Grid Influences from Reactive Power Flow of Photovoltaic Inverters with a Power Factor Specification of One

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ABSTRACT
The quantity of installed photovoltaic (PV) systems in the German distribution grid is still increasing. In some areas the installed PV capacity exceeds 5.0 kW_p [SPR-13a] per house connection (HC). Therefore the load flow changes its characteristics and leads to new requirements for grid dimensioning. In some areas the power feedback is higher than the delivery and the installed PV capacity becomes the decisive factor for grid planning. This article discusses unintended reactive power flows of PV inverter systems. The focus hereby is on the power factor (PF) specification of one. Hence these PV inverters should feed-in only active and no reactive power into the grid. Various observations in low voltage grids show a dispersion of the active and apparent power feed-in and thus a reactive power flow. To investigate these unintended reactive power flows, numerous commercially available inverters in the single and double digit kilowatt range are analyzed. Every single inverter with a power factor specification of one shows a reactive power flow. Finally it is proved, that there is an influence of the unintended reactive power flow on the grid voltage and grid losses. This influence has to be considered in grid planning and power system management.

Keywords: Grid Integration, Photovoltaic, Reactive Current

1 INTRODUCTION

The produced energy of photovoltaic (PV) systems represents a growing part of the electricity supply in Germany. In June 2014 more than 36.7 GW_p [BNA-13] were installed, most of them in Southern Germany. In 2013 PV systems produced 29.7 TWh, corresponding 5.2 % of the German electricity demand. New challenges to guarantee the required network stability and power quality come up due to this high PV penetration. The massive build-up leads to unknown grid conditions, especially in the low and medium voltage level. Furthermore high power feed backs from the low voltage to the medium and even the high voltage-level as well as lifted voltages at feeders with low short circuit powers occur. These voltage deviations have to stay within the normative boarders of the DIN EN 50160 [DIN-50160] of $\pm 10\%$ of the rated grid voltage and have to fulfill the application guide line VDE-AR-N 4105 [VDE-4105] that permits a maximum voltage hub of 3% in low voltage grids. With a view to the voltage stability, PV inverters of the newest generation are able to consume and supply reactive power in order to control the voltage at the grid connection point. In comparison to the reactive power specifications defined in [VDE-4105], the behavior of PV inverters with a nominated pure active power feed-in is not entirely clear. Most of the nowadays installed PV inverters do have this power factor (PF) specification. These inverters are considered in this paper.

2 FUNDAMENTALS

All active, reactive, and apparent power flows in this article refer to the 50 Hz component. The reactive power distortion of inverters with a power factor specification of one can be neglected. This shows a comparison between the 50 Hz component and the total reactive power. The differences between the 50 Hz component and the total reactive power flow are lower than 5 VAr. Therefore, the power factor regarding [IEC-60146] is identical to the power factor of the fundamental wave and the displacement factor. In the following discussion the term "power factor" (= cosφ) is used. In this article, unintended reactive power means reactive power injected/consumed by inverters with a power factor specification of one ($\cos\varphi = 1$). The analyzed inverters do have no dynamic VAR compensators as described in [TUN-11], [CAG-11], [JAH-13]. The reasons for the unintended reactive power flow are the LCL grid filters of the installed inverters. On the input side of these filters (equal to the output side of the bridge) no reactive power flow occurs. Depending on the current through the filter a reactive power flow originates. Consequently the power factor at the grid connection point is no longer one.

Section 3 describes the behavior of the unintended reactive power flow of various PV inverters with a power factor specification of one. In Section 4 a comparison between different inverters is realized. Section 5 and 6 show a simulation of the influences of unintended reactive power flow on grid voltage and grid losses. Finally, Section 7 summarizes the results.

3 CHRACTERIZATION

Measurements in the laboratory of the University of Applied Sciences and field measurements in a project area ("Grid of the Future" [BAY-14]) with high PV penetration deliver the same results: Inverters with a power factor specification of one contribute to unintended reactive power flow in the grids. Thus the question how these reactive power flows can be characterized has come up. As the reactive power flow depend on the amplitude of the irradiation and therefore on the stage of utilization [SPR-13b] this characteristic should be quantified. The result of the majority of the inverters is a linear dependency and therefore a direct proportionality with a positive or negative gradient. These inverters can be allocated a best-fit polynomial of the first degree.

