COMBINED OPERATION OF A BATTERY STORAGE SYSTEM ON DISTRIBUTION GRID LEVEL – IMPACT ON THE GRID AND ECONOMIC BENEFIT

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ABSTRACT

The storage of renewable energy plays a very important role in the transition from fossil-fuel energy generation to a more sustainable supply with renewable sources. Especially in the case of solar energy from photovoltaic systems, electrochemical battery storages offer some advantages over other technologies. Depending on their control strategies, battery storages can fulfill different tasks in the low-voltage network. This applies particularly in distribution grids with a high degree of fluctuating generation such as solar power. Simulation results in this paper show that several use-cases can be combined with one stationary battery storage system in a low-voltage grid without influencing each other. Therefore, a more economic usage of stationary storages can be achieved.

INTRODUCTION

The most important benefit of using battery storages is an increase of the level of self-sufficiency in combination with a solar power system.

Another possible task for battery storages is offloading low-voltage grid areas that suffer from a high degree of installed photovoltaic power. Battery storages can be connected to critical grid-nodes to restore a balanced relationship between energy generation and consumption.

A third use-case for battery storages is the participation in the primary frequency control market. Primary balancing power is used to stabilize the frequency in the European electricity transmission system and is traded on special online platforms.

Due to the relatively high investment costs for stationary battery storages (1,000 to 2,000 €/kWh), the use-cases given above are not economically attractive individually [1]. For this reason, the potential advantages gained through a combination of all three use-cases are investigated in this paper.

STORAGE SYSTEM

Regarding the efficiency of a stationary storage system for increasing the level of self-sufficiency and offloading the grid, previous research has shown advantages of large-scale storages over home-storages [2]. For this reason, a lithium-ion large-scale storage system with a capacity C_{batt} of 150 kWh, a rated power P_{batt} of 150 kW and a maximum depth of discharge *DoD* of 80 % is simulated. The battery lifetime L_{batt} is assumed to be 20 years.

GRID-MODEL

In order to investigate the impact of the different storage use-cases on the low-voltage grid, load-flow simulations must be run in a representative grid-model. Rural village-grids seem most suitable for large-scale battery storages: with power supply lines being quite long and transformers not being dimensioned for high reverse load flows occurring from the characteristically large amount of photovoltaic-systems in those rural areas, necessary grid-reinforcement can be reduced and solar energy can be locally stored and consumed by storage operation. Therefore, a corresponding grid-model of a village in upper Bavaria is investigated by using the grid analysis software PSS Sincal. It mainly consists of two branches and one ring with several short leavings, all connected to a transformer with a rated power of 250 kVA. The whole grid contains 40 consumers and 18 photovoltaic systems. The mean value of the installed power of every photovoltaic system amounts to 17.1 kW, whereby a maximum simultaneity factor of 0.85 is considered. This results in a maximum power generation of 261.6 kW.

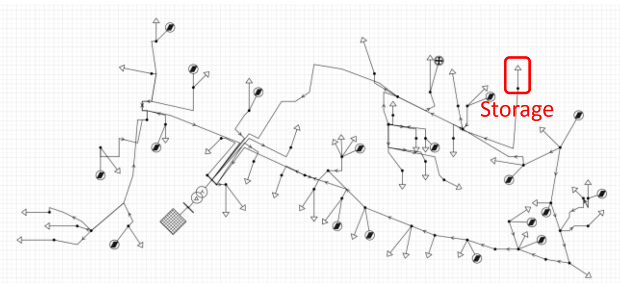

Figure 1: Used model of existing village-grid in upper Bavaria

This grid represents the field test area in the context of the research project EEBatt. The storage is connected to a cable distributor close to the grid area with the highest installed photovoltaic power (see Figure 1).

METHOD

Impact on the grid

In order to investigate the effects of a large-scale storage with different use-cases on the grid, load-flow simulations over a certain time period are necessary. Therefore, weekly load profiles with minute-by-minute precision represent the consumers, photovoltaic systems and the storage. In order to simulate a worst-case scenario, the chosen week in May contains the maximum photovoltaic generation power within the used photovoltaic profile from upper Bavaria of 2005 (see Figure 2). This generation profile is used for every photovoltaic system in the grid-model.

