EFFECTS OF A HIGH PV PENETRATION ON THE DISTRIBUTION GRID

GEORG WIRTH(1) • ANDREAS SPRING(1) • GERD BECKER(1) • ROBERT PARDATSCHER(2) • ROLF WITZMANN(2) • JOHANNES BRANTL(3) • MICHAEL GARHAMER(3)

(1) University of Applied Sciences München · Department of Electrical Engineering 80335 Munich · Germany · Phone +49 (0) 89 1265-3478 · georg.wirth@hm.edu
(2) Technische Universität München · Department of Electrical Engineering and Information Technology - Institute of Power Transmission Systems
80290 Munich
(3) E.ON Bayern AG Assetmanagement
93049 Regensburg

ABSTRACT: The low-voltage network in southern Germany has to cope with an increasing number of photovoltaic (PV) systems. High power feedback to higher voltage levels indicates a discrepancy in the decentralized production and the local consumption and therefore a noticeably impact on the medium and low voltage grid. This paper discusses the characteristics of a real medium voltage grid including its underlying low voltage grids with a distributed PV fleet of about 5 kW per house connection (HC). The focus hereby is on the meteorological caused impacts and the interaction with the consumption. In this context the relevant conditions from a grid planning point of view are identified and characteristic measures are presented.

Keywords: Grid-Connected, Grid Integration, Grid Stability

1 INTRODUCTION

The number of installed photovoltaic (PV) systems in German low-voltage grids is increasing. In more and more areas the installed PV capacity is the decisive rating in network planning, since the decentralized generated PV power exceeds the local consumption and power feedback to overlying grid levels occur. Therefore the characteristics of the distributed PV fleet, the meteorological influences and the interaction with the consumption have to be considered planning the low voltage grid.

This article discusses the impact of a high concentration of decentralized PV systems on the distribution network. The results are based on data from the project "The Grid of the Future" (Netz der Zukunft) of the E.ON Bayern AG in cooperation with the Technische Universität München and Munich University of Applied Sciences. It analyses a medium voltage grid and the underlying low voltages girds in an area with a very high PV penetration in Lower Bavaria. The total installed capacity in the area reaches 5 kW per house connection (HC). The project involves a very detailed measurement campaign. About six hundred smart meters were installed in the area at house connections with and without PV systems. Additionally all 150 transformer stations are equipped with power quality measurement devices. All measurement devices transfer the data to a centralized database.

The low voltage grid has to be designed to handle the occurring maximum load flow. Considering the demand, this load is not the sum of every household’s maximum load as there is a temporal fluctuation of these loads. Especially household loads act strongly asynchronously, so if more than 150 households are considered, the operating experience shows a resulting load of 1 kW per house connection. Households with PV systems show other characteristics since the instantaneous power of production exceeds the consumption during daytime. In this period the characteristics of the PV production dominates and the load flow in the grid shows new load patterns. In combination with the ongoing installation of photovoltaic (PV) systems this leads to new grid requirements and new ratings for grid dimensioning.

2 INFLUENCES ON THE DISTRIBUTION GRID BY DISTRIBUTED PV SYSTEMS

Detailed load flow calculations in the low voltage grids show, that most difficulties caused by a high PV penetration are voltage problems [Wir-11a]. A reversed load-flow over the line impedance leads to a voltage rise at the house connection. The voltage at the house connection has to stay within a ±10 % range according to European standards [EN-50160]. To comply with this rating during normal operation a maximal voltage lift due to the PV fleet’s cumulated feed in power of 3% in the low voltage grid and 2% in the medium voltage grid is specified in the grid code [VDE-4105]. For grid dimensioning purposes in Germany the feed-in power of the installed PV systems can be assumed with 85 % of the installed STC (standard test condition) rating of the modules [Wir-11b, Par-11].

To characterize the influences of the growing numbers of PV systems in the grid, the load-flow of the whole project area over the transformer 20 kV to 110 kV has been analyzed. To evaluate the changing situation historic data from 2009 till 2011 was used. Figure 1 shows the distribution of the load flow. The bars indicate the yearly frequency of the apparent power. Positive power represents an energy supply toward the area whereas negative numbers indicate power feedback to the high voltage level. The absolute value of the apparent power as the relevant rating or grid dimensioning is indicated by the dotted lines. It can be seen that there was almost no power feedback in 2009 whereas in 2010 a significant number of feedback incidents occur. Looking at the 2011 data, this power feedback causes the highest load on the transformer.