Figure 1 displays the active and reactive power flow of one exemplary inverter over five days. A high capacitive reactive power flow in the night is clearly visible, because of the grid filters that do not disconnect. The capacitive reactive power flow starts to reduce as soon as the inverter starts the synchronization with the grid. If the inverter reaches approximately 60% of its nominal power the reactive behavior changes and becomes inductive. There is a direct proportionality with a negative gradient between active and reactive power. The reactive power of this inverter leads to a voltage reducing effect in full load operation.

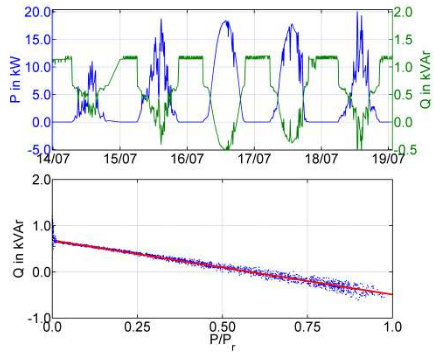

Figure 1: Active and reactive power flow of one exemplary inverter over five days. The lower graph shows the correlation between active and reactive power.

Another exemplary inverter as shown in Figure 2 has an opposed characteristic. Also this inverter performs like a capacitor during the night. By starting the synchronization with the grid, the reactive power jumps in a lower capacitive range and starts to follow the active power. The inverter works like a capacitor again. In full load operation approximately 400 VAr of capacitive power emerge. Hence this inverter has a grid voltage boosting effect in full load operation due to the reactive feed-in. The reactive power best-fit line is not able to describe the behavior during a deep part load operation.

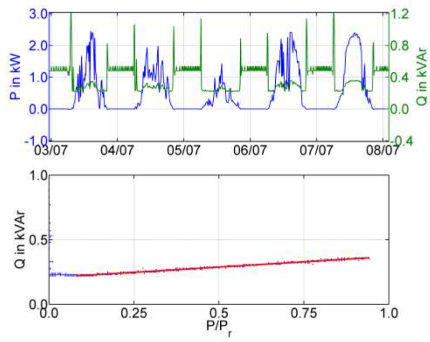

Figure 2: Active and reactive power flow of another exemplary inverter over five days. The lower graph shows the correlation between the active and reactive power.

Beside the proportional behavior of the majority of the analyzed inverters, the measurement values express also some inverters without a linear correlation. Figure 3 shows an exemplary course of the active and reactive power over five days. A reactive power best-fit polynomial of the first degree (red) can approximate this dependency deficiently. A more sufficient approximation of the unintended reactive power flows delivers a reactive power best-fit polynomial of the third degree (green).

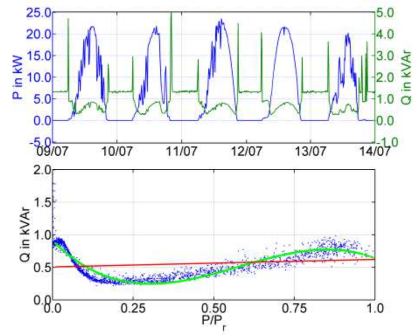

Figure 3: Active and reactive power flow of a further exemplary inverter over five days. The lower graph shows the correlation between active and reactive power.

4 COMPARISON

For each inverter the reactive power best-fit polynomial of the first degree for the day with the highest active power feed-in in 2011 (2011-05-09) is compiled. Figure 4 summarizes this polynomial in dependency of the gradient and the y-intercept (reactive power during no active power feed-in) (left part) as well as in dependency of the gradient and the reactive power in full load operation (right part) for one exemplary low voltage grid. The size of the marker represents the quotient of the reactive power in full load operation of each specified inverter and the sum of all reactive powers in full load operation (left) as well as the maximum reactive power flow of the specified inverter (right). Inverters with a maximum reactive power in the capacitive range are described by circles; in the inductive range a rectangle is used.

Figure 4 displays a low voltage grid (630 house connections) with 24 measured PV systems. The mean reactive power of all 24 systems is slightly inductive and amounts to 15 VAr. There is one 10 kW system with 4.8 kVAr inductive reactive power in near full load operation. This power is equal to more than 50% of the unintended reactive power due to PV systems. The quotient of the reactive power in full load operation and the sum of all reactive powers in full load operation varies for the 24 inverters between 0.25% and 56.4% with an average of 5.2%.