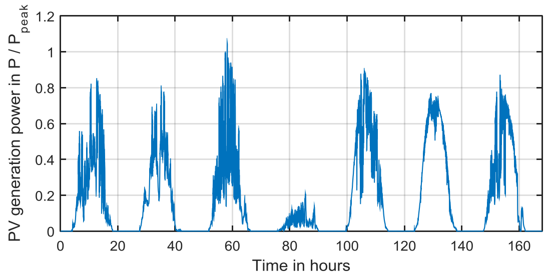

Figure 2: Used weekly photovoltaic profile from upper Bavaria

The load profiles representing the consumers are statistically-generated individual household profiles (see Figure 3) [3]. Every load profile is individually scaled to the real annual energy consumption of the corresponding consumer.

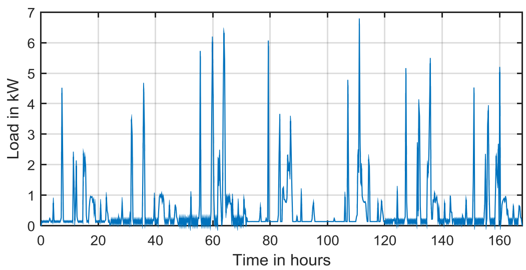

Figure 3: One of the used statistically generated load profiles

The load profiles of the large-scale battery storage are generated individually in Matlab/Simulink, depending on the investigated use case. For simulating the provision of frequency control power, the grid frequency of the year 2012 in middle Europe with second-by-second precision is used. On the basis of these load-flow results, the transformer load and the critical grid-voltages are investigated in order to evaluate the impact on the grid.

Economic benefit

Increasing the level of self-sufficiency

Considering this use-case for large-scale storages, the following approaches for calculating the economic benefit are taken into account:

The amount of photovoltaic surplus energy taken from the storage is multiplied by an amount of money s_{el} between 0.05 €/kWh and 0.30 €/kWh, which represents the savings per consumed kilowatt hour compared to the common grid supply. A feed-in remuneration when feeding surplus energy to the public grid is not considered.

Offloading the grid

The economic benefit of offloading the grid is calculated by the avoided grid reinforcement. A new transformer station is assumed in the case of a maximum transformer load of 85 %, due to the expectant further addition of photovoltaic systems. Furthermore, a replacement of supply cables is assumed in the case of the voltage exceeding the permissible limit value of 103 %. The lifetime L_{eq} of this equipment is assumed to be 30 years. According to [4], investment costs c_t for a new transformer amount to 44.000 € and c_c for cable reinforcement is 80 €/m.

Providing primary frequency control power

When providing primary frequency control, a demand rate during the tender period of one week is paid by the TSO. According to the German online platform for tendering control power, the mean value dr_m of that demand rate amounted to about 2.76 €/kW per week in the year 2012. This value is assumed for calculating the financial benefit of a storage providing primary frequency control power. Because of a minimum set of 1 MW for providing control power, the integration in a pool of several generators is assumed.

STORAGE USE-CASES

Increasing the level of self-sufficiency

When operating the large-scale storage in order to increase the level of self-sufficiency of the connected grid-area, the whole photovoltaic power surplus generated in the grid is used to charge the storage as long as there is still spare capacity left. As soon as there is no more surplus energy generated, the storage covers the load by discharging until it reaches the maximum depth of discharge. With this use-case, the storage will be fully charged before the feed-in peak at noontime and therefore not contribute to an offloading of the grid (see Figure 4).

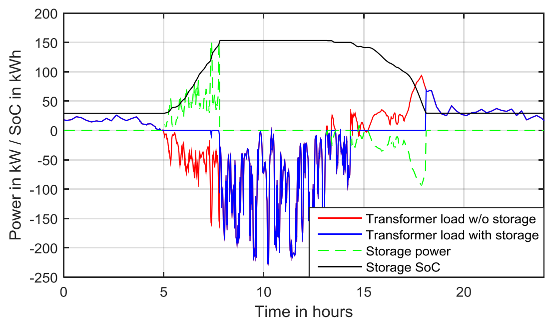

Figure 4: Storage power and transformer load on an exemplary day in May when only increasing the level of self-sufficiency

Offloading the grid & increasing the level of self-sufficiency

By using intelligent control algorithms, battery storages can not only increase the level of self-sufficiency but also offload the grid by storing the surplus power of generation peaks. For this purpose, the approach of damping the feed-in power developed in [5] is used for the simulations in this paper. On doing so, the storage charges with a nearly constant charging power throughout the whole daytime, as long as the load on the transformer is beyond a certain limit. As soon as the limit value is reached, the storage charges an extra amount of power in order to keep the load on the transformer below (see Figure 5).

