VOLTAGE CONTROL USING PV STORAGE SYSTEMS IN DISTRIBUTION SYSTEMS

Jan von APPEN
Fraunhofer IWES – Germany
jan.vonappen@iwes.fraunhofer.de

Martin BRAUN
Uni. of Kassel & Fraunhofer IWES – Germany
martin.braun@iwes.fraunhofer.de

Tanja KNEISKE
Fraunhofer IWES – Germany
tanja.kneiske@iwes.fraunhofer.de

ABSTRACT

PV storage systems are emerging and their grid integration becomes more relevant. This paper assesses the potential of different voltage control strategies for PV and PV storage systems. In conclusion, PV storage systems capable of voltage control can provide a benefit to grid operators as well as to storage system owners.

INTRODUCTION

By the end of 2012 over 32 GWp of PV was installed in Germany [1]. Around 70% of the installed PV capacity is connected to the low voltage level [2], which was not designed to accommodate high amounts of generation. This poses a challenge for stable, reliable grid operation, as voltage rises and reverse power flows from the low to the medium voltage level happen more often [3].

Decreasing costs for PV systems and feed-in tariffs as well as increasing electricity prices are changing the PV market. Increasing self-consumption of PV energy by using storage systems becomes more attractive for households. In this paper the market for PV storage systems and their impact on the distribution system is analysed. The paper addresses the grid integration issues related to PV storage systems. An overview of the current systems as well as a review of existing grid integration challenges is given. Voltage control strategies for PV and PV storage systems are outlined. These control strategies are then assessed from a grid perspective.

GRID INTEGRATION OF PV STORAGE SYSTEMS

To assess the potential impact that PV storage systems might have on the distribution grid, an understanding of the types of systems which are likely to be connected to the grid in the near future is required.

Market for PV storage systems

Currently, the most promising business case for distribution system sized storage systems is to increase the self-consumption of PV energy. The PV feed-in tariff for PV systems smaller than 10 kW is likely to drop below 0.15 EUR/ kWh by June 2013, while the average electricity price for households was around 0.28 EUR/ kWh in January 2013. The growing difference between the remuneration for PV and cost of consuming electricity increases the value of consuming as much PV locally as possible. Today, over 30 different manufactures are offering different home-scaled storage solutions which can be combined with a PV system. Most systems are either lead-acid or lithium ion battery based. They range from a capacity of 2 to 20 kWh and an AC output of 3 kW to 30 kW. Nevertheless, the most common solution for a home-scale PV battery system is likely to be a 5-6 kW PV system with a battery size of 2-12 kWh.

Challenges for grid integration

PV battery systems are available in two different topologies: DC and AC coupled PV storage systems. DC coupled systems describe systems where the PV modules and the battery are connected to the DC link of the inverter. The generated PV power is directly charged as DC power into the battery without passing through the grid. An AC coupled PV battery system consists of two inverters, one for the PV system and one for the battery.

Two main questions arise related to the grid integration of these systems. First, as some systems are designed as single-phase feed-in systems, voltage unbalances might occur from feed-in at one phase with simultaneous consumption at the other two phases. Secondly, the question arises whether such PV battery systems are able to mitigate PV induced voltage rises. A short literature review on these two topics is presented in the next section.

Voltage unbalance

The voltage unbalance is defined *as a condition in which the r.m.s. values of the phase voltages or the phase angles between consecutive phases are not all equal* [4]. It is a result of either uneven consumption on the three phases or uneven power feed-in. According to EN 50160, low and medium voltage systems voltage unbalances are allowed as long as the average ten-minute r.m.s of the voltage unbalance factor does not exceed 2% for 95% of the time within a week [5].

Previous studies have concluded that PV battery systems only increase the grid's voltage unbalance in a worst case scenario. For a low voltage system with high PV penetration where all PV or PV battery systems are connected to the same phase, the above mentioned criterion is likely to be violated. Nevertheless, it was shown that PV battery systems lead to a more balanced voltage than PV systems without batteries. For the standard case in which the phase connections of different PV and PV battery systems are equally distributed over all three phases, no voltage balance violations occur [6].

Voltage rises

The even more interesting question for grid integration of PV storage systems is the voltage rise problem experienced in highly PV penetrated grid sections. The EN 50160 requires the average ten-minute r.m.s. of the voltage to not exceed +10% of its nominal value for the entire time [5]. The interconnection standard for distributed energy resources, VDE AR-N 4105, allows for a maximum 3% increase of the nominal voltage caused by a new PV system connecting to the grid [7].