The exemplary low voltage grid has an inductive medium reactive power flow in full load operation. This means the grid voltage should be decreased due to the unintended reactive power flow. On the other hand there are some inverters that are capacitive in full load operation and boost the grid voltage. Hence, there must be areas in the grid with increased and areas with decreased grid voltages due to the unintended reactive feed-in.

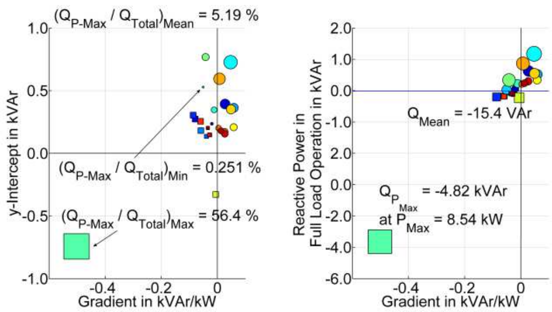

Figure 4: Comparison of diverse inverter types for the day with the highest active power feed-in for one low voltage grid. Each marker represents the approximate path of the reactive power in dependency on the active power. Circles indicate a maximum reactive power in the capacitive range; rectangles in the inductive range.

The markers of one inverter for all days (not shown in Figure 4) lie closely together for the majority of the inverters. These are the markers representing inverters with a strongly pronounced proportionality. Is there a divergence of the markers, the proportionality is not so solidly pronounced. This is for example the case for the inverter displayed in Figure 3. Nevertheless most inverters confirm the linear dependency quite well.

The empiric correlation coefficient (r) can be used for the evaluation of the excellence of a linear approximation. This coefficient is a measure of the quality factor (Q factor) and describes how well a random point cloud can be illustrated by a best-fit line. The closer the coefficient reaches one; the better is the approximation by a straight line. The number of measured values (n), the average value ($\bar{x}, \bar{y}$ see Equation (2)) and the standard deviation (s_x, s_y see Equation (3)) of the point cloud are necessary for the calculation of the empiric correlation coefficient according to Equation (1).

$$r = \frac{\frac{1}{n-1} * \sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{s_x * s_y} \quad (1)$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \text{ and } \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \quad (2)$$

$$s_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \text{ and } s_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \quad (3)$$

The empiric correlation coefficient of the inverters for various low voltage grids is displayed in Figure 5. 79% of the investigated inverters evoke coefficients between 0.9 and 1.0. Thus a linear approximation is quite good for these inverters and the reactive power flow can be estimated out of the active power via a reactive power best-fit polynomial of the first degree. However, 9% of the analyzed inverters do have correlation coefficients smaller than 0.7. For these inverters the linear approximations are not adequate and reactive power best-fit polynomials of a higher degree should be applied.

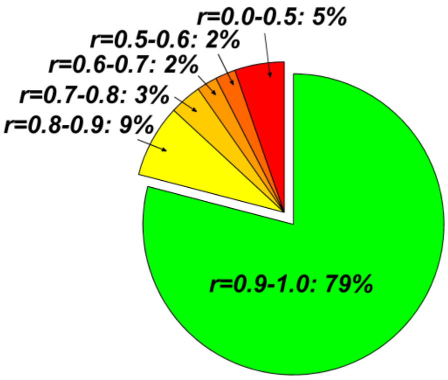

Figure 5: Empiric correlation coefficient to evaluate the quality factor (Q factor) of the linear dependency of the reactive power on the active power. Values close to one express good linear approximations.

5 SIMULATION OF THE GRID VOLTAGE

PV inverters with a power factor specification of one contribute to a reactive power flow in the grids. All power flows do have an impact on the grid voltage. The most interesting scenario is the full load operation. In distribution grids with a high PV penetration the voltages at long feeders with PV are enhanced. An additional capacitive behavior can lead to even higher voltages that reach a critical range. In comparison has an inductive consume in full load operation a voltage reducing effect and mitigates the voltage problems.