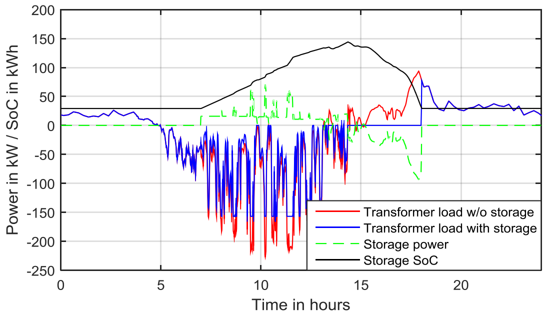

Figure 5: Storage power and transformer load on an exemplary day in May when additionally offloading the grid

When choosing an appropriate grid-connection point, this control algorithm can not only offload the transformer, but also reduce critical voltages in the grid.

Providing primary frequency control power

Frequency control power ensures the balance between energy generation and consumption in the corresponding control area. The available primary frequency control power is accessed automatically according to a given power-frequency-curve, which demands 100 % of the offered control power at a frequency deviation of at least ±200 mHz. For lower frequency deviations down to 0 mHz the accessed power is linearly reduced down to zero, where no power has to be provided for the tolerated deviations up to ±20 mHz.

To avoid inadmissible conditions like a fully charged battery in case of required negative control power, several degrees of freedom are permitted and used by the developed control algorithm to always try to achieve an ideal state of charge SoC_{desired} [6].

Optional overfulfillment (*DoF 1*)

The demanded control power can be increased up to 20 % at any time.

Optional fulfillment within the tolerated deviation range (*DoF 2*)

Control power can also be provided within the tolerated deviation range of ±20 mHz.

Adjustable gradient of power delivery (*DoF 3*)

The demanded control power according to the power-frequency-characteristic has to be provided within 30 seconds or less. According to the current *SoC*, this minimum gradient can be used in order to slow down the charging or discharging process of the battery.

Charging/Discharging by electricity exchange trading

Another way to reach the desired state of charge is trading energy at the electricity exchange. Because of a minimum tradable power of 100 kW, this degree of freedom is not considered for smaller large-scale storages on the low-voltage level investigated in this paper.

To determine the maximum value of the control power to be provided considering the mentioned degrees of freedom, several C-rates and values for SoC_{desired} are simulated for the provision over a time period of one year. Figure 6 shows the resulting lack of delivery dependent on the amount of provided control power and the types of considered degrees of freedom. When using all three possible degrees of freedom and a SoC_{desired} of 59 %, a maximum C-rate of 0.15 can be provided as primary frequency control power without any failures.

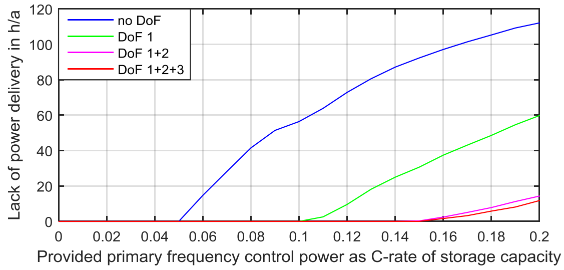

Figure 6: Lack of control power delivery as a function of the provided power as C-rate of the storage capacity

When providing control power with battery storages, the necessary capacity has to be reserved during the whole tendering period and cannot be used for any other use-case. For this reason, a combination with the other mentioned use-cases is only possible when the photovoltaic generation is low and only a part of the capacity is necessary for offloading the grid and storing the surplus energy. Considering a time period of one year, simulation results show an average daily maximum *SoC* of about 48 % in the months November to February compared to about 83 % during the rest of the year. For this reason, a provision of primary frequency control power with half of the storage capacity during these four months is considered in the following simulation results.

RESULTS

Impact on the grid

Increasing the level of self sufficiency

When operating the storage for only optimizing the level of self-sufficiency, an offloading of the grid is not achieved in general.

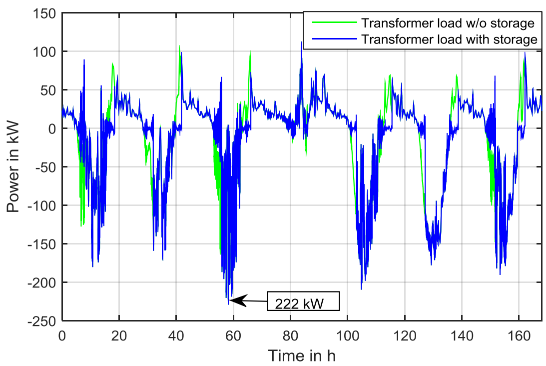

Figure 7: Transformer load during simulated week

Figure 7 and Figure 8 confirm this conclusion by showing the transformer load and the voltage at the most critical node in the simulated grid model when operating a battery storage system according to that use-case as well as without storage.

