Local Voltage Control Strategies for PV Storage Systems in Distribution Grids

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***Abstract*—Local PV storage systems are emerging in Germany as PV feed-in tariffs have dropped below electricity prices for households. These PV storage systems provide the opportunity to increase the local consumption of locally generated PV energy. The so called self-consumption does not imply an explicit benefit for highly PV penetrated distribution grids suffering PV related voltage rises. Hence, this paper introduces several local voltage control strategies using PV storage systems. These strategies focus on adding a voltage control capability to self-consumption strategies through a combination of voltage dependent battery charging, automatic reactive power provision as well as PV power curtailment. Their potential to smooth the grid integration of PV while increasing self-consumption is assessed through grid simulations and an economic evaluation. In conclusion, PV storage systems which are capable of voltage control can improve PV grid integration and provide a benefit to storage system owners.**

***Index Terms*—Energy storage, grid integration, photovoltaic power systems, power distribution, voltage control.**

I. Introduction

DECENTRALIZED generation has experienced a strong growth over the last years in Germany. At the end of Aug. 2013, 34.8 GWp of photovoltaic (PV) systems were installed in Germany [1]. As nearly 70% of the PV capacity is connected to the low voltage level of the distribution grid [2], new challenges for distribution grids and its operators (DSO) arise. The high PV penetration of certain distribution grids is accompanied by voltage rises and reverse power flows from the low voltage (LV) back to the medium voltage (MV) level [3]–[6].

Additionally, economics of PV systems have changed since PV systems reached grid parity for many households in mid-2012 in Germany. Nowadays, self-consuming locally produced PV power is more beneficial than injecting it into the grid. Due to the discrepancy of PV generation and load demand, only a certain amount of self-consumption is achievable without changing a household's electricity demand behavior. However, self-consumption can be increased using electricity storage systems [7]. As the business case for local home-scale PV storage systems is emerging, more households consider investing in such a system rather than in a stand-alone PV system.

Nevertheless, increasing self-consumption does not necessarily imply a grid supporting PV feed-in, if storage systems are only used to save as much PV power as possible rather than to mitigate PV peaks which cause voltage rises [8].

Thus, this paper analyzes how different control strategies for PV storage systems can support increasing self-consumption while simultaneously minimizing PV induced voltage rises in distribution grids. To determine requirements for such control strategies, current market conditions for such systems are analyzed from an economic and a technical point of view. In addition, three new voltage control strategies for PV storage systems are outlined. These control strategies are then benchmarked through grid simulations and evaluated economically.

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II. Economic Market Development

Three main drivers foster the market for small-scale PV storage systems in Germany: decreasing feed-in tariffs (FIT), increasing electricity prices as well as an increasing number of available PV storage systems for the end customer market.

A. Legal Framework and Feed-in Tariff Development

Under the revised German Renewable Energies Act of 2012, PV systems ($< 30\ \mathrm{kWp}$) either have to permanently limit their active power feed-in to 70% of the installed PV capacity or be able to be remotely curtailed in case of system failure.

The FIT varies on a monthly basis from $+0.5\%$ to -2.8% of last month's FIT depending on the PV installation rate within the past year. PV installations are likely to increase by 3.7 GWp in 2013 in Germany [9]. This will result in a FIT of approx. 13 € $\mathrm{ct./kWh}$ for PV systems ($< 10\ \mathrm{kWp}$) by April 2014.

B. Electricity Prices

Electricity prices were at 28.50 € $\mathrm{ct./kWh}$ for an average household customer in Jan. 2013. The average increase has been around 5.7% p.a. since 2000 [10]. Thus, households are likely to pay approx. 30 € $\mathrm{ct./kWh}$ by the beginning of 2014.

C. Market for Storage Systems

The difference of 17 € $\mathrm{ct./kWh}$ between electricity prices and FITs describes the incentive of self-consuming locally produced PV power instead of feeding it into the grid directly. Storage systems aim at collecting this difference by enabling additional self-consumption. The market is targeted by over 40 suppliers. Common storage solutions are lead-acid or lithium-ion batteries. The batteries are designed to cope with a 5–6 kWp PV system for households. Their capacity varies from approx. 2–12 kWh. The prices still vary a lot and highly depends on the used technology and capacity. Yet, most suppliers currently offer their systems between € 10 000–€ 15 000 for a 5 kVA inverter with 4 kWh lithium-ion battery [11].

In May 2013 the German government introduced an investment incentive program for PV storage systems. Next to a soft loan, the program provides up to € 600 per installed kWp of PV power if a battery system is installed. One program obligation is limiting the active power flow over the household's grid connection to 60% of the installed PV capacity [12].

III. Challenges of PV Grid Integration

Storage systems offer a chance to mitigate PV related grid issues [13], such as voltage problems in distribution grids. A brief summary of applicable guidelines and theoretical background is provided in this section.

A. Guidelines

The most important guidelines relating to voltage rises are the EN 50160 for grid operation and the VDE AR-N 4105 which is the interconnection guideline for distributed energy resources such as PV systems for LV levels in Germany.

1) The EN 50160 requires the average ten-minute r.m.s. of the voltage either not to exceed $+10\%$ or to stay below $+15\%$ of the nominal grid voltage V_N for the entire time [14].
2) The VDE AR-N 4105 allows for a max. 3% rise of the voltage caused by PV systems in LV grids. It suggests that PV systems $(< 13.8\,\mathrm{kVA})$ provide reactive power Q either with a fixed power factor (PF) of 0.95 or following a characteristic curve. This curve contains a control deadband until 50% of the installed PV capacity is reached. Then, Q steadily increases with an increasing active power P up to a PF of 0.95 [15].

