TECHNICAL COMPARISON OF MEASURES FOR VOLTAGE REGULATION IN LOW-VOLTAGE GRIDS

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ABSTRACT

Because photovoltaics (PV) is mainly installed (~70 % of the power) to the Low-Voltage (LV) grid, the Distribution System Operators (DSO) face new challenges to provide the required voltage quality. Mainly, voltage rise caused by the generation of PV leads to grid extension measures. In this paper, the effects of a high PV generation on the grid in Epplas will be evaluated along with the detailed simulation of the different measures for voltage maintenance in Low-Voltage grids. As a result, the curtailment of the generation power by Generation Management or Storages or the proportionate installation of PV can be seen as measures with the highest potential to reduce the voltage rise. Solutions like the Regulated Distribution Transformer or String Voltage Regulators decouple the Low-Voltage grid from the local Medium-Voltage grid and can be considered useful for the integration of additional PV plants and the operation of the Low-Voltage grid. Reactive Power Control can lower the voltage effectively and is already provided by the inverters of the PV but comes with an increased loading of the lines.

INTRODUCTION

The electricity grid originally was built as a one-way road supplied by centralized power plants. Nowadays, the renewable generators are mainly connected to the Medium-Voltage (MV) and Low-Voltage (LV) grid. A high share (~70 % of the power) of the photovoltaics (PV) power is connected to the LV grid and causes voltage rise that leads to network extensions. Hence, the Distribution System Operator (DSO) faces new challenges to plan and operate the local LV grid according to the relevant norm DIN EN 50106 [1] which demands compliance of a voltage range within ±10 % around the nominal voltage. Since there is no decoupling, the voltage range must be partitioned between the LV and MV grid. Furthermore, German regulations specify a maximum voltage rise of +3 % [2] in the LV grid and +2 % [3] in the MV grid. The DSO can depart from these values in justified cases and take into account static voltage maintenances. Therefore, in this study we want to investigate the effects of a high installed photovoltaics power on a rural LV grid and compare different measures from a technical perspective.

LV-GRID EPPLAS

About 290 kWp of PV was installed gradually, starting in the year 2005, to the rural grid in Epplas near the city of Hof. The orientation of the PV varies strongly (see **Figure 1**).

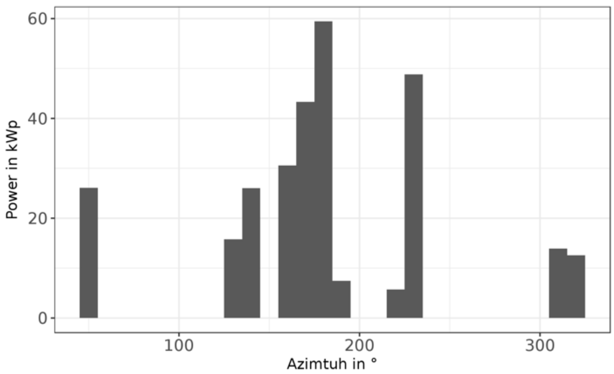

Figure 1: Variation of the azimuth angles of the PV in Epplas

Since then, the local DSO had to extend the grid multiple times to integrate the newly installed PV plants and a sawmill. The grid plan of Epplas can be seen in **Figure 2** and the following numbers refer to the point where the grid extension was built. Firstly, in 1990 all overhead lines, expect one of the lines at ①, were replaced by underground cables. Following the closure of the sawmill, the overhead line was removed in 2007 at ①. In 2011, the PV plant at house Nr. 1 was extended by 58 kWp and therefore, two new lines were laid to enable the supply at ②. Because the sawmill was reactivated, a second line has been built in 2014 at ①.