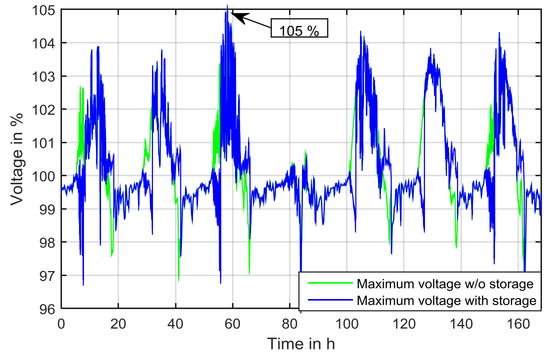

Figure 8: Voltage at most critical node during simulated week

Considering the curves for both cases, transformer load and voltage only differ in the morning and evening of each day when the battery is charging or discharging the surplus energy. During the critical noontime, the storage is fully charged on most of the days and cannot contribute to offloading the grid. Therefore, the maximum transformer load of 222 kW and the maximum voltage of 105 % are not reduced by storage operation.

Offloading the grid & increasing the level of self-sufficiency

When operating the storage for also offloading the grid, transformer load and grid voltage can be reduced.

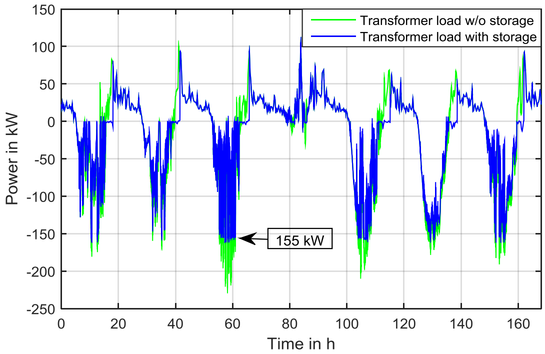

Figure 9: Transformer load during simulated week

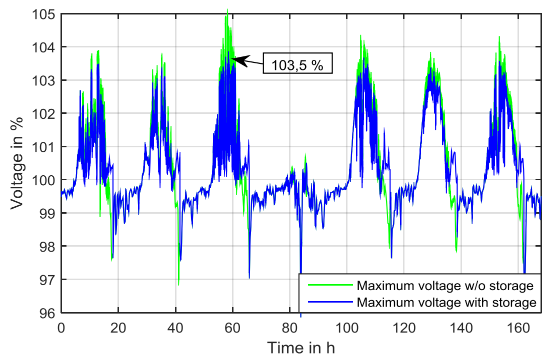

Figure 10: Voltage at most critical node during simulated week

Figure 9 and Figure 10 show the transformer load and the voltage at the most critical node in the simulated grid model when operating a battery storage system according to that use-case as well as without storage. Based on these curves, a transformer load reduction to 155 kW and a voltage reduction to 103.5 % are shown.

Offloading the grid, increasing the level of self-sufficiency and providing primary frequency control power

Due to the maximum possible C-rate of 0.15, the additional provision of primary frequency control power only has a minor impact on the grid.

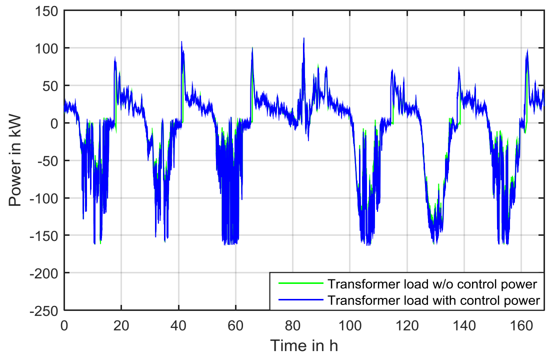

Figure 11: Transformer load during simulated week

Considering a provision with half of the storage capacity, a maximum control power of only 11.25 kW would further influence the grid. This is illustrated by the comparison of the transformer load with and without provision of control power, as shown in Figure 11.

