OPEN LOOP OPERATIONAL STRATEGIES OF A VIRTUAL POWER PLANT AND THEIR IMPACTS ON THE DISTRIBUTION GRID

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ABSTRACT

As an aggregation of multiple Distributed Energy Resources (DER), Virtual Power Plants (VPPs) are able to participate in a much broader range of market activities in comparison to a single DER. Depending on the operational strategy, different power flows occur resulting in different voltage states and loading conditions of the electrical equipment (such as cables and transformers). In this paper several open loop operational strategies of a VPP are introduced and the impacts on a real distribution grid are analyzed with the help of a grid simulation. The term open loop expresses the fact that a feedback of grid states into the strategy control system is not applied. The economic impacts of the operational strategies are not evaluated.

INTRODUCTION

The considered VPP is part of the project In2VPP which is a government-funded project (contract number: 0325607) by the Federal Ministry for Economic Affairs and Energy in Germany with the goal of bridging the gap between the economic and technical challenges associated with VPPs. The VPP under consideration consists of 16 Photovoltaic (PV) household rooftop generators in combination with commercially available lithium-ion storage systems and a 100kW$_{el}$ electricity-driven thermal power station (CHP). In some strategies also the respective household loads of the regarded PV system are considered part of the VPP. All generation units feed their power into a 0,4kV distribution grid, characterized by a rural structure, connected to a 20kV grid by two 630kVA transformers. A total PV capacity of approximately 720kW is installed in the investigated grid, whereby one third of this amount is produced by the generation units of the VPP. Furthermore about 300 household consumers without a PV rooftop system, 35 industrial loads, several heating loads and some agricultural businesses are supplied.

OPERATIONAL STRATEGIES

Strategy input

As well as real irradiation time series for the year 2012, all strategies need a PV forecast in order to place an offer on the EPEX SPOT day-ahead market. Therefore a statistical approach is used to generate a prediction time series out of real measured data [1]. As presented in [2], typical relative root mean square errors (rRMSE) of 4% can be achieved according to (1).

$$rRMSE = \sqrt{\frac{1}{N}\cdot\sum_{i=1}^{N}\left(\frac{x_{forecast}-x_{real}}{x_{nom}}\right)^2} \qquad (1)$$

Furthermore, household load profiles are necessary for most of the strategies. A probabilistic load profile generator was therefore developed. Using statistical data for device usage time and duration along with typical device load curves, a profile for active power demand was created and scaled to the known real annual consumption. In addition to real profiles, predictions for household load profiles are necessary. This is implemented by averaging preceding days. A frequency trend for the year 2012 with a resolution of one second was exclusively used in strategy S5. For all calculations, typical efficiency values and limitations in the battery charge/discharge power are regarded. For the CHP, a realistic activation speed with a magnitude of approximately $\frac{1\%\cdot P_{el}}{sek}$ and a minimum output power of 50% in all strategies due to efficiency reasons [3] is considered.

Strategy ideas

The VPP trades its power on different energy markets, such as day-ahead and primary control market. It should be mentioned that the minimum bid requirements are violated. Nevertheless the message of the results is still valid due to the possibility of scaling.

S1: Decoupled VPP

If a VPP is working in operation mode S1, all units are decoupled and operate on their own. Every unit generates its own power flow forecast and offers this active power on the day-ahead market. Inevitable forecast mistakes occur for the PV systems due to the limited accuracy of the predication method, whereas the thermal power station is regarded as perfect with a constant feed in of 100kW$_{el}$. Regardless of the forecast, all produced energy is fed into the grid. Batteries were neglected in this conventional strategy. The aim of this strategy is to represent a benchmark strategy against which all following real VPP strategies can be compared.

S2: Self-consumption optimization

In S2 the household loads jointly connected to the grid with the PV generators of the VPP are part of the VPP. The primary goal of this strategy is to achieve a preferably high self-consumption. In addition, the gap between predicted power flow and fed in power flow of the whole VPP should be minimised. Therefore a self-consumption optimized forecast is produced for the household. The thermal generation unit offers its nominal electrical power on the day-ahead market. During operation the battery is charged in case of a PV surplus and discharged in case of a shortfall in PV production regardless of the forecast. In order to minimize the forecast error of the whole VPP, the thermal generation unit is curtailed in case of an overall surplus. This strategy is financially rewarding in case of a high electricity price in comparison to a low exchange price on the market.

