PV-BENEFIT: A CRITICAL REVIEW OF THE EFFECT OF GRID INTEGRATED PV-STORAGE-SYSTEMS

Janina Struth\textsuperscript{1,2,3}, Kai-Philipp Kairies\textsuperscript{1,2,3}, Matthias Leuthold\textsuperscript{1,2,3}, Astrid Aretz\textsuperscript{4}, Mark Bost\textsuperscript{4}, Swantje Gährs\textsuperscript{4}, Moritz Cramer\textsuperscript{5}, Eva Szczechowicz\textsuperscript{5}, Prof. Bernd Hirschl\textsuperscript{4}, Prof. Armin Schnettler\textsuperscript{5}, Prof. Dirk Uwe Sauer\textsuperscript{1,2,3}

\textsuperscript{1} Grid Integration and Storage System Analysis Group, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Germany
\textsuperscript{2} Institute for Power Generation and Storage Systems (PGS), E.ON ERC, RWTH Aachen University, Germany
\textsuperscript{3} Juelich Aachen Research Alliance, JARA-Energy, Germany
\textsuperscript{4} Institute for Ecological Economy Research (IÖW), Berlin, Germany
\textsuperscript{5} Sustainable Energy Systems, Institute for High Voltage Technology (IFHT), RWTH Aachen University, Germany

email: batteries@isea.rwth-aachen.de
Tel.: +49 241 80 49308, Fax: +49 241 80 92203

1 ABSTRACT

The quantitative assessment of effects and benefits of battery storage systems in households with photovoltaic (PV) generators and the effects on distribution and transmission grids need to be identified and analyzed for future energy supply systems. As analysis tool a MATLAB-based model of a distribution grid with multiple storage systems has been implemented. The model is applicable for a wide range of different battery storage systems, various PV-system sizes and diverse grid structures. Different battery management strategies such as fixed power limitation, charging interval timer with regard to typical solar radiation profiles, maximizing self-consumption and maximizing the benefit for the grid have been implemented and analyzed. If the storage is managed properly a relief for the grid can be achieved while at the same time the self-consumption can be retained at nearly the same level as a management strategy purely maximizing the self-consumption.

Keywords: photovoltaic (PV), home storage systems, battery management strategies, power supply system, MATLAB Simulink, MATPOWER, battery and grid modeling
2 INTRODUCTION

The integration of battery storage systems in connection with photovoltaic systems (PV-storage-systems) into the power supply system is an important issue when discussing future energy concepts. Especially with regard to the growth of PV-generation, the local low voltage supply systems will partially be overloaded during intense solar irradiation in the future [1]. This leads to shortages in the distribution grid, which needs to be solved by adequate technical arrangements.

In southern European countries the electricity production costs are below the so called Grid Parity [2], that defines the point at which electricity generation from the own PV-system is cheaper than buying electricity from the grid. With the use of battery storage systems the fraction of self-consumed electricity can be raised and the additional difference between purchase price and generation costs can be used to refinance the storage system.

Besides their primary use for the increase of self-consumption battery storage systems can also support the grid and potentially avoid or delay grid expansions if they are operated intelligently. In order to quantify the potential benefits of PV-storage systems adequate modes of operation with positive effects on the entire power supply system have to be identified. In order to simulate different modes of operation a model that combines a battery storage system simulation (implemented in MATLAB/Simulink) and a power supply system simulation (MATPOWER) was developed. The model is able to simulate the reaction of the grid voltage on different modes of operation of battery management strategies.

3 MANAGEMENT STRATEGIES

Storage systems can be operated with different battery management strategies that support the grid or maximize self-consumption in variable ways or in a combination. The presented strategies in this paper are:

- Maximizing the self-consumption
- Static power limitation regarding the nominal capacity of the PV-system
- Charging interval timer with regard to typical solar radiation profiles
- Optimization based on forecasts (solar radiation and load)

Nowadays, battery storage systems in private households are usually operated in a way to maximize the self-consumption. The generated power is used to satisfy the direct load demand preferentially and the excess power is stored. Often the storage is fully charged before the power generation peak at noon, i.e. the grid load remains undiminished from then on (Figure 1).

According to the German Renewable Energy Act (EEG) [3] there are two options for PV systems with less than 30 kW to limit their effect on the distribution grid. Either they are set up with static
power limitation to 70% of the nominal power or they are equipped with an interface which allows a remotely controlled reduction of the feed-in power. The static power limitation reduces the high feed-in at noon, but generated power is lost often.

A simple measure to manage the feed-in of a battery storage system is a timer that constraints charging to the hours of typically high solar radiation. In the implemented strategy charging is allowed from 11:30 am. However, the battery is not used optimally when the radiation is not high enough to fully charge the battery during the allowed time frame.