In the following the variation of the grid voltage in one exemplary low voltage grid (Nominal Voltage - $V_N = 0.4$ kV), introduced in Section 4, during full load operation with and without the unintended reactive power flow will be presented. Therefore the active and reactive power flows of the day with the highest active feed-ins in the year 2011 were chosen (2011-05-09). The input parameters of the simulation are the active and reactive power flows of all measured PV systems in the selected low voltage grid in a ten minute interval. The total capacities of all PV systems in the low voltage grid amount to 670 kW divided on 71 PV systems. The input data is available for 24 PV systems. For these systems the real measured powers are deposited into the network simulation tool PSS®SINCAL [SIN-13]. Out of the measured active power a normalized average value for the active feed-in for the whole day is calculated. This normalized profile multiplied with the rated power of the remaining PV systems is the input data of all non-measured PV systems. The reactive power of the non-measured PV systems is calculated in three different ways: The first way (C1 - Mean) is an average reactive power out of all measured reactive power flows. In the second calculation (C2 - Ind) the course of the PV system with the maximum inductive power flow is divided by the rated active power of this system. This course is then multiplied by the rated power of the non-measured systems and finally the specific system assigned. The third way (C3 - Cap) is similar to the second by using the maximum capacitive power. Inverters with lower rated powers can produce higher reactive power flows. Normally, PV inverters with a higher rated power do have higher reactive power flows. This correlation takes the calculation ways two and three into account. Therefore the calculation ways two and three are worst case simulations.

The structure and parameters of the simulated low voltage grid are known and available in the network simulation tool. All simulations and calculations are done with and without the unintended reactive power flow of PV inverters with a power factor specification of. The low voltage grid is connected to the overlaid medium voltage grid. All connections between this medium voltage grid and other low voltage grids do have a constant load and supply and therefore no day-courses of the power flows. The loads in the analyzed low voltage grid are chosen for a low-load-scenario [KER-11] and are constant over the whole investigation period.

Figure 6 displays the results of the grid voltage on all nodes in the low voltage grid with and without reactive power for the timestamp with the highest active power feed-in for the calculation way C1 - Mean. Therefore the difference between the two calculations is exposed. The color bar displays the relative voltage change (Δv_{rel}) in % according to Equation (4).

$$\Delta v_{rel} = v_{with\,Q} - v_{without\,Q} \quad (4)$$

Blue areas symbolize regions with decreased voltages by applying the unintended reactive power flows whereas red regions describe increased voltages.

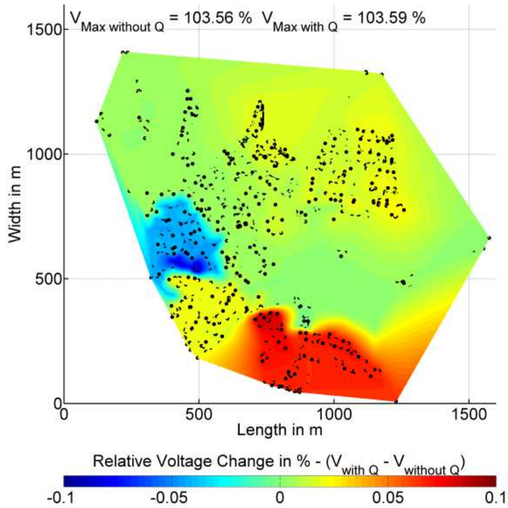

Figure 6: Comparison of the grid voltage in near full load operation of the PV systems with and without the unintended reactive power flows of PV inverters with a power factor specification of one for the simulation variant C1-Mean.

Figure 6 visualizes the distribution of the voltage on all nodes in the low voltage grid with eleven local network areas. The black points represent the grid nodes. The grid is posed in the correct position. The annotation of the axes describes the geographical extent of the grid. By means of the changing colors the borders of some local

network areas are clearly visible. As shown in Figure 4, there is one inverter with a strong inductive behavior. This inverter reduces the voltage in the dark blue colored network area. The maximum reduction is around 0.5 V. The borders of this network area are clearly visible. The area in the southeast from the blue one depicts a slight voltage hub. This is the area where the node with the maximum voltage is located. Therefore this voltage is increased by applying the unintended reactive power flows. The highest voltage hubs occur in the southern-most network area and amount up to 0.5 V. The voltages in the other local network areas remain nearly constant.
The analysis of Figure 4 and Figure 6 is done for two more low voltage grids. These grids do have an installed PV capacity of 700 and 780 kW and are also highly PV penetrated. Summarized, all three low voltage grids do have an inductive overall attitude. Nevertheless the voltage range reflections are quite different. A compilation of the maximum voltage with and without the unintended reactive power flows for the three distribution grids is exposed in Table 1. The influence of the voltage depends strongly on the distribution of the different PV inverters. An inductive overall behavior of a low voltage grid does not automatically mean that the maximum voltage of this grid is reduced. On the contrary, these simulations show an even bigger voltage spread in the distribution grids due to the unintended reactive power flows.