S3: Schedule optimization

In S3 household loads are again regarded as part of the VPP. The primary goal of this strategy is to optimally fulfil the traded schedule on the day-ahead market with a high self-consumption rate. It can be regarded as S2 with transposed priorities. The schedule is the same as for S2. However during operation the batteries are charged if the local schedule is exceeded (caused by an overshot in PV production or less consumption of the household) and discharged if the local schedule is undershot. The thermal generation unit again is curbed in case of overproduction. This strategy is especially rewarding in case of high penalties for violating the schedule.

S4: Feed-in Damping [4]

This strategy combines the advantages of high self-consumption and a damping in the feed in power and is described in detail in [4]. Households are part of the VPP. In comparison to usual self-consumption strategies where the battery already reaches its maximum SOC before the peak values of the PV system occur, S4 damps throughout the day with a constant charging power P_{batt} (2) in order to achieve a maximum SOC at the end of the day so that a maximum amount of self-consumption during night times can be gained. C_{spare} stands for the spare capacity of the battery and t_{re} for the time until sunset.

$$P_{batt} = \frac{C_{spare}}{t_{re}} \qquad (2)$$

A threshold of $P_{Grid\text{-}max}$ $(= 0.5 \cdot P_{PVnom})$ should not be exceeded. Above all, this guideline is accomplished by a higher charging power in case of high insolation combined with low consumption. In general, the battery is responsible for the load which can´t be covered by PV energy and therefore the battery is discharged in case of $P_{load} > P_{PV}$. Especially during nighttime, an algorithm determines the amount of energy needed during the next two days with the help of load and PV prediction. If the actual SOC exceeds the calculated demand of energy for load covering, the battery feeds energy into the grid in order to be able to store the surplus energy during the next day and therefore damp the PV power flow.

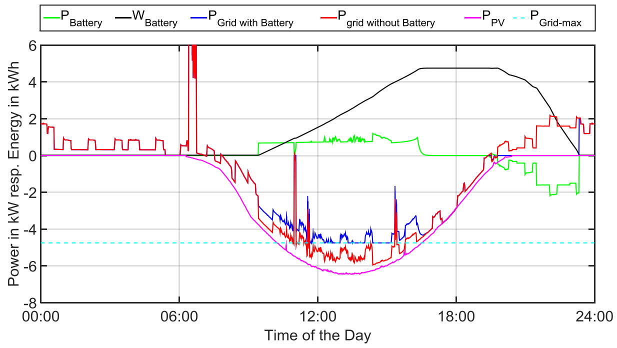

Figure 1: S4-Profiles of a typical summer day for one exemplary system consisting of PV, battery and household load

An example is given in figure 1, whereby a positive value represents consumption. The CHP is traded on the day-ahead market with its full power. Occurring overachievements of the balancing group are counteracted by curtailing the CHP.

S5: Primary control (PCL)

S5 represents an economically interesting strategy. The batteries offer a part of their maximum charging/discharging power on the primary control market. The financial benefits are directly coupled to the offered power and are not affected by the fed in or absorbed energy. Thereby, the battery pool has to measure the grid frequency with a high resolution in the range of seconds in order to control the output power according to the characteristic shown in figure 2.

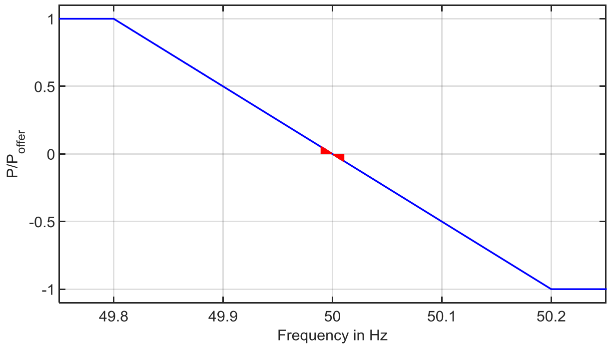

Figure 2: Characteristic for primary control

Related to the contract between the VPP and the transmission system operators (TSO), a 100% availability has to be ensured [5]. In order to fulfil these standards, some degrees of freedom are granted [6].

- Within a tolerance band of ± 10 mHz at 50Hz (marked as red area in figure 2), the battery can either decide if the power is kept zero or the power is exchanged with the grid by reference to the characteristic already mentioned.
- The yielded power can be overfulfilled by 20%.
- A new operation point does not have to be (but can) approached immediately after determining the new point. However a minimum activation speed of $\pm\frac{100\%\cdot P_{offer}}{30sek}$ is dictated.