Storage systems have the potential to shave off the peak of the PV feed-in and thereby ease PV grid integration. However, several studies have pointed out that the positive impact of a storage system highly depends on its operation strategy [6, 8, 9, 10]. In case of a strategy solely based on maximizing the self-consumption, the battery is likely to be fully charged before the PV feed-in reaches its peak on a sunny day. This implies that the storage system does not contribute to lower the PV feed-in peak.

Based on this review, different control strategies aiming to comply with the technical requirements and the economic goal of increasing the self-consumption are presented in the next section.

VOLTAGE CONTROL STRATEGIES FOR PV STORAGE SYSTEMS

To address voltage rises caused by PV systems, it is important to recapitulate the fundamentals behind a voltage rise. In most distribution systems the voltage angle is assumed to be small. In this case, the real part of the voltage rise $d\underline{U}$ over the grid impedance $\underline{Z}$ caused by the PV current $\underline{I}$ can be approximated as [11]:

$$\frac{d\underline{U}}{|\underline{U}_N|} = Re\left\{\frac{d\underline{U}}{|\underline{U}_N|}\right\} = Re\left\{\frac{\underline{Z}\cdot\underline{I}}{|\underline{U}_N|}\right\} \approx \frac{(P\cdot R)+(\pm Q\cdot X)}{|\underline{U}_N|} \qquad (1)$$

As equation 1 indicates, PV and PV storage systems are able to contribute to voltage control in two ways: active power P reduction or inductive reactive power Q consumption. Based on this, several voltage control approaches for PV systems are summarized below.

The German law and the interconnection requirements demand PV systems to comply with following rules:

The active power output should be limited to 70% of the installed PV capacity for systems under 30 kWp. Besides, reactive power should be provided depending on the active power output following a characteristic curve. This curve suggests linear reactive power provision for active power output within the range of 50%-100% of the installed capacity. It reaches its minimal power factor cosφ of 0.95 at maximal active power output [7].

PV storage systems usually operate as follows [9]:

- The battery is charged when the produced PV power exceeds the demand of the loads and the battery's state of charge (SOC) is less than 100%.
- The battery is discharged when the produced PV power is smaller than load demand and the battery is not empty.

The PV battery system tries to fulfil a maximum of the demand. The grid balances additional demand.

This operation ensures maximum self-consumption. Yet, it is missing a voltage controlling element. Hence, a new control strategy for PV storage systems is introduced. The $P_{Bat}(V)$-$Q_{PV}(V)$-$P_{PV}(V)$ control strategy tries to maximize self-consumption while also controlling the voltage. It has four modes depending on the grid voltage and the SOC [12]:

- Mode 1 (Standard operation): As long as the grid voltage is within its desired limits, the system follows the charging-discharging algorithm described above.
- Mode 2 ($P_{Bat}(V)$): If the voltage reaches its critical limit and the SOC is below 100%, the system starts charging the entire PV output into the battery. It reduces the power feed-in at the point of common coupling (PCC) to zero.
- Mode 3 ($Q_{PV}(V)$): The inverter starts to feed-in reactive power above a certain critical voltage level to lower the grid voltage again.
- Mode 4 ($P_{PV}(V)$): If the grid voltage stays above the critical level despite reactive power provision, the inverter starts to gradually reduce the active power output of the system.

The $Q_{PV}(V)$-$P_{PV}(V)$ part of the control strategy can of course also be applied to regular PV systems [11].

The process of the $P_{Bat}(V)$-$Q_{PV}(V)$-$P_{PV}(V)$ control strategy is schematically displayed in of Fig. 1.

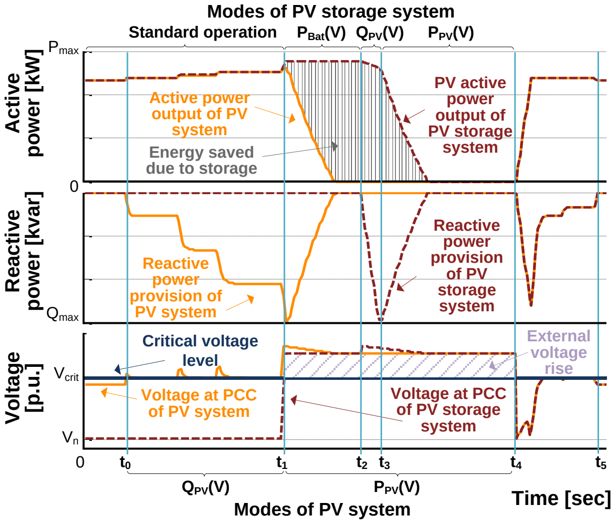

Figure 1. Schematic comparison of voltage dependent control strategies for PV and PV storage systems [12]

In this constructed example, both systems are analysed separately using the same generic input data. The rising PV power output of the PV system causes the voltage to exceed the critical threshold at t_0. The PV system starts to provide reactive power. Meanwhile, the PV storage system is still able to keep the voltage low, since it is still charging the battery with excess PV production. The load flow at its PCC is still zero, therefore the voltage does not go up with an increasing PV power output.