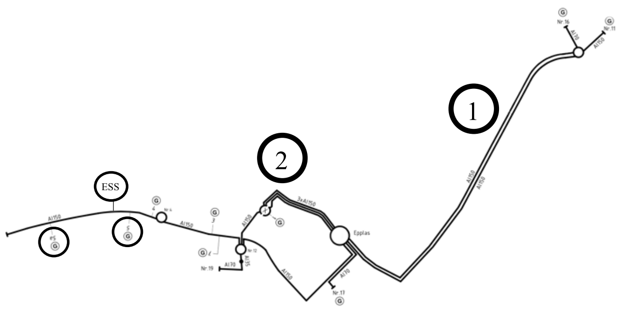

Figure 2. Schematic grid plan of Epplas; (G) indicates a PV generator; (EES) is the Community Electrical Energy Storage; PV 5 & PV 5 (circled) are curtailed with the use of the EES

At the end of 2014, we installed Smart Meters to measure all PV generators and the demand of almost all households separately to investigate the grid parameters (voltage, current and cos φ). The Smart Meters acquire data with a maximum resolution of 15 seconds and offer a high reliability. Furthermore, we also installed a Community Electrical Energy Storage (EES) near PV 5, as presented by Schmidt et. al. [4] to reduce the voltage rise in the grid. The EES provides a nominal power of 72 kVA and a usable capacity of 330 kWh and is operated with a peak shaving strategy that curtails the generation of PV 5 and PV 5a (circled in **Figure 2**).

VOLTAGE REGULATION IN LV GRIDS

The DSO can take multiple actions to regulate the voltage in the distribution grid. **Figure 3** shows a scheme of a distribution grid and **Equation 1** explains the influencing factors on the voltage U_{LV}.

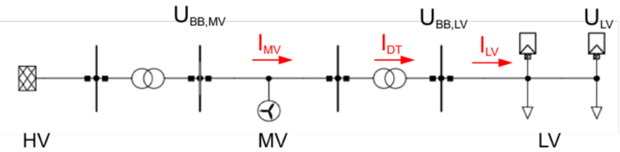

Figure 3. Scheme of a distribution grid

$$\underline{U}_{LV} = \underline{U}_{BB,MV} - \frac{1}{2}\underline{U}_{RB,MV} - \left(I_{A,MV} - j \cdot I_{R,MV}\right) \cdot \underline{Z}_{MV} - \underline{I}_{DT} \cdot \underline{Z}_{DT} - \underline{U}_{TC} - \left(I_{A,LV} + j \cdot I_{R,LV}\right) \cdot \underline{Z}_{LV} \quad (1)$$

U_{LV}	Voltage in the LV grid
$U_{BB,MV}, U_{BB,LV}$	Bus bar voltages
$U_{RB,MV}$	Regulation bandwidth of the on-load tap-changer in the substation
U_{TC}	Voltage of the tap changer in the transformer station
Z_{MV}, Z_{LV}, Z_{DT}	Impedances of the MV/LV lines and the MV/LV transformer
I_{DT}	Current through MV/LV transformer
$I_{A,MV}, I_{R,MV}, I_{A,LV}, I_{R,LV}$	Active and Reactive Current in the MV/LV lines

Reduction of the impedances

The reduction of the impedances $\underline{Z}_{MV}$ and $\underline{Z}_{LV}$ by laying new cables, erecting new transformer stations or meshing the grid was resp. is probably the most preferred option by DSOs. These measures are often quite inflexible and require a high investment and also come with an interference of the local residents.

Reactive Power Control

The voltage can be reduced by Reactive Power Control (RPC) in form of an additional under-excited reactive current $I_{R,MV}$ resp. $I_{R,LV}$. Therefore, decentralized generators in the LV grid up to a size of 13,8 kVA must be able to provide a power factor $cos\varphi$ in the range of $\pm$0,95 according to [2]. Generators with an installed power greater than 13,8 kVA must provide a power factor of $\pm$0,90. The power factor can either be set as a fixed value or as a characteristic curve $cos\varphi(P/P_n)$ depending on the present power. **Figure 4** shows the characteristic as implemented in PV inverters.