B. Voltage Rise

Equation (1) describes the voltage change dV over the grid impedance $\underline{Z}$ in case of PV current feed-in $\underline{I}$. Assuming the voltage angle is small, dV is mainly determined by the real part of the product of $\underline{I}$ and $\underline{Z}$[5].

$$\frac{dV}{V_N} = \frac{\underline{Z} \cdot \underline{I}}{|V_N|} = \mathrm{Re}\left\{\frac{\underline{Z} \cdot \underline{I}}{|V_N|}\right\} = \frac{(P \cdot R) + (\pm Q \cdot X)}{|V_N|^2}. \quad (1)$$

While $\underline{Z}$ is split into its resistance R and reactance X, $\underline{I}$ is denoted by its P and Q component. dV can be influenced from the grid side by changing the R/X-ratio or from the PV system's side by controlling P or Q supply. Consuming inductive reactive power $(-Q)$ or reducing P lowers the voltage V_{PCC} at the system's point of common coupling (PCC) [5]. The sensitivity of V_{PCC} towards Q or P depends on the grid's R/X-ratio.

IV. Control Strategies for PV Storage Systems

To fulfill the voltage guidelines, DSOs usually focus on influencing $\underline{Z}$ by conducting grid reinforcements, such as new lines or replacing the grid's transformer [5], [6]. In this study, the focus lies on performing local voltage control with PV or PV storage systems instead of implementing grid reinforcement measures. A short review of possible voltage control strategies for such systems follows. Afterwards, new voltage control strategies for PV storage systems are introduced.

A. Voltage Control Strategies Using PV Inverters

Voltage control using PV inverters by injecting Q_{PV} and/ or limiting P_{PV} have been discussed in the literature [5], [6], [16], [17]. The difference between most strategies is whether a static or dynamic approach based on local voltage measurements or current PV power output is used [5]. Table I summarizes the analyzed strategies for PV systems in this paper.

TABLE I
Analyzed Voltage Control Strategies for PV Systems

No.	Strategy	Description
PV 1	P_{PVmax}	- Full P feed-in: PV systems always injects P_{PV}; no Q_{PV} is provided.
PV 2	70%-P + PF(P)	- Fixed P-curtailment: P_{PV} is limited to a 70% of the installed PV capacity P_{STC} (under standard test conditions). - Q-provision according to a characteristic curve based on the VDE AR-N 4105, described in III. A. 2.
PV 3	Automatic voltage limitation (AVL)	- Voltage dependent dynamic Q_{PV} provision: above a predefined critical voltage threshold V_{thres} the PV system provides Q_{PV} to reduce V_{PCC}. - Voltage dependent dynamic P_{PV} reduction: if Q_{PV} provision is not sufficient enough to lower V_{PCC}, the PV system's P_{PV} output is reduced. As long as V_{PCC} stays above V_{thres}, P_{PV} is reduced further.

TABLE II
Analyzed Voltage Control Strategies for PV Storage Systems

No.	Strategy	Description
PVBat1	Stand. operation	- No voltage control
PVBat2	60%-P + PF(P)	- Fixed P_{PV} curtailment with Q_{PV} provision
PVBat3	P_{Bat}-Q_{PV}-P_{PV}	- Voltage dependent charging of the battery with priority on P_{PV}-charging
PVBat4	Q_{PV}-P_{Bat}-P_{PV}	- Voltage dependent charging of the battery with focus on Q_{PV}-provision
PVBat5	$P_{Bat}(P)$-Q_{PV}-P_{Bat}-P_{PV}	- P_{PV} -peak oriented and voltage dependent charging of the battery

The operation area of Q is limited by the allowed min. PF.

B. Voltage Control Strategies Using PV Storage Systems

Storage systems have the ability to address PV related voltage rises. So far most studies have investigated voltage control strategies using central storage systems [18]–[20]. However, the German business case nowadays relies on local PV systems with local storage systems. Previous studies regarding their grid integration have concluded that the technical benefit for the grid voltage is limited under standard operation. Most available systems charge their battery according to a simple rule-based algorithm, described in Section IV-B.1 Basically, the battery is charged when PV power exceeds load. Usually, an economically optimal sized battery reaches its max. state of charge (SOC) too early during the day to avoid the PV peak feed-in which causes voltage rises [8], [12], [21], [22].

Yet, storage systems provide an extra degree of freedom to support existing guidelines compared to stand-alone PV systems. Charging the battery according to V_{PCC} can improve grid integration of PV and PV storage systems. It enables a control approach allowing for increased self-consumption while improving grid voltage. Table II summarizes the investigated strategies for PV storage systems based on static and dynamic control using not only the PV inverter, but also the battery.

1) Strategy PVBat1 (Standard Operation): In this paper, P and Q are counted from a generator perspective, as shown in Fig. 1. Self-consumption can be increased using a rule-based control approach: If the residual load P_{res}, defined as the difference of P_{PV} and the absolute load demand P_{Load} in (2), is positive, the battery $P_{Bat,ch}$ is charged with P_{res} until the

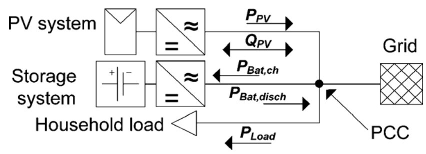

Fig. 1. Grid connection of PV storage system.

SOC reaches 100%. Vice versa, the battery $P_{Bat,disch}$ is discharged with P_{res}, if P_{res} is negative and the SOC is above 0%, as shown in (3) and (4). The SOC varies from 0–100%, where 100% is defined by the useable battery capacity.

$$P_{res} = P_{PV} - /P_{Load}/ \tag{2}$$
$$P_{Bat,ch} = -P_{res} \text{ if } SOC < 1 \text{ and } P_{res} > 0 \tag{3}$$
$$P_{Bat,disch} = /P_{res}/ \text{ if } SOC > 0 \text{ and } P_{res} < 0. \tag{4}$$

This control strategy serves as a reference case for the max. possible self-consumption, since P_{PV} is not curtailed and no Q_{PV} is provided. It does not incorporate a specific voltage supporting functionality. Q-supply using the battery inverter is neglected, the battery is only used for P-control.

