GRID VOLTAGE INFLUENCES OF REACTIVE POWER FLOWS 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 kWp [1] per house connection (HC). Therefore the load flow changes its characteristics and leads to new requirements for grid dimensioning. Additionally, the feed-in is carried out via inverter systems and a lot of power electronics have to be integrated in the existing grid infrastructure. This leads to new challenges to ensure the required grid stability. Due to the rapid extension of PV systems, primarily in low and medium voltage grids, the state of the grid is increasingly unknown. 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 no reactive but only active power. 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 kW range are analyzed. The investigations are based on the analysis of data from a very detailed measurement campaign in a distribution grid with high PV penetration in southern Germany. Every single inverter with a power factor specification of one shows reactive power flows. Finally it is shown, that there is an influence of the unintended reactive power flows on the grid voltage. This influence has to be considered in grid planning and power system management.

INTRODUCTION

The produced energy of photovoltaic (PV) systems represents a growing part of the electricity supply in Germany. In the end of 2013 more than 35.5 GWp [2] 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 [3] of ±10 % of the rated grid voltage and have to fulfill the application guide line VDE-AR-N 4105 [4] that permits a maximum voltage hub of 3 % in low voltage grids. With a view to the voltage stability, PV inverters of the latest 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 [4], 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.

CHARACTERIZATION

Measurements in the laboratory of the University of Applied Sciences and field measurements in a project area deliver the same results: inverters with a power factor specification of one contribute to unintended reactive power flows. Thus the question how these reactive power flows can be characterized has come up. As the reactive power flows depend on the amplitude of the irradiation and therefore on the stage of utilization [5] 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. A best-fit polynomial of the first degree can be allocated to these inverters.

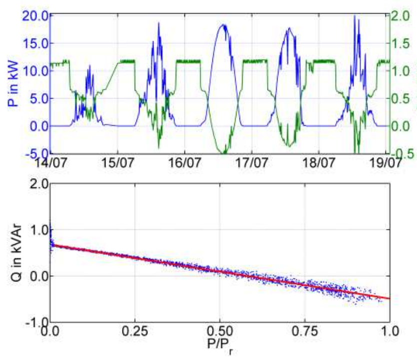

Figure 1: Active and reactive power flow of one exemplary inverter over five days. The lower graph shows the correlation between active and reactive power.

Figure 1 displays the active and reactive power flow of one exemplary inverter over five representative days. A high capacitive reactive power flow in the night is clearly visible, because of the grid filters of the inverter 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.

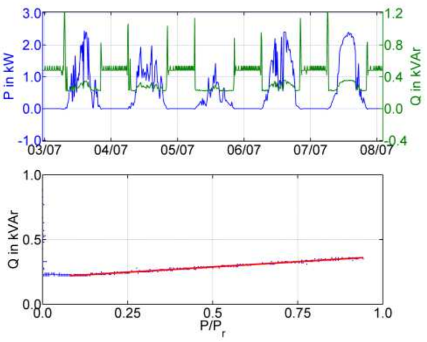

Figure 2: Active and reactive power flow of another exemplary inverter over five days. The lower graph shows the correlation between the active and reactive power.

Another exemplary inverter as shown in Figure 2 has an opposed characteristic. There is a correlation between active and reactive power and a direct proportionality arises. 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. 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 power feed-in.

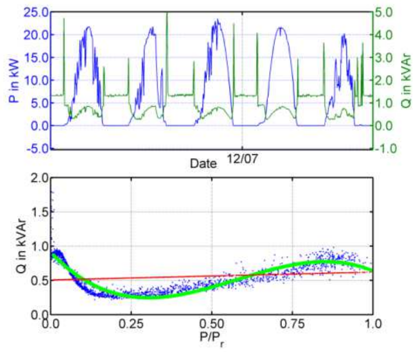

Figure 3: Active and reactive power flow of a further exemplary inverter over five days. The lower graph shows the correlation between active and reactive power.

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 only deficiently. A more sufficient approximation of the unintended reactive power flows is delivered by a reactive power best-fit polynomial of the third degree (green).

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 is compiled (2011-05-09). Figure 4 communicates this polynomial in dependency of the gradient and the y-intercept (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 (114 house connections) with 7 measured PV systems. There is one 20 kW system with 4.4 kVAr inductive reactive power in near full load operation. The mean reactive power of all seven systems is also inductive and amounts to 339 VAr. The quotient of the reactive power in full load operation and the sum of all reactive powers in full load operation varies for the seven inverters between 1.32 % and 58.3 % with an average of 14.3 %.

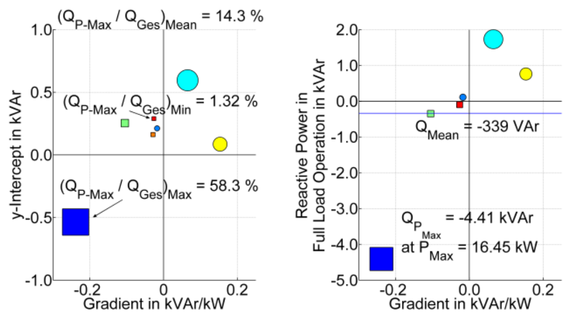

Figure 4: Comparison of diverse inverter types for the day with the highest active power feed-in for one low voltage grid. Each marker represents the approximate path of the reactive power in dependency on the active power.

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 flows. On the other hand there are some inverters that feed-in inductive reactive power 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.