Economic benefit

Increasing the level of self sufficiency

To determine the yearly economic benefit when increasing the level of self-sufficiency b_{lss}, the difference in the amount of solar energy consumed by the grid area within one year when operating a storage $W_{\mathrm{c,solar,batt}}$ and without storage $W_{\mathrm{c,solar}}$ is calculated and multiplied by the possible savings s_{el} according to (1).

$$b_{\mathrm{lss}} = (W_{\mathrm{c,solar,batt}} - W_{\mathrm{c,solar}}) \cdot s_{\mathrm{el}} = 34.420\ \mathrm{kWh} \cdot s_{\mathrm{el}} \quad (1)$$

The resulting marginal investment costs $c_{\mathrm{i,m,lss}}$ for the battery storage are calculated according to (2).

$$c_{i,m,lss} = \frac{b_{lss} \cdot L_{batt}}{C_{batt}} \quad (2)$$

Offloading the grid & increasing the level of self-sufficiency

The yearly economic benefit $b_{\mathrm{lss+off}}$ of this use-case is the sum of b_{lss} and the avoided costs for grid-reinforcement by offloading the grid b_{off}. Due to a transformer load of 89 % and a maximum voltage of more than 103 % without storage operation, b_{off} is calculated by the sum of transformer- and cable costs.

$$b_{off} = \frac{c_t + c_c}{L_{eq}} \quad (3)$$

With a necessary cable reinforcement of 496 m, b_{off} is calculated according to (4).

$$b_{off} = \frac{44.000\,€ + (496\,m \cdot 80\frac{€}{m})}{L_{eq}} \cdot \frac{L_{batt}}{L_{eq}} = 2789\,€ \qquad (4)$$

The resulting marginal investment costs $c_{i,m,lss+off}$ for the battery storage are calculated according to (5).

$$c_{i,m,lss+off} = \frac{b_{lss+off} \cdot L_{batt}}{C_{batt}} \qquad (5)$$

Offloading the grid, increasing the level of self-sufficiency and providing primary frequency control power

The yearly economic benefit $b_{lss+off+pfc}$ of this use-case is the sum of b_{lss}, b_{off} and the earnings from providing primary frequency control power $b_{pfc.}$ Considering a provision of 11.25 kW during the four winter months, b_{pfc} is calculated according to (6).

$$b_{pfc} = 16\frac{w}{a} \cdot dr_m \cdot 11.25\,kW = 497\,€ \qquad (6)$$

The resulting marginal investment costs $c_{i,m,lss+off+pfc}$ for the battery storage are calculated according to (7).

$$c_{i,m,lss+off+pfc} = \frac{b_{lss+off+pfc} \cdot L_{batt}}{C_{batt}} \qquad (7)$$

Overview

Figure 12 shows the marginal storage investment costs as a function of the savings by self-consumption s_{el} and the considered use-case.

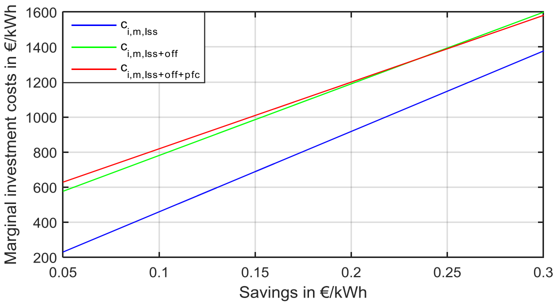

Figure 12: Marginal storage investment costs depending on s_{el}

The avoided reinforcement costs when offloading the grid can offset a big part of the storage investment costs. On average, the storage investment costs can be 78 % higher compared to an operation for only increasing the level of self-sufficiency, despite a lower level of self-sufficiency when additionally offloading the grid. Providing primary frequency control power has a very low influence on $c_{i,m}$ and becomes uneconomic for $s_{el} > 0.22$ €, due to the distinct losses of self-consumption during the winter months.

SUMMARY

Large-scale battery energy storage systems in low-voltage networks for increasing the level of self-sufficiency in combination with photovoltaic systems can additionally offload the grid when being operated according to smart control algorithms. Especially in rural grid areas, this additional use-case can avoid extensive grid-reinforcement and therefore generate considerable further financial benefit. Participating in the primary frequency control market within the four winter months can be considered uneconomical due to the low power to be provided. For this reason, the secondary and tertiary control power market has to be considered in further research. Regarding the circumstances given in this research work, an economic storage operation can be possible for savings from 0.15 €/kWh when taking energy from the storage instead of the public grid. In this case, realistic marginal storage investment costs of 1.000 €/kWh are achieved.

In order to make profound statements in general, a more detailed investigation of the parameters for calculating the financial benefit and further representative grid-models is necessary. Especially the lifetime of electrical grid equipment and the storage system represent influential values.

ACKNOWLEDGMENTS

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