2) Strategy PVBat2 (60%-P+PF(P)): Battery charging and discharging follow the logic of (3) and (4). Yet, the SOC influences the PV system's output. Once the battery is fully charged, P_{PV} is limited to 60% of P_{STC} plus P_{Load}, as shown in (5), to cope with the requirements of the storage incentive program, described in Section II-C.

$$P_{PV} = \begin{cases} P_{PVmax} & \text{if } P_{PV} \leq 0.6 \cdot P_{STC} \\ & \quad +/P_{Load}/ \\ 0.6 \cdot P_{STC} + /P_{Load}/ & \text{if } P_{PV} > (0.6 \cdot P_{STC} \\ & \quad +/P_{Load}/) \text{ and SOC} = 1. \end{cases} \tag{5}$$

P_{PVmax} describes the max. possible P_{PV}, whether Q_{PV} is supplied or not. Since the max. apparent power S_{max} of the PV inverter limits a simultaneous Q- and P-provision, following (6), P_{PV} might be curtailed in case of high Q-provision [5].

Q is provided with the characteristic curve described in 2) in Section III-A. It is also influenced by the inverter sizing.

$$\sqrt{P^2 + Q^2} \leq S_{\max}. \tag{6}$$

3) Strategy PVBat3 $(\mathrm{P_{Bat} - Q_{PV} - P_{PV}})$*:* To avoid constant Q-provision and fixed P-curtailment, the advantages of the battery's standard operation and voltage dependent control strategies for PV systems are combined.

In case V_{PCC} exceeds the voltage threshold V_{thres} and the battery is not fully charged, all of P_{PV} instead only P_{res} is charged into the battery, as shown in (7). The PV system's impact on V_{PCC} is completely off-set and P_{Load} helps to lower the voltage.

$$P_{Bat,ch} = \begin{cases} -P_{res} & \text{if } SOC < 1 \text{ and } V_{PCC} < V_{thres} \\ & \quad \text{and } P_{res} > 0 \\ -P_{PV} & \text{if } SOC < 1 \text{ and } V_{PCC} > V_{thres} \\ & \quad \text{and } P_{res} > 0 \\ 0 & \text{if } SOC = 1 \text{ or } P_{res} < 0. \end{cases} \tag{7}$$

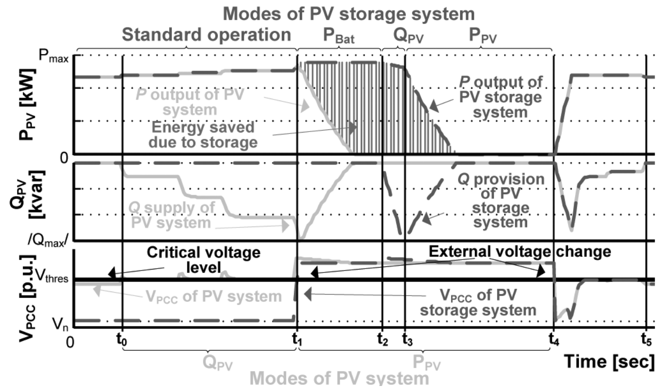

Fig. 2. Schematic comparison of voltage dependent control strategies for PV (strategy *PV3*) and PV storage systems (strategy *PVBat3*) [8].

If battery charging is not enough to lower V_{PCC} again, the PV system follows the AVL strategy *(PV3)*:

$$P_{PV} = \begin{cases} P_{PVmax} & \text{if } V_{PCC} < V_{thres} \\ P_{PVmax} & \text{if } SOC < 1 \text{ and } V_{PCC} > V_{thres} \\ & \quad \text{and} /Q_{PV}/ < Q_{PVmax} \\ P_{PVred} & \text{if } SOC = 1 \text{ and } V_{PCC} > V_{thres} \\ & \quad \text{and} /Q_{PV}/ = Q_{PVmax}. \end{cases} \tag{8}$$

P_{PVred} describes the limited P_{PV} after Q_{PV}-provision reaches its maximum.

$$Q_{PV} = \begin{cases} 0 & \text{if } V_{PCC} < V_{thres} \\ 0 & \text{if } SOC < 1 \text{ and } V_{PCC} > V_{thres} \\ -Q_{PV} & \text{if } SOC = 1 \text{ and } V_{PCC} > V_{thres}. \end{cases} \tag{9}$$

Discharging follows (4). Only in case of an overvoltage at the system's PCC, no discharging is allowed, as (10) shows. This enhances a grid-friendly behavior, since the power flow over the PCC is negative due to P_{Load} and thus lowers V_{PCC}.

$$P_{Bat,disch} = \begin{cases} /P_{res}/ & \text{if } SOC > 0 \text{ and } V_{PCC} < V_{thres} \\ & \quad \text{and } P_{res} < 0 \\ 0 & \text{if } V_{PCC} > V_{thres} \text{ or } P_{res} > 0. \end{cases} \tag{10}$$

The advantages of such a control strategy for a PV storage system compared to the AVL strategy *(PV3)* for PV systems are displayed in Fig. 2.

This constructed example shows, how PV inverter and PV storage system react to the same generic input data. Increasing P_{PV} causes V_{PCC} to exceed V_{thres} at t_0. The PV system starts to provide Q_{PV}. Meanwhile, the PV storage system is still able to stabilize V_{PCC}, since P_{res} is charged into the battery. The load flow over the PCC is zero, hence there is no impact on V_{PCC}.