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 strong 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. To quantify this, the empiric correlation coefficient (r) can be used for the evaluation of the excellence of the 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 is necessary for the calculation of the empiric correlation coefficient according to Equation (1).

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

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

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

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 reactive power best-fit polynomials of a higher degree are more adequate.

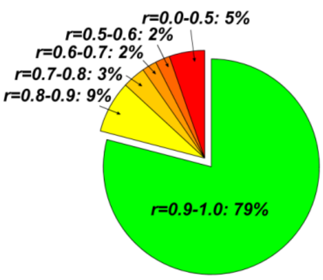

Figure 5: Empiric correlation coefficient to evaluate the quality factor of the linear dependency of the reactive power on the active power. Values close to one express good linear approximations.

SIMULATION OF THE INFLUENCES ON THE GRID VOLTAGE

PV inverters with a power factor specification of one contribute to reactive power flows 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 inductive reactive power feed-in 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 ($U_N = 400V$, Figure 4), during full load operation with and without the unintended reactive power flows 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 700 kW divided on 30 PV systems. The measured input data is available for 7 PV systems. For these systems the real measured powers are deposited into the network simulation tool PSS®SINCAL [6]. 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. This approach takes into account that the maximum reactive power flow does not compulsory depend on the rated power (first calculation way). Normally, PV inverters with a higher rated power do have higher reactive power flows. The calculation ways two and three take this correlation 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 flows 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 and are constant over the whole investigation period [7].

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 colorbar displays the relative voltage change (Δv_{rel}) in % according to Equation (4).

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

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

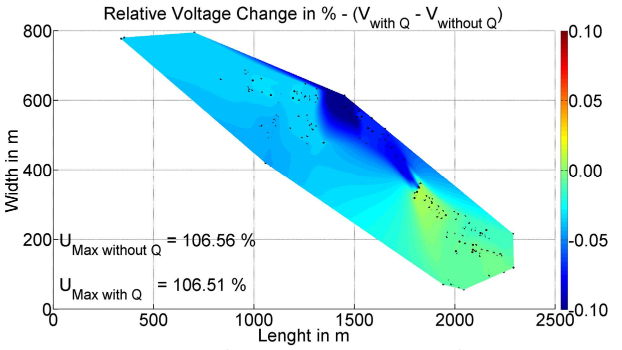

Figure 6: Comparison of the grid voltage in near full load operation of the PV systems with and without the unintended reactive power flows of PV inverters with a power factor specification of one.

Figure 6 visualizes the distribution of the voltage on all nodes in the low voltage grid with three local network areas. The area in the northwest shows slightly decreased voltages of around 0.2 V. By means of the changing colors are the borders of the local network area clearly visible. The medium network area shows decreased voltages of up to 0.4 V, whereas the southeast network area reveals slightly increased voltages. This fits quite well with Figure 4. The mean voltage is reduced by applying the unintended reactive power flows but there are still nodes with enhanced voltages due to the capacitive behavior of some inverters. The node with the maximum voltage in the whole low voltage grid lies in an inductive network area. Hence the voltage by applying the unintended reactive power flows is declined.

Table 1: The maximum voltages with and without reactive power flows of the three low voltage grids for the three simulation variants.

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

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 670 and 780 kW and are also highly PV penetrated. Summarized, all three low voltage grids do have an inductive overall attitude. Nevertheless are the voltage range reflections quite different. A compilation of the maximum voltage with and without the unintended reactive power flows for the three distribution grids exposes 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.

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 voltage reduction for the scenario C2 – Ind to 101.83 % in the second distribution grid is quite huge because of one strong inductive inverter. 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. The voltages on all nodes of the distribution grid introduced in Figure 4 and Figure 6 for the scenario C2 - Ind and C3 - Cap are shown in Figure 7.

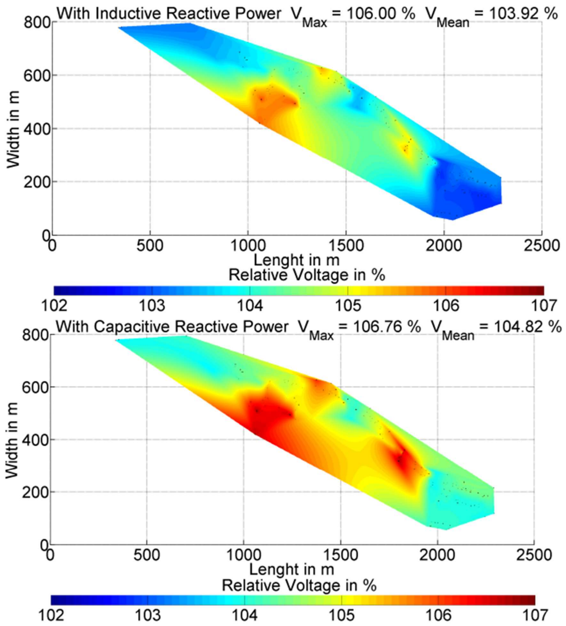

Figure 7: Voltages on all grid nodes in one exemplary low voltage grid for the simulation scenarios C2 - Ind and C3 - Cap.

RESULTS

Reactive power flows of PV inverters do have an influence on the electricity grid. 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. Nevertheless also these inverters contribute to reactive power flows in the grids.

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 of 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.

Voltage or overload problems that are not explainable by the means of active power flows can be a result of the unintended reactive power flows and their influence on the grid voltage. The grid region with failure has to be analyzed by applying the unintended reactive power flows 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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