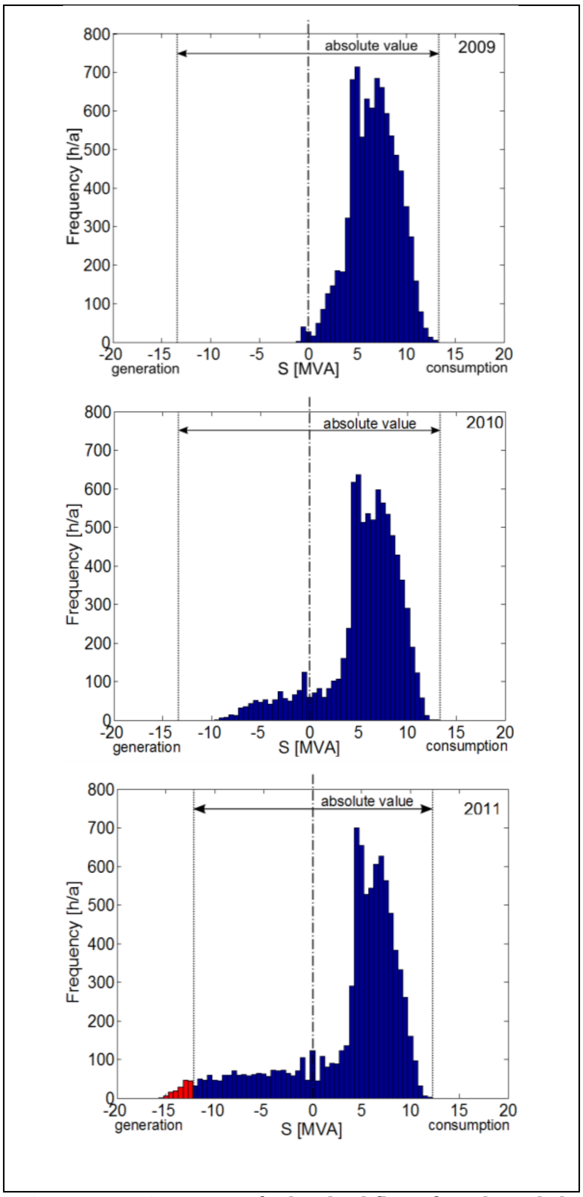

Figure 1: Histogram of the load-flow for the whole observation area for 2009, 2010 and 2011. Negative values indicate power feedback to higher voltage levels.

Moreover the distribution of the reverse load flow indicates that the high feedback levels show a low frequency compared to the consumption loads. This distribution is unfortunate from a grid operating point of view. The highest occurring load is distinctive for network reinforcement. To achieve an acceptable return of investment the installed grid capacity must also be reasonably utilized.

A closer look at a 24 hour period provides a deeper understanding of the sub flows in the grid. For this analysis the 10 days with the highest power feedback to higher voltage levels in 2011 were examined. The load profile of different villages and towns is calculated as sum of the related transformers load profiles. To divide load and consumption the measured house connections are normalized and classified with the corresponding standard load profile (SLP) or the PV system size. These normalized SLPs are then scaled with the number of house connections and the installed PV capacity.

Figure 2 shows the PV production, the load and the resulting load flow for one of the villages in the observation area. The village has an installed PV capacity of 1.7 kW per house connection, which is roughly average all over Bavaria. The day on display is the day with the highest power feedback to overlaying grid levels in 2011. Recognizable is that this day shows a theoretically energy autonomy of the village over a 24 h period. To cover that electricity demand the PV production with the typical bell shaped curve builds a peak up to 700 kW around 13:00. The highest feedback with just above 400 kW however occurs past 14:00 as there is a dull in the energy demand. Due to this characteristic feed in pattern the ratio of the PV production to the power consumption at the time of the highest feedback power is just above two. This peak is already above the highest supply power for the area with an average PV penetration. This highlights that for optimized grid integration the production of the distributed PV fleet should be more equalized.

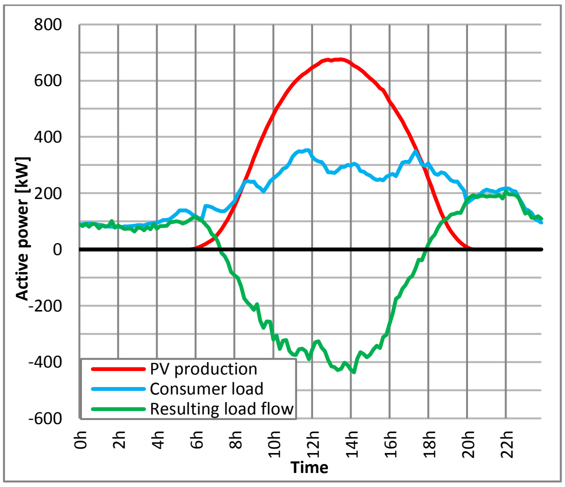

Figure 2: The power consumption (blue), PV production (red) and the resulting load flow on a summer day with a theoretically 24 h energy autonomy for a low voltage grid with a medium pv penetration.