At t_1, an external voltage rise leads to a reduction P_{PV} of the PV system, since the Q_{PV}-provision is not sufficient to stabilize V_{PCC} anymore. In comparison, the PV storage system switches into the next charging mode. It charges P_{PV} into the battery until a SOC of 100% is reached. In Fig. 2 the grey shaded area marks the energy the PV storage system is able to store, while a PV system without storage system has to curtail this energy.

At t_2, the PV storage system starts supplying Q via its PV inverter. Starting at t_3, P_{PV} of the PV storage system is additionally reduced, since V_{PCC} is still above V_{thres}. Yet, in this example the external voltage rise is too high despite a complete P-reduction. After the external voltage rise declines at t_4, both systems provide Q_{PV} until P_{PV} reaches its full output at t_5[8].

4) Strategy PVBat4 ($\mathrm{Q_{PV} - P_{Bat} - P_{PV}}$)*:* Since *PVBat3* might lead to an unnecessary fast battery charging in case of overvoltages and does not exploit the full potential of Q-provision, an approach, where first Q- and then P-management using battery and PV reduction, is applied.

If V_{PCC} exceeds V_{crit}, Q_{PV} is provided by the PV system:

$$Q_{PV} = \begin{cases} 0 & \text{if } V_{PCC} < V_{thres} \\ -Q_{PV} & \text{if } V_{Pcc} > V_{thres} \\ & \text{and } /Q_{PV}/ < /Q_{PVmax}/. \end{cases} \tag{11}$$

If V_{PCC} is not reduced sufficiently, charging the battery with P_{PV} is applied once the Q-provision reaches its max. Q_{PVmax}:

$$P_{Bat,ch} = \begin{cases} -P_{res} & \text{if } SOC < 1 \text{ and } V_{PCC} < V_{thres} \text{ and} \\ & P_{res} > 0 \\ -P_{res} & \text{if } SOC < 1 \text{ and } V_{PCC} > V_{thres} \text{ and} \\ & P_{res} > 0 \text{ and} /Q_{PV}/ < /Q_{PV\,\max}/ \\ -P_{PV} & \text{if } SOC < 1 \text{ and } V_{PCC} > V_{thres} \text{ and} \\ & P_{res} > 0 \text{ and} /Q_{PV}/ = /Q_{PV\,\max}/ \\ 0 & \text{if } SOC = 1 \text{ or } P_{res} < 0. \end{cases} \tag{12}$$

When the battery is fully charged and V_{PCC} is still too high, the P-reduction is applied, as described in (8). The discharging of the battery follows the concept already shown in (10).

5) Strategy PVBat5 ($\mathrm{P_{Bat}(P) - Q_{PV} - P_{Bat} - P_{PV}}$)*:* This strategy is more peak shaving oriented than the previous ones. Battery charging starts after a certain difference P_{diff} of P_{res} is surpassed, as shown in (13). Assuming that only during high P_{res} a high PV feed-in causes voltage rises, the battery is not charged with the first excess of P_{res} and thus reaches its max. SOC later during the day to avoid these rises.

$$P_{Bat,ch} = \begin{cases} -(P_{res} - P_{diff}) & \text{if } SOC < 1 \text{ and} \\ & V_{PCC} < V_{thres} \text{ and} \\ & P_{res} > P_{diff} \\ -P_{res} & \text{if } SOC < 1 \text{ and} \\ & V_{PCC} > V_{thres} \text{ and} \\ & P_{res} > 0 \text{ and} \\ & /Q_{PV}/ < /Q_{PVmax}/ \\ -P_{PV} & \text{if } SOC < 1 \text{ and} \\ & V_{PCC} > V_{thres} \text{ and} \\ & P_{res} > 0 \text{ and} \\ & /Q_{PV}/ < /Q_{PVmax}/ \\ 0 & \text{if } SOC = 1 \text{ or } P_{res} < 0. \end{cases} \tag{13}$$

If voltages exceed the threshold, first Q is provided, as shown in (11). Additionally, battery charging is switched to P_{res}. Afterwards, the logic of $\mathrm{Q_{PV} - P_{Bat} - P_{PV}}$ is applied again.

V. Simulation Assumptions

This section provides an overview of the input data, applied models and simulated scenarios used for the evaluation.

A. PV Data and Model

1-sec PV DC measurement data is used as input data for the PV systems. It was measured over the course of the year 2010 in Stuttgart, Germany; further details can be found in [23]. To cope with an acceptable simulation speed, the data is averaged

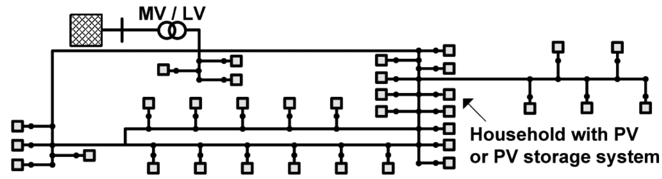

Fig. 3. Schematic of the used LV network.

to 1-min DC data. To incorporate inverter losses P_{losses}, the DC power is converted into AC power $\mathrm{P_{PV}}$ using (14) [24].

$$P_{losses} = c_{self} + c_v \cdot P_{PV} + c_r \cdot P_{PV}^2 \tag{14}$$

c_{self} stands for losses due to inverter self-consumption, c_v for voltage and c_r for current dependent losses. The inverters are sized to 90% of P_{STC}, following the proposed sizing in [25].