Nevertheless, it is not feasible for the battery pool to offer its maximum power (C-rate=1) without violating the requirement of availability. Based on simulation results, a possible C-rate of approximately 10% could be achieved, dependent on different parameters. With the objective of increasing the offered power, a small part of the thermal generation unit (1.5% of P_{el}) is used to support the battery pool in extremely low or high state of charge (SOC) situations. The remaining power is traded on the day-ahead market. Based on the obligations of production proof for primary control, the thermal generation unit must be divided into two separate units, each with $50kW_{el}$. The generated solar power is traded on the day-ahead market independently of the batteries. The second part of the thermal generation unit is responsible for an equalized balancing group and curbs its fed-in power in case of overproduction.

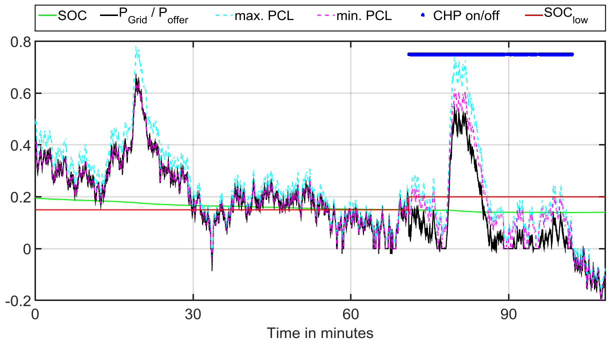

Figure 3: Battery and CHP behavior in S5 for an extract of a day in February (negative values represent consume)

Figure 3 illustrates the behaviour of the battery interaction with one part of the CHP. While the SOC (green line) is above a critical value (red line), the CHP is not activated. However, the SOC is relatively low causing the output power of the battery (black line) using the minimal allowed fed-power respectively the highest allowed charging power (magenta line). The presence of a minimum respectively maximum PCL limit is based on the different degrees of freedom and can be used for battery management. In case of falling short of the minimum accepted SOC, the CHP is activated (blue stars) and the battery output power is below the minimal PCL line. In addition to that, the critical SOC value is raised in order to achieve a hysteresis behaviour.

Strategy results

All strategies were simulated for the year 2012 and are compared by means of the physical degree of autarky (as calculated by formula 3), the number of battery cycles and the rRMSE of the prediction accuracy (formula 1).

$$aut = \frac{\int \min\left(P_{load} - P_{grid}, P_{load}\right) dt}{\int P_{load}\, dt} \qquad (3)$$
$$where\ (P_{load} > 0)\ \&\ (P_{load} > P_{grid})$$

Figure 4 and 5 illustrate the results, whereby the degree of autarky is normalized to the value of S1.

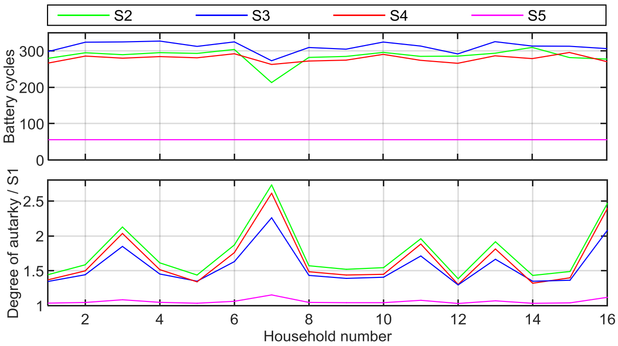

Figure 4: Physical degree of autarky and battery cycles of every household participating in the VPP