The medium voltage grid "Seebach" and its underlying low voltage grids show 241 days with power feedback to higher voltage levels in the year 2011. To demonstrate the impact of the local load these incidents are analyzed for every day of the week as the weekends have a different load pattern. Figure 3 visualizes this interaction of production and consumption for every day of the week. The green line shows the maximum power feedback of the whole project area normalized to the installed PV capacity. The local consumption is included to demonstrate its impact. High values can occur on working days and on weekends but the highest simultaneity of the PV fleet happens to be on a Sunday.

The bars in Figure 3 represent the energy feedback of the whole area towards higher voltage levels. The energy is shown in utilization hours, calculated as sum of the feedback power on the specific day of the week normalized to the installed capacity. Again the data represents the whole year 2011. It becomes visible that most feedback incidents happen at Saturday and Sunday as there is less local load in the grid. This gives an impulse to coordinate the local PV production and the local power demand for optimized grid integration.

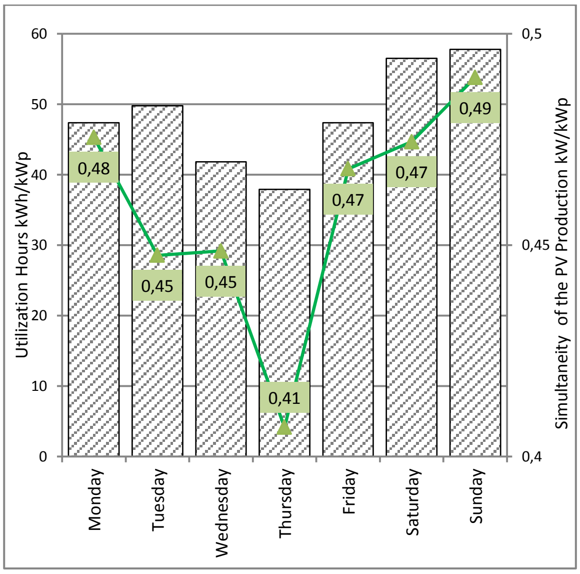

Figure 3: Maximum simultaneity of the PV production (green line) and cumulated utilization hours (blue bars) including the consumption for the days of week in 2011.

3 METEOROLOGICAL CLASSIFICATION

In [Wir-11b] two competing scenarios for the maximum feed-in power were introduced. The output power of the PV system depends on different system immanent and meteorological parameters. In summary the highest performance of the system results at high irradiance and low module temperatures at the same time. Considering the prevailing weather conditions on this background two competing Scenarios, clear sky and fluctuating cloud cover, were identified. Looking at these scenarios allows a meteorological classification of the occurring difficulties in the grid.

• On summer days with clear skies the irradiation in Southern Germany reaches values around 950 W/m². In this case the diurnal cycle of solar radiation has the shape of a bell curve. The generated power of distributed PV systems shows a high simultaneity due to the homogeneous weather situation. This means that all plants in a region feed high power to the grid. Because of the slowly increasing irradiation and high ambient temperature, the high irradiation levels come along with high module temperatures. Thus the plant output remains well below the STC performance. Due to the high simultaneity an assessment of an increasing area with an increasing number of PV systems leads to a stabilization of the normalized feed in power at high levels. These are the days with the highest power feedback towards higher voltage levels.

• The second scenario arises on days with a fluctuating cloud cover. Cloud reflections cause increases of the global radiation up to values above the solar constant. These irradiation enhancements meet low cell temperatures due to the thermal time constant of the PV module. The resulting power peaks are limited by the maximum inverter output power. Because of the cloud movement, the simultaneity of the feed in power is lower as the one of clear skies. Considering an increasing area with an increasing number of PV systems the normalized power of the whole fleet decreases. However the highest feed in power of a single PV system and thereby the voltage problems in the end of feeders appear on these days.