B. Load Model

High resolution load profiles are generated using measured power profiles of different household appliances P_{App} [26]. These are aggregated into a load profile for different households $P_{Load,k}$, as shown in (15).

$$P_{Load,k} = \sum_{i=1}^{n} P_{App,i} \cdot p_{time,i} \cdot b_{i,k}$$
$$for\ b_{i,k} = \begin{cases} 1 & \text{if appliance } i \text{ is part of household } k \\ 0 & \text{else} \end{cases} \tag{15}$$

p_{time} describes the probability that appliance i is turned on and b the existence of i in household type k. Twelve household types and their appliance portfolio are representative of the typical composition of the different German households [26].

C. Battery Model

As a battery model, an equivalent circuit model of a lithium-ion battery is used [27], [28]. The SOC is determined based on the charging current of the battery I_{Bat}. Simplifying an equivalent circuit model of battery to a voltage source V_{OCV} *(SOC)* and an internal resistance *R(SOC)* [28], I_{Bat} can be derived depending on the input power P_{Batin}, as shown in (16).

$$I_{Bat} = -\frac{V_{OCV}(SOC)}{2 \cdot R(SOC)} + \sqrt{\left(\frac{V_{OCV}(SOC)}{2 \cdot R(SOC)}\right)^2 + \frac{P_{Batin}}{R(SOC)}}. \tag{16}$$

$V_{OCV}(SOC)$ and *R(SOC)* are functions of the SOC and are modeled as characteristic curves which are derived from a battery data sheet [29]. The SOC is a function of I_{Bat} and the battery's nominal capacity C_n, as shown in (17).

$$SOC = SOC(0) + \int \frac{I_{Bat}(t)}{C_n} dt. \tag{17}$$

D. Distribution Grid

The analyzed LV grid is part of an existing distribution system in Southern Germany. It consists of 34 households as shown in Fig. 3. Further details can be found in [13].

E. Scenarios

To analyze potential benefits which voltage control supporting PV storage systems have, a highly PV-penetrated grid

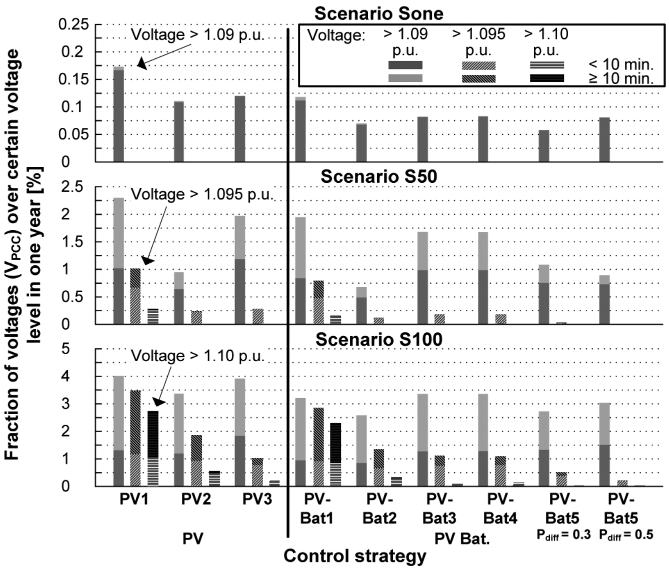

Fig. 4. Duration of voltage values over certain voltage level for different control strategies for PV and PV storage systems at most critical grid node (for systems with a 7.0 kWh battery and a $\mathrm{PF} = 0.8$).

is simulated. Its hosting capacity is determined and at each household's PCC a PV system of 11.4 kVA is installed. It is assumed that the voltage at the transformer's LV-side reaches 1.06 p.u. due to a PV penetration of the MV level. Under this set-up both guidelines can be fulfilled. Any further PV installation would violate the 3%-criterion and would exceed 1.09 p.u. as max. voltage. 0.01 p.u. is set as a safety buffer by the DSO to comply with the 1.10 p.u.-limit of the EN 50160.

Three different scenarios are simulated to determine the impact additional PV and PV storage systems have on the grid voltage, on the self-consumption and the PV feed-in.

First, one additional 5.5 kWp PV system is installed at the PCC with highest voltage. An annual grid simulation is performed for different strategies for PV systems with varying min. PFs (0.8, 0.9, 0.95). The simulation is repeated with a PV storage system with varying min. PFs and three effective battery capacities: 3.5 kWh, 7.0 kWh and 10.6 kWh. To cope with lifetime requirements of lithium-ion batteries the effective capacity is smaller than the nominal capacity. P_{Diff} is varied from 30–50% of the max. inverter output for strategy *PVBat5*.

The simulations are repeated with additional systems at 50% (scenario 50%) and 100% (scenario 100%) of the PCCs. Here, the focus is on analyzing how high PV penetration rates influence P-curtailment and self-consumption over all systems compared to the system at the most critical grid node.

VI. Evaluation and Assessment

First, the voltage control strategies are benchmarked by comparing their ability to support the mentioned guidelines. Next, an analysis on their economic performance follows.

A. Technical Evaluation

Fig. 4 displays the annual time fraction the voltage V_{PCC} at the most critical grid node exceeds a certain voltage level (1.09 p.u., 1.095 p.u., and 1.10 p.u.) for different control strategies. The critical node constitutes the node with the highest voltage measurements in all three scenarios. The controller's voltage threshold V_{thres} is set to 1.09 p.u. to ensure that V_{PCC} stays below the critical voltage V_{crit} of 1.10 p.u. Two voltage durations above the defined voltage levels are considered: voltages lasting less than 10 min. and longer than 10 min.

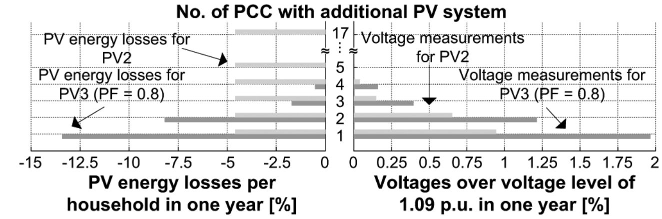

Fig. 5. Distribution of PV energy losses (left) and voltage measurements over threshold of 1.09 p.u. (right) over systems at different PCCs for S50.