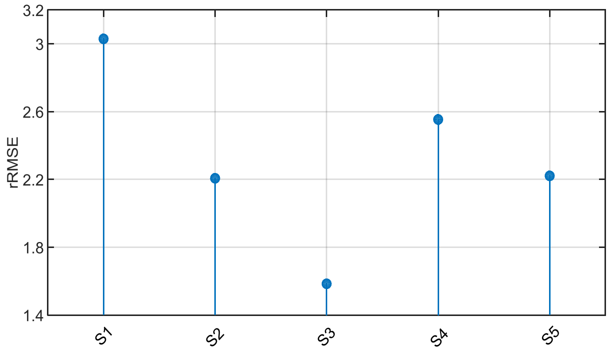

Figure 5: Accuracy in prediction of the overall VPP

As expected, S2 shows the highest values for the degree of autarky and is followed by S4. Nevertheless, S3, which is actually specialized in equalizing the balancing group, achieves convenient values. Concerning battery cycles, again these three strategies lie close together, whereby S3 shows the highest level of deterioration. S5 represents an outlier. Due to the relatively low offered power on the primary control market (C-rate=0.15), the number of cycles of each battery in the pool is low. The fact that the behavior of the battery is totally decoupled from the load (no consideration in prediction respectively in real application) the physical degree of autarky is low but still better than for the strategy S2. All strategies exhibit a lower rRMSE value than a hypothetical VPP consisting exclusively of PV. Despite involving the load in the VPP, S3 still shows the best properties with regard to the rRMSE. On the one side this could be explained with the algorithm of the battery designed to minimize the error in the balancing group. Beyond that the prediction mistake for load curves is, due to the averaging process, mostly negative. This circumstance can be counteracted with a curbed CHP effectively.

IMPACTS ON THE GRID

Grid simulation model

All represented strategies were simulated with a conventional grid simulation tool. Due to significant computing times, only the two weeks with the highest respectively lowest irradiation in 2012 were simulated. Industrial load, agricultural loads and heat loads were reproduced with their typical standard load pattern respectively real measured curves. For all these consumers, realistic values for cosφ were considered. Active and reactive power of households were replicated by the probabilistic load profile generator described at the beginning. All active power curves were scaled to the known energy consumption. CHP as well as PV and battery system were simulated with a cosφ=1.

Grid simulation results

Grid losses

First of all, figure 6 illustrates the squared dependence between grid losses and power flow whereby all data points refer to the maximum values of S1. Positive x-values represent overall generated power in the highest irradiation week. Negative x-values represent the overall consumed load in the week of lowest irradiation. Due to the ratio of generators and load this squared dependence was expected (at least for the summer week) but cannot be assumed as generally applicable.

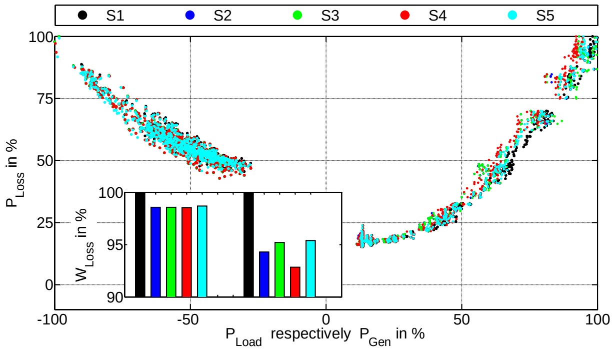

Figure 6: Grid losses dependent on different strategies and the overall generated power (for high insolation week) resp. overall consumed load (for low insolation week).

The bar chart illustrating the energy losses with respect to S1 for the particular week (left = lowest irradiation week, right = highest irradiation week) identifies S4 as the best strategy considering grid losses for high irradiation periods. Among others, this result can be explained by the less fed-in power in comparison to the other strategies, visible by the red points in figure 6 not reaching 100% of P_{Gen}. In addition to that, the high value of autarky preventing power flow in the grid explains this result. All other strategies are ranked according to their degree of autarky. The behavior of the CHP underpins the relatively poor performance of S5 feeding in more power than S2-S4 which could not be consumed locally. For the winter month, the difference between S1 and the other strategies is due to the continuous operation of the CHP, feeding in more power in comparison to the partially curbed operation in other strategies due to the reason of schedule balancing and PCL (only S5).

Voltage trend

In place of all other households with PV and a battery system taking part in the VPP, the upper part of figure 7 illustrates the voltage trend for the week with high irradiation for one grid connection point with respect to S1.

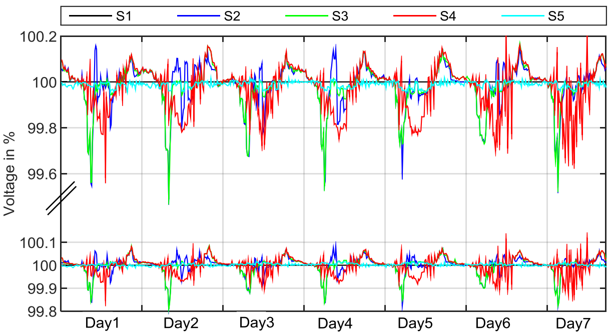

Figure 7: Voltage trend of an exemplary VPP household in respect to S1 (at top) and voltage trend at the grid connection point with the highest occurring voltage value in respect to S1.