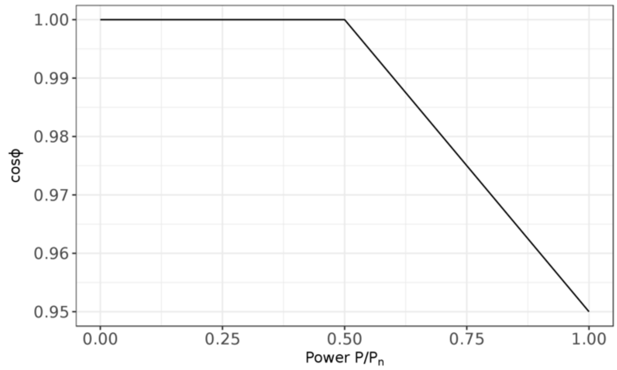

Figure 4: $\cos\varphi(P/P_n)$-characteristic for PV inverters

Active Power Control

The reduction of the active current $I_{A,MV}$ resp. $I_{A,LV}$ leads to a reduction of the voltage rise and can be achieved by either Generation Management (GM), Demand Side Management (DSM), Demand Side Response (DSR) or Electrical Energy Storages (ESS). Whereby, the potential of DSM and DSR seems limited in LV grids and is therefore not considered in this paper. Generation limits of 100 %/60 %/30 %/0 % are recommend as proven in [2]. The ESS must be operated with peak-shaving strategy to reduce the generated power which requires an accurate weather forecast to be operated properly. In our study we used a 100 % forecast and an ideal storage without loses.

Direct Voltage Regulation

The voltage levels at the bus bars $U_{BB,MV}, U_{BB,LV}$ can be regulated using transformers equipped with an on-load tap-changer (OLTC).

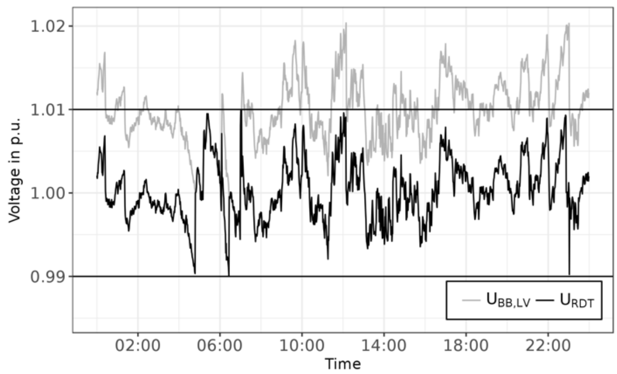

Figure 5: Voltages at the LV bus bar with and without a Regulated Distribution Transformer

A very common measure is a Regulated Distribution Transformer (RDT) that decouples the LV from the MV grid and therefore the voltage range can be used within the LV grid (see **Figure 5**). Another solution is a Sting

Voltage Regulator (SVR) for voltage maintenance. For this measure, the OLTC is installed in the regarded string and keeps the voltage within given thresholds. The OLTC switches if the measured voltage leaves the prescribed threshold. Therefore, the voltage fluctuation at the node of the OLTC can be kept within defined limits.

LOAD FLOW CALCULATION

In the following sections we present the assumptions for the load flow calculations of the grid in Epplas.

Conventional Grid Planning

Since there is almost no measurement equipment installed in the Distribution Grid, the DSOs normally use so-called Worst Case scenarios to plan the grid. For the determination of the load power in of the single strings in the Demand Case we used the partly electrified approach presented by Kaufmann [5] and a value of 0,98 p.u. for $U_{BB,LV}$ to consider the voltage fluctuations from the MV grid. For calculating the Generation Case, the power under Standard Test Condition (STC) was used as the generation power of the PV plants and a minimum load of 100 W was considered. $U_{BB,LV}$ was set to 1,02 p.u..

Detailed Simulation

Because of the time-consuming simulation of the load flow in a minutely resolution we first culled specific points. In **Figure 6** the courses of the highest ($max\,V$) and lowest voltage ($min\,V$) as well as the minimum voltage at the time of the highest voltage ($min\,V(max\,V)$) per day in the present grid are shown.