For one additional system (Sone), all control strategies are able to support the EN 50160 requirements. Yet, the safety buffer of 0.01 p.u. is reduced. Especially, full feed-in strategies (*PV1* and *PVBat1*) as well as fixed P-curtailment strategies (*PV2* and *PVBat2*) are not able to reduce critical 10 min.-intervals over 1.09 p.u. The 3%-rise criterion is not fulfilled as the grid's host capacity is exceeded. Yet, voltage rises are immediately reduced by voltage dependent control strategies.

For scenario 50% (S50) V_{PCC} surpasses 1.10 p.u. for *PV1* and *PVBat1*. All other strategies are able to keep V_{PCC} below V_{crit}. The safety buffer is further reduced as static (*PV2*, *PVBat2*) and dynamic control strategies lead to periods over 1.095 p.u. Dynamic control strategies such as *PV3* and *PVBat3–5* significantly reduce voltages above this limit compared to a full PV feed-in (*PV1*, *PVBat1*).

For scenario 100% (S100) voltage violations occur for full feed-in and static strategies. Overshoots occur even for dynamic control strategies as the controller reacts according to V_{thres}. The controller's settling time leads to short periods over V_{crit} in this scenario. Yet, the EN 50160 is fully supported as the 10-min. averages of V_{PCC} are kept under 1.10 p.u. Here, peak shaving oriented strategies (*PVBat5*) have an advantage over *PVBat3* and *PVBat4*. The battery reserves more capacity for charging the peak feed-in. This leads to less PV current flow into the grid during times of high irradiation.

Due to the 1-min. time resolution of the simulation, averaging effects also result in higher voltages, as V_{PCC} fluctuates around V_{thres}. When comparing the time V_{PCC} is over 1.09 p.u., 1.095 p.u., and 1.10 p.u., longer periods of higher voltages decrease sustainably with an augmented voltage threshold. This indicates that voltage dependent control strategies reduce V_{PCC} efficiently.

The fixed P-curtailment (*PV2* and *PVBat2*) leads to a lower percentage of higher voltages than the other strategies. Here, all systems curtail the peak feed-in; whereas for the dynamic strategies not all systems curtail the peak but only the ones where V_{thres} is exceeded. Thus, more PV current is injected into the grid, which accumulates to additional voltage rises at the most critical node, as Fig. 5 shows for S50 (only strategies *PV2* and *PV3* are shown to simplify the graphic).

The analysis of the voltage distribution indicates that only a few PCCs experience higher voltages. The major difference between the two strategies is the number of systems contributing to voltage support. With strategy *PV2*, all systems reduce their active power output; with strategy *PV3*, only four systems achieve the same result. This underlines the effectiveness of dynamic voltage control strategies compared to static ones.

The impact of the battery size on high voltages is also analyzed. Furthermore, the max. allowed PV grid feed-in for

TABLE III
IMPACT OF BATTERY SIZE ON DURATION OF VOLTAGE VALUES OVER 1.095 P.U. FOR STRATEGY PVBAT2 AND PVBAT3 AT MOST CRITICAL GRID NODE FOR S100

No.	Limit of PV grid feed-in	Useable battery capacity		
		3.5 kWh	7.0 kWh	10.6 kWh
PVBat2	60% of P_{STC}	1.6%	1.3%	1.2%
	50% of P_{STC}	1.3%	1.1%	1.0%
	40% of P_{STC}	1.0%	0.8%	0.7%
PVBat3	-	1.2%	1.1%	1.0%

strategy *PVBat2* is decreased to assess the effectiveness of the fixed P-curtailment, as Table III shows.

Increasing the battery capacity slightly reduces the duration of high voltages. The effect saturates with larger sizes, since local load demand is not sufficient enough to discharge battery completely again during night time. Lowering the max. PV grid injection to 50% or 40% of P_{STC}, as described for *PVBat2* in Section IV-B, has a similar impact reducing the duration of high voltages as increasing the battery capacity. In comparison to dynamic control, here *PVBat3*, an improvement can be seen if PV grid feed-in is limited to max. 40% of P_{STC}.

In summary, several outcomes are to be highlighted:

1) PV storage systems reduce voltage levels compared to stand-alone PV systems, since less P_{PV} is injected into the grid. The battery size and the PF influence voltage rises: a bigger battery and a lower PF further reduce voltage rises.
2) Voltage dependent control strategies support the limitation of PV related voltage rises. These strategies can entirely remove the critical 10-min. voltage rises. V_{thres} has to be set under V_{crit} to fully support the EN 50160. Depending on the PV penetration of the grid, V_{thres} can be set closer to 1.10 p.u.
3) P-curtailment strategies (*PV2* and *PVBat2*) are only able to reduce higher voltages up to a certain PV penetration of the grid. A combination of peak-oriented approaches with dynamic voltage support, as in *PVBat5*, provides a good alternative.
4) When comparing strategies *PVBat3* and *PVBat4*, both strategies lead to similar results. Hence, a clear advantage of first charging the battery or providing Q is not distinguishable.

B. Economic Assessment

One of the main drivers for local PV storage systems is the increase of self-consumption. An evaluation of the control strategies regarding their abilities to increase self-consumption and to minimize PV energy losses resulting from P-curtailment and Q-provision is necessary. The left part of Fig. 5 displays PV energy losses related to voltage control for S50. While fixed P-curtailment strategies (e.g., *PV2*) cause constant losses at all nodes, dynamic control strategies (e.g., *PV3*) only lead to losses at nodes which experience voltages above V_{thres}.

