of the PV BESS.

Figure 10 illustrates the annual energy throughput of a PV BESS for the different operation strategies. If the maximization of self-consumption operation strategy is applied, the annual energy throughput is the highest. This strategy aims to increase the self-consumption by charging the battery as soon as positive residual power is available. Consequently, the energy throughput of the other strategies is lower, since charging is limited and also delayed with these strategies. Nevertheless, the annual throughput is only slightly lower because both strategies preferentially store cut-off energy in times of high power feed-in from the PV system.

The defining factor for the profitability of the BESS is the overall energy throughput over the total lifetime of the battery system. Since we do not assume any differences in the initial investment, the total yield from energy provided by the PV system depends on the effective lifetime of the BESS.

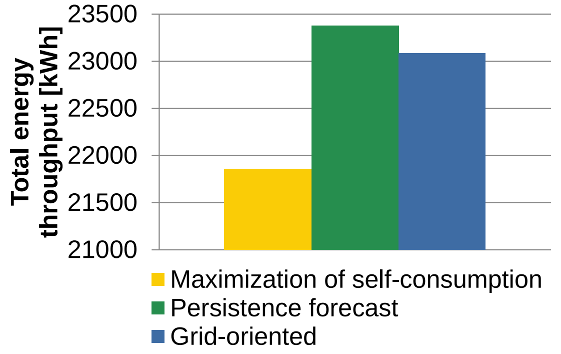

Figure 11: Total energy throughput of the PV BESS over lifetime.

To compare the energy throughput over the battery lifetime, the battery lifetime is multiplied with the annual throughput for each operation strategy. The results are depicted in Figure 11. The persistence forecast and the grid-oriented operation strategy have a distinctly higher energy throughput over the battery lifetime compared to the maximization of self-consumption. The total energy throughput only slightly differs between the persistence forecast and the grid-oriented operation strategy. This indicates that the grid-relieving operation of PV BESS does not influence the economy of such systems if these strategies are combined with lifetime enhancing algorithms. In summary, this paper shows that intelligent operation strategies of PV BESS can gain a significant grid relief without a negative influence on the economy.

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