Table 1: Maximum relative grid voltages with and without the unintended reactive power flow of the three low voltage grids for the three simulation variants.

		C1-Mean	C2-Ind	C3-Cap
Distribution Grid One	**P**	103.56%	103.56%	103.56%
	P, Q	103.59%	101.83%	103.71%
Distribution Grid Two	**P**	106.56%	106.56%	106.56%
	P, Q	106.51%	106.00%	106.67%
Distribution Grid Three	**P**	103.98%	103.98%	103.98%
	P, Q	103.99%	103.95%	103.99%

The simulation ways C2 - Ind and C3 - Cap are worst case scenarios. In C2 - Ind, the maximum inductive power nominated to the respective inverter power for all non-measured PV systems is applied. Consequently the voltages are declined. C3 - Cap is similar to C2 - Ind by applying the maximum capacitive inverter power. Table 1 displays the results of the maximum voltages for the three analyzed low voltage grids. The relative voltages on all nodes of the distribution grid introduced in Section 4 for the scenario C2 - Ind and C3 - Cap for the timestamp with the highest active power feed-in are shown in Figure 7. The reduction of the maximum voltage for the scenario C2 - Ind to 101.83 % is quite huge because of one strong inductive inverter (Figure 4) and the influence of this inverter on all non-measured inverters. This system consumes more inductive reactive power than half of the active feed-in. In the third distribution grid the maximum inductive and capacitive powers are much lower than in the first and second. That is the reason why the voltage changes between the three different simulation ways are marginal (Table 1).

6 SIMULATION OF THE LOSSES

Figure 8 exposes the influence of the unintended reactive power flow on the grid losses. For a worst case estimation, the simulation way C2 - Ind (upper part of Figure 8) for the low voltage grid according to Figure 4 and Figure 6 is taken into account and described in the next paragraphs. Simulation way C1 - Mean can be seen on the lower part of Figure 8.

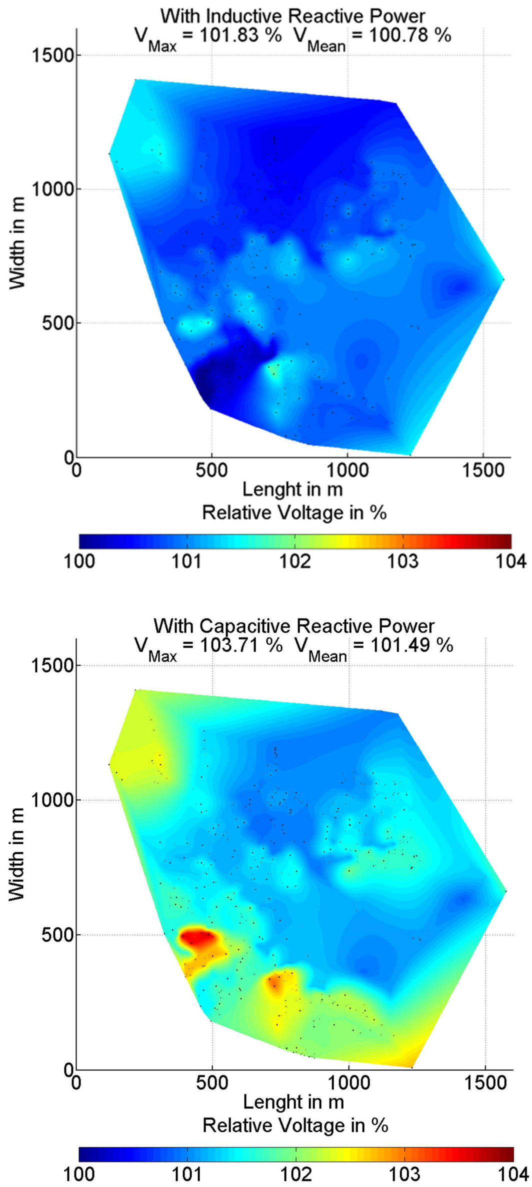

Figure 7: Relative voltages on all grid nodes for the simulation scenarios C2 – Ind and C3 – Cap.