The distribution of PV energy losses and the contribution of different systems towards voltage control possess a direct economic impact on the profitability of a PV storage system. Its owner needs to decide whether to favor a static or dynamic voltage controlling system to maximize the system's profit as a limited PV feed-in reduces the potential value. Fig. 6 shows the PV energy losses each system experiences compared to the overall losses depending on the control strategy for S50.

While a fixed P-curtailment leads to an even distribution of losses over all systems, for the dynamic strategies (e.g., *PV3,*

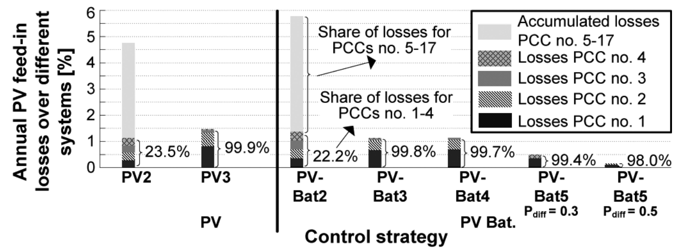

Fig. 6. Distribution of PV energy losses over different PV systems and PV storage systems depending on the control strategy for S50.

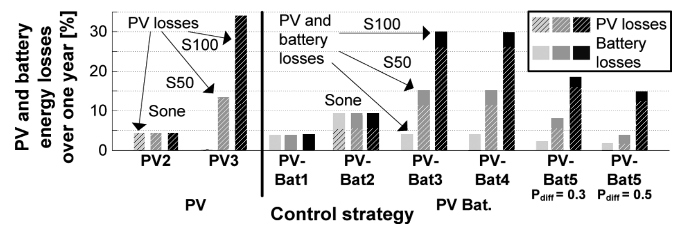

Fig. 7. Overall losses related to PV curtailment and battery losses for the different control strategies over all scenarios at the most critical node (system configuration: 7.0 kWh battery and $\mathrm{PF} = 0.8$).

TABLE IV
ASSUMPTIONS FOR NET PRESENT VALUE ANALYSIS BASED ON SECTION II-C

Scenario	Elect. price	FIT	Annual increase rate of elect. price	Discount rate
Best case	30 €ct./kWh	13 €ct./kWh	5%	3%
Neutral case	30 €ct./kWh	13 €ct./kWh	2%	6%

PVBat3–5) the system at the most critical node incorporates the highest share of losses. This results in lower benefits for the system owner at this PCC, since the losses account for about three times PV energy compared to *PV2* or two times more PV energy compared to *PVBat2* in this scenario.

An uneven distribution of losses over the different systems increases with higher PV penetration. This implies potentially higher losses for the system at PCC no. 1, as shown in Fig. 7.

While for low PV penetration rates, voltage control related PV losses are lower for dynamic control strategies (e.g., *PV3*), they tremendously increase for the system at the most critical node with an increasing PV penetration. Voltage control related PV losses decrease when using a PV storage system (e.g., *PVBat3*). Strategy *PVBat5* leads to lower PV losses than the other strategies for the two high PV penetration scenarios.

Yet, additional losses of PV energy are experienced due to charging and discharging of the battery. These losses are similar for the different scenarios and only decrease when the full potential of the battery is not used, e.g., for strategy *PVBat5*.

To assess the economic impact of losses and increased self-consumption, a net present value (NPV) analysis is performed based on assumptions shown in Table IV. The systems are assumed to be operated over 20 years using the same load and PV profiles. A yearly 1%-efficiency drop in PV generation and battery usage is adopted.

The financial value of the PV or PV storage system is determined for each control strategy and scenario by calculating the net present value of the cash flow received from PV grid injection and of the saved electricity costs resulting from self-consumption. PV feed-in is valued with the fixed FIT, while self-consumption is valued with the increasing electricity price. The discounted sum describes the value added that a PV or PV storage system potentially creates for its owner. It is equal to the

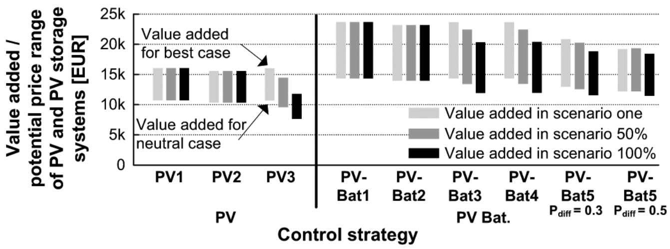

Fig. 8. Value added range of PV and PV storage system for different control strategies for household at most critical voltage node (system configuration: 7.0 kWh battery and $\mathrm{PF} = 0.8$).

minimum cash flow the owner expects to receive to finance the investment and reach a break-even point. Thus, the value added describes the owner's willingness to pay for a PV or PV storage system. By calculating the value added for best and neutral case a price range for a given system with a certain control strategy can be obtained. This value added range, and thus price range, for different control strategies and scenarios for the system no. 1 is displayed in Fig. 8.