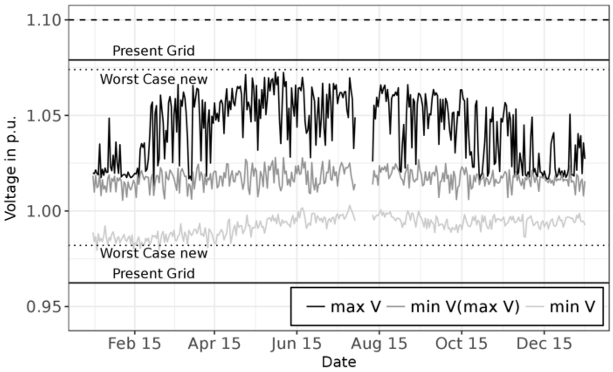

Figure 6: Course of voltages in Epplas in 2015 and the voltages of the Worst Case scenarios (conventional and new approach)

Since PV is installed in all strings of the grid, the lowest voltage at the time of the highest voltage is measured at the bus bar and is higher than the absolute minimum voltage of the same day. It also can be recognized that voltage deviations stay within the permissible margins (± 1,1 p.u.), whereas the deviations in positive direction are more distinct because of a minor load pervasion in the rural grid. Hence, voltage drop is not a problem in the given grid. Furthermore, the highest and lowest voltage value stay within the values of the Worst Case scenarios.

Since the highest voltage values appear between 11:00 and 13:00 from May to June because of a lower temperature leading to a higher efficiency of the PV modules, we used the acquired demand and PV generation data for this time to calculate the load flow using DIgSILENT PowerFactory [6] to investigate the following scenarios:

- Grid from 1990
- Grid extension to present grid
- Reactive power control $\cos\varphi(P/P_n)$
- Generation Management
- Community Energy Storage System with peak shaving of PV 5 & PV 5a
- Regulated Distribution Transformer
- String Regulator

RESULTS

The following results were determined using the detailed measurements of the demand and the PV. Moreover, we evaluated the values used for the calculation of the Worst Case scenarios. Before using the gird model, we ran a validation test and detected an average relative error of 0,1 % which can be neglected in the following.

Worst Case Scenarios

The calculated values for the Generation Case and the Demand Case for the grid in Epplas as it is configured as in 1990 can be seen as solid horizontal lines in **Figure 9**. The voltage rise (1,093 p.u.) and drop (0.962 p.u.) of the grid were overestimated and because of the high calculated voltage the local DSO had to extend the grid as described before. Also, the worst case calculation for the present grid were overestimated as seen in **Figure 6**. The reasons for the overestimation may lay in the input data for the Worst Case Scenarios.

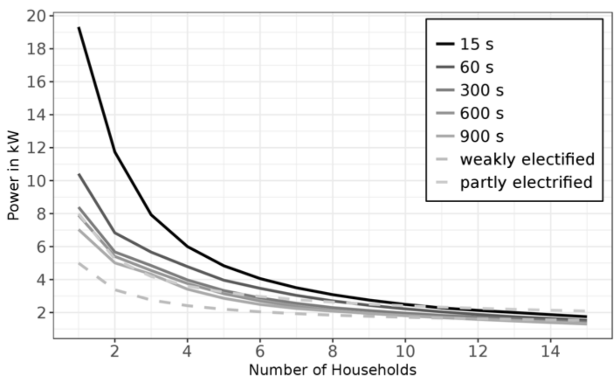

Figure 7: Comparison of the approach of Kaufmann [5] (dashed) and the measured values from Epplas (solid)

Figure 7 shows a comparison of the values presented by Kaufmann and the measured values in Epplas in a different time resolution. Whereas the values from Kaufmann fit the determined values for a resolution of

900 s (15 min), the approach underestimates the values for few households that are measured in a high time resolution. For more households (>10) all load curves converge to 2 kW. Thus, the values for Kaufmann fit the measured values for multiple household and can be used for Worst Case load flow calculations. But as it seems that the values from Kaufmann were derived from commonly used 15 min values, the values for few households can differ because short term load peaks are not acquired.