The first row shows the results of the cable and transformer losses simulation in the complete medium voltage grid (including the underlying low voltage grids) without reactive power of PV inverters. Therefore displays the bar chart the probability density of the losses over one complete year of investigation (2011). The mean value of all losses sums up to 113.35 kW. The maximum value occurred on a sunny spring day and is as high as 121.93 kW. In more than half (55%) of the investigation period are the losses around 112 kW. This is the case if no PV feed-in arises. The highest losses of more than 120 kW can be obtained on clear sky early-summer days.
The second row displays the cable and transformer losses with the unintended reactive power flow of PV inverters. The maximum losses increase to 123.81 kW and are around 1.9 kW higher than without reactive power. The medium value amounts to 113.78 kW. Also this value is around 0.4 kW higher than without reactive power.
The green graph of the third row shows the profiles of the day (2011-05-09) with the highest power flows and therefore the highest losses with reactive power. The red graph is the profile of the losses on the same day without reactive power but not the profile with the highest losses by neglecting reactive power flows. There are almost constant losses during the night of around 112 kW in the whole medium voltage grid. The elevated losses during

daytime are a result of the feed-in in the investigated low voltage grid due to the fact that the loads and supplies in all other connected low voltage grids are constant over the whole simulation period. Hence this low voltage grid causes maximum additional losses because of the high active power feed-in of around 9 kW or 1.3% of the installed PV capacity. This means the maximum power losses on this specific day without reactive power are 121 kW.

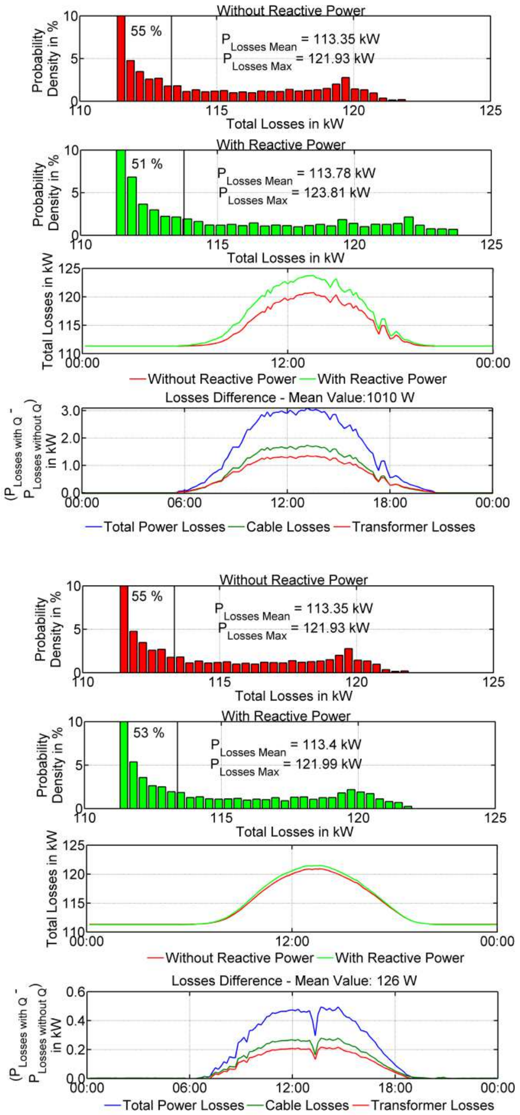

Figure 8: Comparison of the grid losses with and without the unintended reactive power flows of PV inverters with a power factor specification of one. The average and also the maximum losses are higher by applying the reactive power flows into the simulation. Simulation way C2 - Ind (upper part) and C1 - Mean (lower part).

Due to [WIR-11] and [WIR-12] is the maximum PV feed-in power 85% of the rated system power. This means the maximum PV feed-in cumulates to around 570 kW in this low voltage grid and the losses are 1.6% of the active PV feed-in.