Three findings have to be pointed out:

1) Depending on the control strategy and the scenario the value added of a PV storage system increases by € 1.8k–€ 7.6k for Sone, € 2.2k–€ 7.6k for S50 and € 2.8k–€ 7.6k for S100 compared to a stand-alone PV system. To compare these results to the price range described in Section II-C, one has to subtract the investment incentive from the PV storage system's price range; in this case € 3.3k. Thus, a positive investment decision is possible for this household. The best case scenario increases the possibility of investing into a PV storage system rather than into a stand-alone PV system. This emphasizes the importance and sensitivity of the analysis towards changes in electricity prices, as they determine the value of increased self-consumption enabled through the battery.
2) An increased PV penetration in S50 and S100 leads to a reduction of the value added for dynamic control strategies such as *PV3* and *PVBat3*. Thus, the willingness to pay decreases by € 1.5k (€ 2.6k) for the PV system and € 1.2k (€ 2.1k) for the PV storage system for S50 (for S100) compared to the price range in Sone for these two strategies. Here, PV storage systems help maintaining a higher value added as the reduction is not as steep as for PV systems. Static strategies such as *PV2* and *PVBat2* do not experience these reductions, as they are not subject to voltage dependent P-curtailment.
3) Despite lower PV losses of peak-shaving oriented strategies such as *PVBat5*, a decreased self-consumption reduces their potential value added. For a stand-alone PV system self-consumption is at 22.5% for PCC no. 1. By adding a 3.5 kWh battery it increases to 41.3%, for a 7.0 kWh battery to 51.8% or for a 10.6 kWh battery to 55.7% for this household. Only, *PVBat5* has different self-consumption rates, since it charges less P_{PV} into the battery. Here, self-consumption varies between 31.3–43.1% for $P_{diff} = 0.3$ and 30.5-39.1% for $P_{diff} = 0.5$. It even increases for S50 and S100 as voltage control related charging happens more frequently with higher PV penetration.

An analysis regarding the value added of different battery capacities is performed, as shown in Table V. Again, the impact of varying the fixed PV feed-in limit is also displayed.

TABLE V
IMPACT OF BATTERY SIZE ON VALUE ADDED RANGE FOR STRATEGY PVBAT2 AND PVBAT3 AT MOST CRITICAL GRID NODE FOR S100

No.	PV limit	Useable battery capacity		
		3.5 kWh	7.0 kWh	10.6 kWh
PVBat2	60%	€12.6k - €20.3k	€14.0k - €23.2k	14.5k - €24.3k
	50%	€12.2k - €19.8k	€13.7k - €22.8k	14.2k - €23.9k
	40%	€11.7k - €19.3k	€13.3k - €22.3k	13.8k - €23.5k
PVBat3	-	€10.2k - €17.0k	€11.9k - €20.3k	12.7k - €21.7k

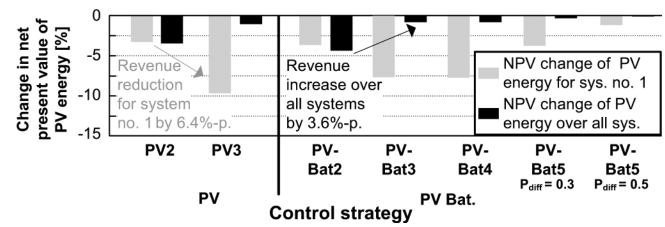

Fig. 9. Change in NPV of PV energy for all PCCs with add. systems and for PCC no. 1 for S50 (system configuration: 7.0 kWh battery and $\mathrm{PF} = 0.8$).

Since higher battery capacities enhance self-consumption the value added also increases. Yet, scaling the system from a 7.0 kWh to a 10.6 kWh battery only marginally augments the potential price range. Thus, an investment into higher sizes is unlikely in this example. Lowering the allowed max. PV grid feed-in decreases the potential value added slightly, since less PV production can be sold to the grid.

In most cases, the reduction in value added decreases the possibility of a positive investment decision. A trade-off between a voltage friendly behavior and increased PV grid feed-in becomes visible for dynamic control strategies. While these strategies sustainably stabilize the voltage as shown in Section VI-A, they entail reduced potential cash flows with an increasing PV penetration for the owners of such PV or PV storage systems. Thus, households connected to critical nodes prefer investing in systems operated with fixed P-curtailment which limit their risk exposure to reduced PV feed-in.

At large, the value of the total reduced PV energy of all systems determines whether it is favorable to implement fixed P-curtailment or dynamic voltage control strategies. Thus, the NPV of the reduced PV feed-in has to be determined. To enable a comparison between losses of the system at PCC no. 1 and losses over all systems, the NPV change is calculated by using the NPV of a full feed-in system as a basis. These changes are displayed for all strategies in Fig. 9.

Due to its voltage control PCC no. 1 experiences a decrease in potential revenue of -6.4%-points when switching from PV2 to PV3, while at the same time the NPV of PV energy of all systems increases by 2.4%-points. With storage systems the decrease is not as steep for PCC no. 1, but still -4.1%-points of potential revenues from PV feed-in are lost when shifting from *PVBat2* to *PVBat3*. Simultaneously, the overall NPV increases by 3.6%-points. Thus, an incentive should be set for PCC no.1 to implement dynamic voltage control as it implies a higher overall benefit in this example. In general, this is a viable option as long as a potential compensation for all voltage controlling systems is lower than the potential savings of the other households. As this analysis and previous results suggest (see Fig. 6), this is the case in this example.

VII. CONCLUSION

As self-consumption becomes a more attractive business case the market for PV storage systems is growing. Hence, this paper outlined the potential PV storage systems have for mitigating PV related voltage rises. Different voltage control strategies for PV and PV storage systems were introduced and assessed. Dynamic voltage dependent control strategies for PV storage systems offer a high potential to handle the trade-off between curtailing energy and violating voltage limits.

A high self-consumption under minimum voltage violations is achievable in the given analyzed scenarios using the proposed strategies. When implementing voltage dependent control strategies the critical voltage threshold has to be chosen carefully to entirely support the existing guidelines. From an economic point of view, the overall PV energy losses of all systems could be minimized when using dynamic instead of static control strategies. Yet, the benefit for the system owner at the most critical voltage node might be reduced. Therefore, to foster the implementation of voltage dependent control strategies for PV storage systems to increase the PV hosting capacity of LV grids, mechanisms to share the costs among all system owners need to be examined in further investigations.

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