It can clearly be seen that S2 and S3 feature lower voltage values in the morning hours. This fact can be explained by the respective strategy goal to reach a high level of autarky, causing the battery to store all PV energy directly after sunrise until the maximum SOC is reached and therefore preventing the PV system to feed in power to the grid. However, a balanced schedule has an even higher priority in case of S3, leading to differences with the trend of S2 as it can be examined in the morning hours of day 5. In general, S4 exhibits the lowest voltage level during lunchtime which is caused by the constant damping of the battery charging process throughout the day. During the nighttime, the battery systems in S2:S4 try to cover the power of the loads, causing the voltage to be higher than for S1. The voltage trend at the lower part of figure 7 represents the maximum voltage point during the regarded summer week. Even though there is no VPP participant connected at this point or in the close surrounding area, the trend of all different strategies is clearly visible. It should be mentioned that, in view of values, the presented differences are very small which is because of the well-developed grid infrastructure.

Utilization of grid infrastructure

In contrast to the distinct dependency between power flow and voltage level (if control interventions are neglected, a power flow infeed at any point of the grid provokes a voltage increase at every other point) the distinct coherence between power flow and utilization of grid infrastructure is missing. Feed-in power could for example cause a high level of utilization in a state of low load. On the other hand high feed-in power could contribute to a utilization relief in states of a high load level. Figure 8 depicts this statement. The lower part of this figure shows the overall power infeed into the grid of S2:S5 relative to S1.

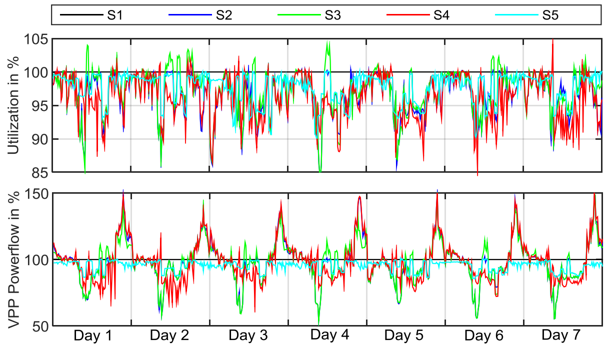

Figure 8: Overall VPP power flow scaled to S1 (below) and grid utilization scaled to S1 for the high insolation week.

At nearly every time of the week obvious deviations of up to 50% are recognizable. As already mentioned, strategy S2 and S3 feature a significant power flow reduction in the morning hours. In general, most of the strategies exhibit a lower power infeed during the day, whereas an increase during nighttime occurs. This circumstance results due to the discharging batteries trying to cover the energy consumption of the households. The partially curbed CHP operation in comparison to a constant feed in of 100% in S1 is negligible because of a high prediction accuracy during the night. The upper side of figure 8 illustrates the average level of utilization of all cables and both transformers scaled to S1. The trend of the VPP power flow is not clearly identifiable. As already mentioned, this result is due to the fact that the utilization is a result of the interaction of every participant in the grid. However, it can be concluded that different strategies cause distinct differences in utilization states. Similar results were gathered for the week of low irradiation.

CONCLUSION AND OUTLOOK

Depending on the development of the energy market, every presented strategy could be economically rewarding and therefore be used by the VPP operators. Due to the growing share of decentralised renewable power generation the grids are stretched to their limits, which justifies the idea of a coupled energy market rewarding local grid facilities. As shown in the chapter “Grid simulation results”, different power flows at any grid connection point result in more or less sensitive voltage variations at any other point in the grid. In addition to that, it was also visible that the degree of utilization can be influenced by a deviation in power injection, whereas the direction of influence is not obvious at the first glance.

On Basis of these results, another VPP strategy is conceivable using a so called sensitivity matrix. The goal of this matrix is to describe the sensitivity of a modification in power flow (active and reactive) at a distinct point to the voltage respectively utilization level at any other grid location. The matrix must be recalculated at every operation point of the grid. The process of this grid supportive closed loop strategy could be identical to all other presented strategies with the difference of a constant available communication between the grid operator and the VPP. The VPP receives a current sensitivity matrix, his grid connection points and the points of desired changes. With these information the VPP is able to decide which power generation unit is the most effective. This emergency service could be an additional income for the VPP. However the current energy market is not designed for such activities.

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