Figure 4 shows the distribution of the irradiation data from the weather station in the investigation area and the corresponding incidents of high voltage levels and high feedback power in investigation area. The days are classified according to the maximum occurring irradiation peak into classes of 50 W/m² (bars, left axis). Additionally the cumulative and absolute frequency (blue lines, right axes) is shown. To match the difficulties in the grid, the relevant dates are outlined above the bars. The days with the highest power feedback indicated in green, appear all on days with irradiance levels up to 900 W/m². The red marked days with the highest voltage at the end of the feeder appear at days with irradiance levels over 900 W/m²

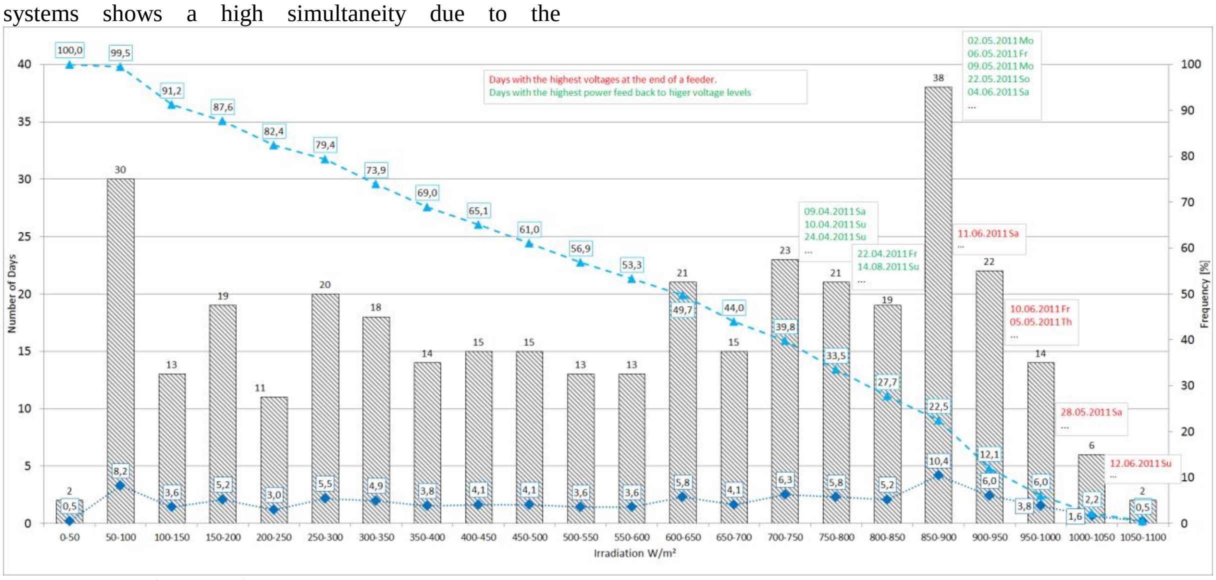

Figure 4: Classification of the year 2011 according to the maximum occurring irradiation peak on a Day. The bars represent the absolute number of days, the light blue line the frequency an the dark blue line the cumulated frequency. The dates in the Boxes above the bars indicate the five days with the highest voltages (red) the ten days with the highest power feedback (green) and irradiation energy (yellow).

4 ANALYSIS IN REAL NETWORKS

The impact of the variations of different weather situations can also be seen in the grid voltage. For this analysis representative feeders in the observation area were chosen [Wir-12]. The feeders are characteristic for rural grids with a high PV penetration. The data used are 10 minute mean values of the load profile from the smart meters at the house connection. As a reference value the voltage for a fixed load-flow calculation with a minimum load and 85% respectively 100% of the installed PV capacity is determined.

This data indicates that the maximum of the voltage level on the clear sky days is below the maximum values on the days with a fluctuating cloud cover. Almost all analyzed situations stay below the voltage limits of a static calculation with 85 % of the installed PV capacity. Only the five in Figure 4 marked days with very high irradiance levels at one feeder with very high PV density exceed this limit. Figure 5 shows the voltage on a clear sky day (green), a typical fluctuating day (yellow) and a fluctuating day with an extreme peak (blue) on a feeder with a very high PV penetration. The light and dark red line indicates the reference voltage level at 100% and 85% of the installed PV capacity.

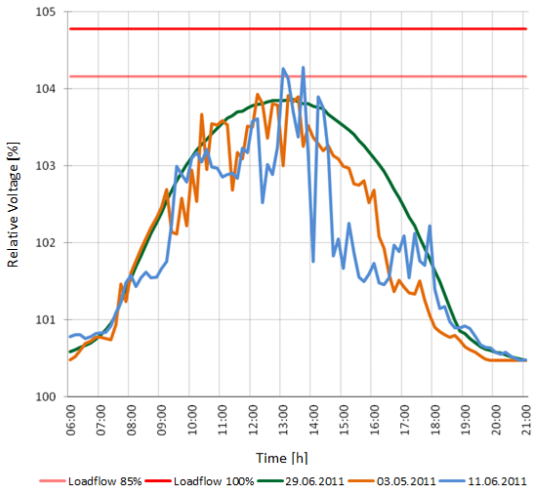

Figure 5: Relative voltage on a clear sky day (green), a typical day with fluctuating clouds (yellow), and a day with very high fluctuation (blue). The light red line indicates the 85% and 100% STC limit.