At $t_{1,}$ an external voltage rise forces the PV system to reduce its active power output, since the reactive power provision is not sufficient to stabilize the voltage anymore. In comparison, the PV storage system switches into mode 2. It charges all its PV output into the battery until the battery is fully charged. Here, the grey shaded area marks the amount of energy the PV storage system is able to store, while the PV system curtails this energy.

At t_2, first reactive power is supplied. Afterwards, at t_3, the active power is curtailed. Yet, in this example the external voltage rise is too high. The grid voltage stays above the critical level despite an active power reduction to zero. After the external voltage rise declines at t_4, both systems assist in lowering the voltage again by providing reactive power until the active power is back to its full output at t_5.

To evaluate the benefits for grid operators and PV storage system owners, the next section provides an analysis of the different control strategies based on grid simulations.

ANALYSIS

In this section a brief summary of the simulation assumptions is provided. Afterwards, the simulation results are analysed and the control strategies are benchmarked regarding to their ability to reduce voltage violations while maximizing self-consumption.

Simulation assumptions

The assessment of the strategies is based on a monthly r.m.s. grid simulation. The following input data is used:

- PV data and inverter model: From an annual 1-sec PV DC measurement data set, a sunny period from mid-June through mid-July 2010 is chosen. DC-power is then converted into AC power using an inverter model based on an efficiency curve as described in [13].
- Load profiles: Different high resolution load profiles are used based on the method developed by Fraunhofer IWES. For a chosen household type, the load profile is generated according to an aggregation of different appliance load profiles that are typical for such a household.
- Grid: A generic, rural grid consisting of two feeders with seven PCC each is used [6]. All PCC, except one, have a non-controllable PV system installed, yet the voltage is still within the limits of the EN 50160.

Now, a controllable 5 kW PV system is installed at the PCC at the end of one feeder. Several scenarios are simulated for the different control strategies. For the $Q_{PV}(V)$-$P_{PV}(V)$-strategy the power factor is varied between 0.80 and 0.95. Also, a battery varying in size between 4.4-13.2 kWh, with and without voltage control is simulated.

Assessment of control strategies

The benchmark of the control strategies breaks down into two parts, an energy analysis and a voltage analysis.

Energy analysis

Fig. 2 shows the energy losses the owner of the PV or PV battery system experiences under the different control strategies compared to a full feed-in PV system.

Three aspects have to be pointed out concerning the potential losses. The fixed active power limitation leads to the highest losses. A lower minimal power factor also decreases the losses for both PV and PV battery systems, since more voltage peaks can be mitigated through reactive power provision rather than immediate active power reduction. PV battery systems diminish the potential losses compared to voltage controlled PV systems. They are able to stabilise the voltage longer by storing the excess PV production as shown in Fig. 1. Additionally, the self-consumption was increased from approx. 15% with a PV system to around 43% using a battery system for the simulated month.

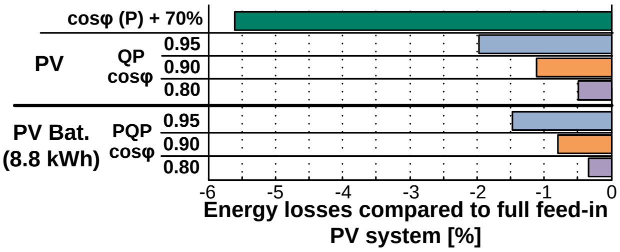

Figure 2. Comparison of energy losses for the PV or PV battery system owner due to improved grid integration [12]

Voltage analysis

The control strategies are benchmarked according to their ability to keep the voltage within the limits required by the guidelines. Fig. 3 shows how the voltage violations are distributed over different time intervals depending on the length of the violation. It is differentiated between the voltage at the PCC of the neighbour household of the controllable system and the voltage at the PCC the PV or PV battery system is connected to.