As the PV in Epplas is installed in different azimuth angles (see **Figure 1**), the influence on the generated power can be evaluated. The highest power that was fed-in simultaneously by the Southern orientated PV was 91 % of the STC power and the highest value of all PV with multiple orientation was just slightly lower (88,7 %). Hence, the influence of the orientation on the PV generation can be neglected because of a small error. Further influence factors as heating, shading, geographic irradiance dispersion, the dimensioning of the inverter and aging may have a more relevant influence that should be considered in the grid planning process.

Our evaluations for the measurement values of Epplas propose a value of 90 % of the installed STC power, whereas single PV plants can feed-in with a power greater than the STC power because of cloud enhancement. With the use of an undersized inverter, the short term peaks are curtailed. As a result, the voltage rise is overestimated using the STC power for the Worst Case scenarios.

The fluctuation of the MV is also a possible error source. In our Worst Case calculations we used a fluctuation of ±0,02 p.u. around the nominal voltage. **Figure 8** illustrates the deviation of the voltage values on the bus bar of the transformer station. It can be noticed that the mean value of the voltage is shifted to 1,01 p.u. and the standard deviation of 0,005 p.u. is relatively low. But the extreme values are spread wide to 1,033 and 0,979.

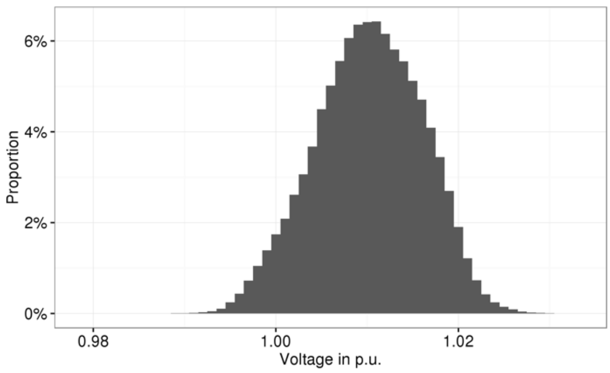

Figure 8: Deviation of the voltage values at the bus bar of the transformer station

In **Figure 6** the results of the calculation with a more accurate approach can be seen. In this scenario, we use 90 % of the STC power of the modules as generation power for the PV power plants. The demand values were still obtained from the values of Kaufmann and for the bus bar voltage values of 1,01 p.u. ± 2σ (standard deviation) were chosen. The results are now closer to the extreme values with some values falling under the minimum Worst Case value which may be caused by the installed heating pumps in winter or a low voltage at the bus bar of the transformer station.

Detailed Simulation

Figure 9 shows the highest voltage in the grid for the investigated measures and **Figure 10** shows the highest value of the loading of the local lines. It can be noticed that the voltage in the Grid for 1990 reached a maximum voltage of 1,087 p.u. and therefore it was a reasonable decision of the DSO to extend the grid. By laying new cables the maximum voltage in the grid was reduced to a value of 1,078.

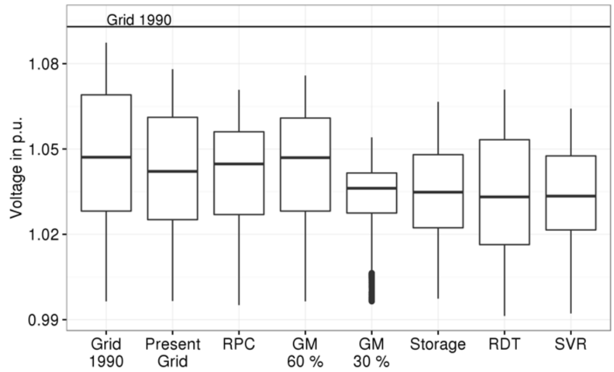

Figure 9: Distribution of the higehst voltage values in Epplas for different measures and the Worst Case calculation for the higest voltage

A further and cost efficient solution to reduce the voltage is RPC because the inverters of the PV already support this measure for voltage regulation. With the use of RPC, the voltage can be reduced up to 1.070 p.u., but comes with a higher maximum current in the lines and the DSO must depend on a correct operation of the inverter of the PV and has no direct access in case of failure.