For better results a management strategy was developed which includes forecasts of load demand and power generation. The implemented persistence forecast predicts a load demand profile for the actual weekday based on the profile the week before. The predicted power generation is assumed to be the same as the day before. The battery storage management calculates a power limit with this forecast and the free capacity of the battery to store power above this value and relieves the grid at times of high power generation. With this strategy an uncertain forecast could cause losses if the predicted power is higher than the real and could cause non-optimal grid relief if it is the other way around. To reduce this deviation the forecast algorithm predicts a state of charge (SOC) of the battery. Any time there is a difference of more than 2.5 percentage points between the predicted and the actual SOC the power limit is adjusted by 10%. If the battery is not fully charged at 6 pm the power limitation is abrogated. This optimization makes sure that high power feed into the grid is reduced and the battery is charged as much as possible.

In the ideal case the battery is fully charged with the energy generated at the power peak around noon (Figure 2). However, optimal timing would require perfect forecast for generation and load.
All realistic management strategies are a compromise between peak power reduction, battery utilization and management effort.

Figure 2: Ideal battery management with perfect forecast.

4 INPUT DATA

The battery model is programmed in MATLAB Simulink based on the Sol-ion system setup [4] and contains a lithium ion battery based on the type SAFT VL 45E. The storage capacity can be changed according to requirements such as the dimension of the appropriate PV generator and household load demand. The battery storage system operates with a DC-DC-topology.

The household load profile is synthesized out of measured load demand profiles of 32 typical household appliances. This generated profile differs between weekday and season [5]. For this profile a static and a smart load transfer is available and will be used in later analyses but not in this paper.

The values used for the generated power were measured over the year 2008 in 60-second intervals in northern Bavaria, Germany, for a 5.04 kWp roof PV-system installed in 2004 with an azimuth angle of 13° south-west and an angle of slope of about 45° [5].

The distribution grid model is programmed in MATPOWER. It also uses generic load demand profiles to calculate the voltage but without the opportunity of load transfer [6]. For the study in this paper an exemplary grid structure for a power supply system in a village is implemented [7]. It comprises 71 households including 21 with a PV-storage system, 3 farming and one industry each with a PV-storage system. The sum of the whole grid has a load demand of about 269 MWh/a besides 203 kWp PV-systems and 204 kWh battery capacity are installed. Individual PV-systems were varying between 3-5 kWp and between 30-45 kWp for farming, combined with 1-2 kWh/kWp battery capacities.
5 RESULTS AND DISCUSSION

Two exemplary days in April were analyzed to demonstrate the effect of the different management strategies. The system is simulated in 60 s intervals; figures show 10 min average values for better visibility.

Figure 3 indicates the power exchange with the power supply system. Negative values mean grid delivery and positive values represent grid feed-in from PV-systems. The black curve represents the household load demand and the thick purple curve illustrates the behaviour of a PV-system without any storage system.

The battery management which maximizes self-consumption transfers all power exceeding local demand into the battery. This way the battery is charged as early as possible in the day. Therefore the utilization of the battery is maximal. However, the battery is fully charged before noon and the height of the feed-in peak at noon remains unchanged. Only the beginning of the feed-in is delayed in comparison to the system without storage. The battery management strategy with an interval timer charges the battery at a later but static point of time. It can to some extend reduce the feed-in peak at noon, however, before and after the charging time the feed-in remains high.

Figure 3: Generation and load at an exemplary household in the power supply system for different management strategies for a 5 kWp PV-system, 4.5 MWh/a load demand and a battery storage of about 6.2 kWh.
For simplicity the effect of a simple timer is shown. A timer in combination with a charging power limitation can lead to better results.

Significantly better performance can be reached with the strategy based on persistence forecast which determines charging intervals and charging power adjusted to the actual weather situation.

As can be seen in Figure 4 all battery management strategies lead to a fully-charged battery for these exemplary days. However, the different charging strategies result in different times, when the battery is fully charged. The battery that is operated for maximal self-consumption always charges the battery at the earliest possible time and with highest power. The battery utilization is maximal and the grid relief is minimal. The interval timer strategy has the highest risk to reach only a partial state of charge during the day. The persistency forecast strategy optimizes towards a fully-charged battery at 6 pm.

![Figure 4: State of charge of the battery for different management strategies.](image)

The developed system model that combines the grid and the battery storage systems in the grid is able to calculate the influence of different battery management strategies on the system voltage. The voltage at the power supply node corresponding to the upper figures is shown in Figure 5. The voltage is measured in parts per unit (pu) according to the voltage at the local distribution grid station that is 230V and is an indicator for the load of the grid caused by PV-systems.