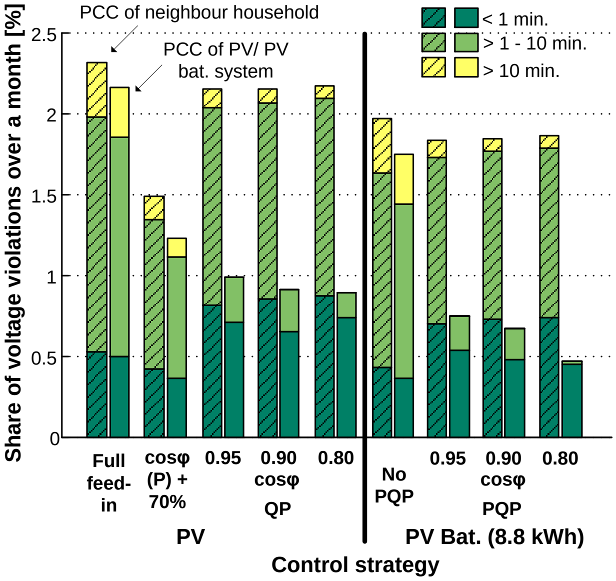

Figure 3. Voltage violations at the PCC of the neighbour household and at the PCC of the PV/ PV battery system for different control strategies [12]

Several outcomes have to be highlighted:

1) The EN 50160 is not fulfilled. Yet, the amount of the critical time intervals (over ten minutes, marked yellow) in which the voltage exceeds the allowed maximum is reduced by applying the presented voltage control strategies.

2) A fixed power limitation with reactive power provision based on active power output leads to the shortest time of violations overall at the PCC of the neighbour household. This is a result of the strategy's constant peak

shaving. Yet, the critical time intervals over ten minutes are longer compared to the other strategies.

3) The $P_{Bat}(V)$-$Q_{PV}(V)$-$P_{PV}(V)$ strategy for storage systems leads to the best results at the system's PCC. It erases the critical time intervals and decreases the overall number of voltage violations more than the $Q_{PV}(V)$-$P_{PV}(V)$ strategy for PV systems. Most peaks at the system's PCC are a result of transient effects of the controller. The controller reacts with a small delay to the voltage violation causing these short-term peaks.

4) At the system's PCC, a decreasing power factor allows for an even better performance. It decreases the number of events as well as their duration.

5) Conversely, at the PCC of the neighbour household the number of voltage violations increases with a decreasing power factor at the system's PCC. Here, only the short-term violations increase, the critical violations above ten minutes still decrease. This is a result of the different load demand profile used at this PCC. A higher power factor also implies that active power reduction reacts faster. Especially, in case of fluctuating voltages, this results in fewer transients caused by reactive power control.

The general weakness of the local voltage control also becomes visible. While the voltage violations are reduced locally, the grid might still experience problems in cases of higher voltage rises. Yet, voltage control of storage systems improves the voltage stability. In order for grid operators to benefit from that, they have to know the critical nodes in their systems and foster the use of voltage controlled storage systems at these PCC.

Sensitivity analysis for different battery sizes and different household types

Fig. 3 also indicates that a PV battery system under standard operation is able to reduce the time of voltage violations, but not the critical ten minute-intervals. To verify that this is not a result of an undersized battery or the used load profile, analyses with different type of load profiles and larger batteries are conducted.

The analyses show that higher battery capacities only increase the ability to mitigate voltage violations marginally. The consumption of an average four-to-five person household is not high enough to discharge the battery during the evening and the night. As a result, the full capacity is not available for charging the next day.

Furthermore, households with higher consumption during the middle of the day see a marginal decrease in voltage violations at the system's PCC and its neighbour's PCC when using PV battery systems. The general conclusions drawn above remain the same.

CONCLUSION

The market for PV storage systems is growing as the self-consumption becomes a more attractive business case. The paper outlined potential grid integration issues of which grid operators should be aware. To ensure an additional benefit for highly PV penetrated distribution systems, different voltage control strategies for PV and PV storage systems were introduced and assessed. The introduced $P_{Bat}(V)$-$Q_{PV}(V)$-$P_{PV}(V)$ control strategy provides a solution to handle the trade-off between curtailing energy and violating voltage guidelines. A high self-consumption under minimum voltage violations is achievable in the given analysed scenario using this strategy. Still, additional improvements are necessary to address the rather local voltage improvements of the strategy. Such could result from lowering the controller threshold at which voltage deviations are controlled. Further investigations will evaluate how such control strategies perform using different input data and when more than one system actively controls the voltage.

ACKNOWLEDGMENTS

The presented paper is based on research performed in the project 'PV-Integrated'. This project is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The authors take full and sole responsibility for the paper's content.

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