By applying the unintended reactive power flow the maximum losses increase to almost 124 kW and are around 3 kW higher than without reactive power. This means around 0.5% of the active PV feed-in is lost because of the additional reactive power flow.

The energy lost due to the reactive power flow amounts to 22 kWh on this day. In contrast, the total active feed-in energy on this day in this specific low voltage grid amounts to 4827 kWh. This suggests that approximately 0.45% of the produced energy is lost due to the unintended reactive power flow. The total loss caused by the unintended reactive power flow over the entire year under investigation is summed to 2598 kWh. This is more than half of the energy that is produced on the most profitable day.

In the last row the difference between the losses with reactive power and without reactive power over the day with the highest power flow and therefore the highest losses are exhibited. The red graph illustrates the difference in transformer losses with a maximum of around 1.3 kW. The green curve elucidates the losses-difference on all cables of the distribution grid. This maximum amounts to approximately 1.7 kW. To sum it up, the additional losses due to the unintended reactive power flows of maximal 3 kW are a result of additional transformer and cable losses whereby the additional cable losses are higher than the supplementary transformer losses.

By applying the reactive power according to the simulation method C1 - Mean (lower part of Figure 8), the maximum and also medium losses of the distribution grid, compared to C2 - Ind, are reduced. The maximum losses of the complete medium voltage grid and the subordinate low voltage grid amount to 121.99 kW. This value is 1.8 kW lower than in the C2 - Ind scenario and only marginally higher than without reactive power flow. The additional maximal cable and transformer losses are in the range of 200 to 300 W. Again, the additional cable loss is higher than the additional transformer loss.

The energy that is lost due to the supplementary unintended reactive power flow on the day with the highest power flow amounts to 3.8 kWh. The energy that is lost over the whole year of investigation aggregates to 453 kWh. This means the energy loss because of unintended reactive power flow is 10% of the energy produced on the most profitable day.

6 RESULTS AND CONCLUSIONS

Active and reactive power flows do have an influence on the electricity grid. The grid voltage increases due to active and inductive reactive power feed-in and decreases due to active and inductive reactive power consume. An inductive reactive power consume is able to mitigate the voltage problem at long feeders with a huge amount of renewable energy systems, especially in low voltage grids.

Most of the nowadays installed PV inverters are inverters with a power factor specification of one. The unintended reactive power flows of most of the analyzed inverters confirm a linear dependency on the active power. Therefore a reactive power best-fit polynomial of the first degree for each inverter is developed. The application of this polynomial of each inverter in voltage and load flow simulations leads to more precise results of the real system conditions.

The simulation of the voltage shows an inductive overall attitude in the three exemplary low voltage grids. The influence of the voltage depends strongly on the distribution of the different PV inverters. An inductive overall behavior of a low voltage grid does not automatically mean that the maximum voltage of this grid is reduced. In general, the grid conditions in low voltage grids are not known by the grid operators. Distribution network operators simulate the grids to figure out the conditions and to make sure that all grid parameters are in an allowed range. For all PV systems, including an installed inverter with a power factor specification of one, only active power values are applied. Hence the real voltages deviate from the simulated voltages and therefore less or even more grid enforcement due to too high voltages is necessary.

The losses in the grid increase by applying the unintended reactive power flow of PV inverters into the simulation. Also the utilization rates of the cables and transformers are increased. This means that the real utilization rates are higher than the simulated ones and an earlier respectively higher grid enforcement to prevent overload is necessary.

Summarized, PV inverters with a power factor specification of one contribute to uncontrolled and unintended reactive power flow. These power flows do have an impact on the grid voltage and increase the utilization rate of cables / transformers and expanses the grid losses.

Under normal operating conditions the reactive power flow of PV inverters with a power factor specification of one is not relevant for grid operation and network planning. The results of this study show an inductive behavior of the inverters with the highest deviation from the power factor specification in full load operation. Also the influence on grid power loss is marginal.

Voltage or overload problems that are not explainable by the means of active power flows can be a result of the unintended reactive power flow and their influence on the grid voltage. The grid region with problems has to be analyzed by applying the unintended reactive power flow of PV inverters with a power factor specification of one. This approach can help network operators to locate and understand the reason of grid problems.

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