The relation of the dynamic voltage levels with the fixed load flow calculation in a simulation framework allows examining the behavior on fluctuating days without the influences of the household loads and the grid impedance. Thereby the smoothing in the grid on days with a fluctuating cloud cover can be shown. In a first step the different voltage levels in the grid for a fixed feed in power of 85 % of the installed PV capacity and a minimum power consumption is calculated as a reference value. The second step determines the dynamic voltages on the fluctuating day. Figure 6 shows the relation of both profiles. The red line indicates the 85 % STC capacity reference value. The four curves represent the voltage levels on different points of the path from the house connection over the grid connection and a bus bar towards the low voltage side of the local grid transformer (20kV/0,4kV).

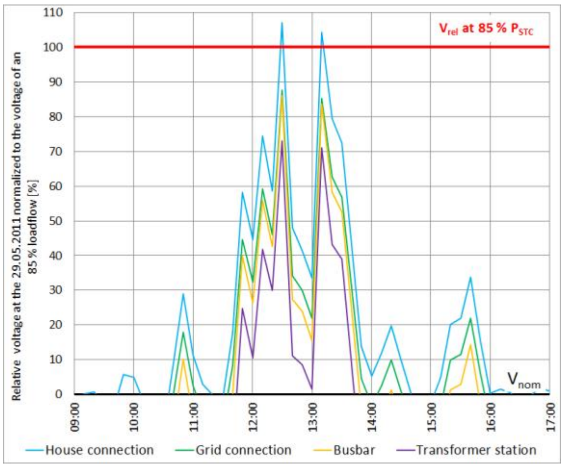

Figure 6: Relative voltage normalized to the 85 % STC loadflow at different points of the feeder on the path from the house connection to the low voltage side of the transformer.

The voltage at the house connection exceeds the limit of the static 85 % load flow calculation. Looking at the interconnection with the feeder the voltage is already below the static 85 % values. The further path along the feeder to the low voltage side of the transformer shows a further decrease of the voltage level even so there are more PV systems connected along this way. This demonstrates the spatial smoothing effects in the grid. They are based on the cloud movement and the different performance due to the quality of the individual systems.

5 CONCLUSION

In areas with a high PV penetration the decentralized production is the reason for grid reinforcement. High power feedback to higher voltage levels appears especially on weekends with a low decentralized consumption. Clear sky days show the highest power feedback to higher voltage levels. Days with a changing cloud cover show the highest voltages at the end of feeder lines. For optimized grid integration the production of the distributed PV fleet should be more equalized, additionally the local energy supply and demand should be better coordinated. Both goals can be achieved with various technologies which are not addressed in this paper.

6 REFERENCES

[DIN-50160] DKE: DIN 50160 Merkmale der Spannung. in öffentlichen. Elektrizitätsversorgungsnetzen; Deutsche Fassung prEN 50160, Stand November 2008

[EBY-10] E.ON Bayern AG, research project, Netz der Zukunft, Project webpage, http://www.eon-bayern.com/pages/eby_de/Netz/Smart_Grid/Forschungsprojekt_Netz_der_Zukunft/Projektgebiet/index.htm, Regensburg 2010

[Par-11] Pardatscher , Witzmann, Wirth, Becker, Brantl, Garhamer: Untersuchungen zu den Auswirkungen von Photovoltaikeinspeisung auf das Nieder und Mittel-spannungsnetz, Internationaler ETG-Kongress 2011, Würzburg, November 2011

[VDE-4105] Erzeugungsanlagen am Niederspannungsnetz – Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz, Stand August 2011

[Wir-11a] Wirth G., Spring A., Becker G., Pardatscher R., Witzmann R., Brantl J., Garhamer M.,: Felduntersuchung der Netzauslastung und Spannungsanhebung durch PV-Anlagen, 26 PV Symposium, Bad Staffelstein, März 2011

[Wir-11b] Wirth G., Spring A., Becker G., Pardatscher R., Witzmann R., Brantl J., Garhamer M.,: Field Study on Changing Grid Requirements due to High PV Penetration. 26th European Photovoltaic Solar Energy Conference and Exhibition Hamburg, September 2011

[Wir-12] Wirth G., Spring A., Becker G., Pardatscher R., Witzmann R., Brantl J., Garhamer M.,: Möglichkeiten zur Netzintegration einer hohen Anzahl an Photovoltaikanlagen im niedrigen Leistungsbereich. 27 PV Symposium, Bad Staffelstein, März 2012