The strategy that maximizes only the self-consumption has no effect on the grid voltage peak. A limitation of the feed-in power to 70 % of the nominal capacity reduces the voltage only about less than 1 percentage point. The interval timer reduces parts of the peak power until the battery is fully charged. An additional reduction of the charging power would lead to more peak reduction but causes extra losses if the battery could not be charged completely. Most grid release can be reached by the intelligent management strategy with a persistency forecast.
However, any strategy that does not operate in a way to maximize self-consumption causes energy losses for the owner of the PV battery system. In the following, the increase of self-consumption by the use of storage systems and the influence of different battery management strategies are analyzed. The self-consumption is defined as the ratio between the locally used power to the generated PV-power:

\[
\text{self-consumption} = \frac{\text{self consumed PV-power}}{\text{generated PV-power}}
\]

For PV-systems without storage system the self-consumption is given by the instantaneous overlap between generation and load. The smaller the PV-system in a given household the bigger the fraction of energy which is instantaneously consumed, i.e. the higher the self-consumption. The use of a battery storage system can increase the self-consumption. Figure 6 shows the self-consumption rate as a function of storage capacity for different sizes of PV-systems. The management strategy shown is maximal self-consumption, i.e. the shown rates are the maximal possible self-consumption rates. Increasing battery capacity leads to higher self-consumption rates. However, the bigger the storage capacity the smaller the relative gain in self-consumption. Besides that the gradient depends on the relative size of the PV-system compared to the electricity consumption of the household. Small PV-systems do not produce much excess electricity which could be stored in a battery. For large PV-systems the relative effect of a battery is small because the generated energy cannot be used completely with a low household load demand. The biggest relative effect of storage systems is achieved for a ratio between PV-system
and household load demand of about 0.2-1.1/1000h, e.g. for a 5kWp PV-generator and a yearly household load demand of 5000 kWh.

Figure 6: Self-consumption rate in dependency of the PV-system size and the battery capacity normalized to the household load demand while operating with a management strategy to maximize self-consumption.

Strategies that were not operated to maximize the self-consumption as the first condition lead to lower self-consumption and create monetary losses for the owner of the PV-storage-system. Table 1 lists the self-consumption that could be reached by different management strategies for one exemplary year of a PV-storage-system with a ratio of 1.1/1000 h for the PV-system to the household load demand and battery capacity per household load demand of 1.4*1000.

Table 1: Self-consumption rates for different battery management strategies.

<table>
<thead>
<tr>
<th>Management strategy</th>
<th>Self-consumption [%]</th>
<th>Additional loss of the yearly energy by 70% power limitation [%]</th>
<th>Additional loss of the yearly energy by 60% power limitation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without storage system</td>
<td>20.0</td>
<td>3.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Maximize self-consumption</td>
<td>54.1</td>
<td>2.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Interval timer</td>
<td>51.1</td>
<td>1.0</td>
<td>2.8</td>
</tr>
<tr>
<td>persistence forecast</td>
<td>52.6</td>
<td>0.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Every battery management strategy raises the self-consumption in comparison to a PV-system without storage between 31 and 34 percentage points. The strategies that operate to reduce the high power generation at noon result in a little lower self-consumptions than a system that maximizes the self-consumption.

A power limitation to 70 % of the nominal capacity of a PV-system without storage system generates quite small losses. A battery storage system reduces these losses but does not compensate the simultaneous losses of self-consumption\(^1\).

The situation changes if the power limitation is set to 60 %. This measure would lead to a similar reduction of the voltage excess at the power supply node as storage systems with a persistence forecast strategy. Without storage such a lower power limitation would cause 7.2 % losses. With a storage system and persistence forecast the losses can be reduced to 2.4 %, i.e. 2.5% less losses than with the maximum self-consumption strategy.

If such a feed-in power limitation would be a condition of a funding scheme for storage systems, this intelligent management strategy would raise the profit of the owner of the PV-storage system and relief the grid by reducing the voltage at the same time.

### 6 CONCLUSION

A combined model including the battery storage system and the power supply system has been developed. The combination of both aspects is a necessary step forward in order to analyze the interaction of battery storage systems and the power supply system. The storage systems can be simulated with different battery management strategies to analyze the influence on the grid voltage and the self-consumption.

In a first qualitative analysis with the developed model, one grid structure was exemplarily evaluated. The study has shown that the generated model is able to picture the effect of different battery management strategies on the grid voltage.

A reduction of the maximal grid feed-in to 70 % of the nominal capacity of the PV-generator has only marginal effects on the grid voltage. In contrast, a reduction to 60 % lowers the grid voltage twice as much. The persistence forecast strategy has a similar influence on the grid voltage as the reduction to 60 %. The loss of the yearly energy is nearly the same in comparison to the strategy that maximizes the self-consumption and a reduction to 70 %. Hence an intelligent management strategy such as the persistence forecast releases the grid but does not cause additional energy losses and within that income losses for the owner.

To generate general assessments relating to grid relief different grid structures, variable arrangements of battery storage systems and connected PV-systems and household load profiles need to be evaluated. Additional storages from electro mobility cause an extra effect and will be considered in future studies.

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\(^1\) Monetary gains and losses depend on the feed-in tariff of the system and the energy purchase price. Gain and loss here are used purely with respect to energy.
7 ACKNOWLEDGEMENT

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8 REFERENCES


[2] Dr. H. Wirth, „Aktuelle Fakten zur Photovoltaik in Deutschland“, Fassung vom 2.2.2012, Fraunhofer ISE

[3] §6 Abs. 2 Nr. 2 EEG 2012