The curtailment of the generation only shows efficiency for a higher curtailment threshold which comes with high energy losses of the PV energy. Whereas the energy losses are relatively low (6,2 % of the yearly yield in Epplas) for a GM with a curtailment threshold of 60 %, the losses in Epplas rise up to 33 % of the yearly energy production for a threshold of 30 %.

With a higher curtailed energy, the costs of this measure rise because the curtailed energy must be compensated by the DSO. The installed storage system can reduce the maximum voltage to a lower value (1.067 p.u.) than the RPC, GM 60 % and the grid extension. As advantage, no power needs to be curtailed when using an EES and the self-sufficiency in the grid increases. As the energy production of the PV plants within the grid exceeds the demand multiple times (maximum about 10 times) in summer, the storage needs to be completely discharged during the night which is often reached by feeding the energy into the MV grid because the demand of the local households is too low for a complete discharge.

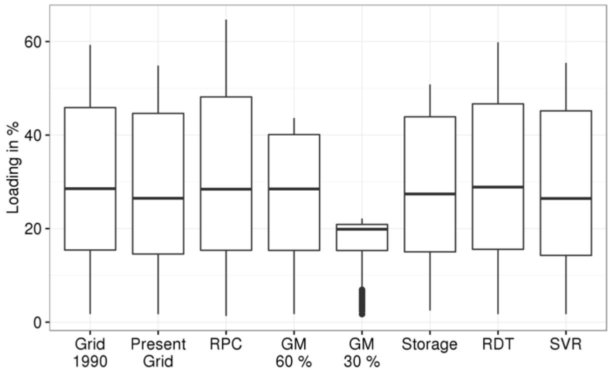

Figure 10: Distribution of the highest loading of lines in the grid of Epplas for different measures

The RDT and the SVR also can lower the maximum voltage in the grid because of the decoupling from voltage fluctuations. The SVR can set a more adapted value to the considered string. Therefore, these two measures facilitate the operation of LV grid as voltage fluctuations from the overlaying grid are adjusted to a determined bandwidth. A narrower bandwidth leads to a higher count of switching operations of the OLTC [7].

Furthermore, in none of the scenarios the maximal loading was the cause for further grid extension. The maximal loading was always beneath a maximal average of 0,7 which is necessary for an appropriate aging of the lines. Only by using RPC for voltage maintenance the maximal loading rises and, therefore, must be considered designing the local LV grid.

CONCLUSON & OUTLOOK

Although the simulated voltage values in the original grid rose up to almost +9 %, the voltage range defined by DIN EN 50106 is not violated. Hence, the grid planning with Worst Case scenarios is inaccurate and still contains voltage range reserves. Therefore, we evaluated measurement values in Epplas to achieve a more accurate result. In our approach, we used 90 % of the STC data and had possession of the exact voltage values at the bus bar that enabled a more accurate grid planning. Although, the voltage range was not violated within the grid planning, the grid extension was reasonable because additional feeders or switching operations in the MV grid can cause a change of the voltage level at the bus bar of the LV gird and can lead to voltage range violations.

Furthermore, the different measures all lead to a reduction of the voltage rise and offer the possibility to control the voltage in LV grids more accurately than conventional network extensions like cables or transformers and, therefore, should be considered as an alternative by the DSOs. Especially, an adapted installation of PV to the local demand can prevent expensive grid extensions.

ACKNOLEDGEMENT

The project "Smart Grid Solar" is co-financed by the Bavarian ministry of economics and media, energy and technology and the European Regional Development Fund (ERDF).

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