IMPACT OF PHOTOVOLTAIC GENERATION ON VOLTAGE VARIATIONS – HOW STOCHASTIC IS PV?

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ABSTRACT

Among Renewable Energy Resources (RES), wind power and photovoltaics are generally regarded as "fluctuating" sources. This characteristic is often associated with power quality concerns. This paper presents the main results of an analysis of the "very-short voltage variations" caused by photovoltaic generation. This analysis is based on measurements and simulations made for a large photovoltaic installation in Austria.

INTRODUCTION: PHOTOVOLTAICS AND VERY-SHORT VOLTAGE VARIATIONS

Together with wind power, photovoltaic (PV) generation is often qualified as *fluctuating*, *intermittent*, *unpredictable* or even *stochastic*. From the possible impacts resulting from the fluctuating nature of PV generation, only the voltage effects are considered here.

Results from power quality measurement campaigns reported in the literature (e.g. [1]) clearly show that PV generation does not cause any flicker increase. Indeed, various analyses of solar irradiance have shown that fast irradiance variations are usually very limited. In [2], irradiance variations of 5 W/m^2 (about 0,5 % of the PV generator power) measured as the 95 %-percentile of irradiance variations within 1 s are mentioned for Central Europe. Such irradiance variations are then damped by the various dynamics of the system (e.g. spatial filtering due to the size and location of the PV arrays, the maximum power point tracker and the DC to AC conversion).

Rapid voltage change is usually defined as ([3]): "*a single rapid variation of the rms value of a voltage between two consecutive levels which are sustained for definite but unspecified durations*". As explained in [3], rapid voltage changes are usually caused by load changes or switching in the system. Regarding the effects of voltage fluctuations on users' equipment, the following points should be mentioned ([4]):

- braking or acceleration torques from motors connected directly to the network
- impairment of electronic equipment when fluctuations pass through the power supply

Although various documents mention some limits for *rapid voltage changes* (e.g. [6], [7]), no standardised measurement method is available for quantifying these variations. The use of the so-called very-short variation index to quantify the difference between the 3-second and the 10-minute mean values of the rms voltage is proposed in [5]. As output of the computation, a value is obtained for each 10-minute interval. In the study presented here, this concept has been applied to voltage (very-short voltage variation index: VSV), current (very-short current variation index: VSC) and power (very-short power variation index: VSP).

The investigations presented in this paper build on the method proposed in [5]. The main objective is to quantify the very-short voltage variations caused by PV generation.

APPROACH OF THE STUDY

Within the European project DISPOWER, extensive measurements have been performed in a Low Voltage network (see Figure 1) with a large PV installation (100 kW PV noise barrier) in Gleisdorf, Austria in order to investigate the probability of islanding ([8]).

The LV network which groups about 160 customers (residential, commercial, public and small industry) is supplied by a 630 kVA distribution transformer. The loads grouped as "Local loads 1" and "Local loads 2" on Figure 1 are connected by cables to the transformer. The PV installation is situated at about 300 m from the transformer station and is also connected trough cables. Finally, some small electronic loads ("Service loads" on Figure 1) for monitoring and displays are also connected to the Point of Common Coupling (PCC).

The fault level at the PCC is about 3 MVA (R/X~1,1). With a ratio between maximum power (considering a maximum generation of 80 kW) and fault level of about 2,5 %, the PV generation can be qualified as quite large.

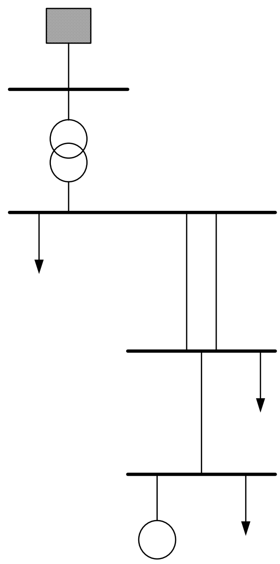

Figure 1. Overview of the LV network used for the analysis

The measurement data (1-second rms voltages and power flows for a whole year) have been used to investigate the very-short voltage variations in this network. In order to be able to perform further investigations, the network has been implemented into the simulation environment DIgSILENT PowerFactory®. The MV voltage as well as all the relevant power flows (local loads, service loads and PV generation) has been imported into the software, thus allowing simulating various *penetration levels*. In this way, the effect of PV generation at higher penetration levels could be investigated. Simulating higher penetration levels by multiplying the PV power flow is still realistic due to the size of the PV installation.
By comparing the simulation results with the measurements, the model could be validated. For the analysis, the scenarios presented in Table I have been considered.

Scenario	Description
0	No generation (base case)
1	Original system (for validation)
2	Generation causing a voltage rise of 3 %
3	Generation causing a voltage rise of 5 %
4	Generation causing a voltage rise of 7 %
5	Generation causing a voltage rise of 10 %

Table I. Scenarios selected for the simulations

For the definition of the scenarios, the penetration level has been "measured" by the expected voltage rise computed according to [7]:

$$\frac{\Delta U}{U} = \frac{S_N}{S_{SC}} \times \cos(\psi - \varphi)$$

with

S_N: *nominal power of PV installation*
S_{SC}: *short-circuit power at the Point of Common Coupling*
φ: *generation angle (PF=tan(φ))*
ψ: *grid impedance angle (R/X=tan(ψ))*

The voltage rise has been chosen for quantifying the penetration level since this is considered as the most limiting factor for the integration of distributed generation in rural areas of Austria.
While Scenario 1 allows validating the simulations (by comparing with the measurements), Scenario 2 corresponds to the 3 % voltage rise limit specified in [7] for the connection of distributed generation to the LV network. Scenarios 3, 4 and 5 simulate higher penetration levels.
For the investigations, a set of representative days has been selected (e.g. sunny, cloudy and variably cloudy). A comparison between various days is provided later.

IMPACT OF PV GENERATION ON VERY-SHORT VARIATIONS

Following, the results of the measurements analysis and an attempt to quantify voltage variations are shortly presented.

Analysis of the very-short variations from the measurements

Figure 2 shows the results of the computation performed with the measurement data (Scenario 1) for a variably cloudy day (13/09/2004). The following magnitudes are presented:

- voltage at the PCC
- very-short voltage variations (VSV) at the PCC
- very-short current variations (VSC) for the PV generation
- generated power

Figure 2 shows that the VSV background level is about 0,5 V and that some spikes exceed 1 V. While the spikes occurring in the morning hours (between 5:00 and 11:00) probably result from load switching or transformer tap-changer operation (most spikes have a similar height), the ones occurring between 12:30 and 14:00 seem to be caused by the PV power variations: the VSC spikes exceeding 20 A seem to correspond to VSV spikes exceeding 1 V.

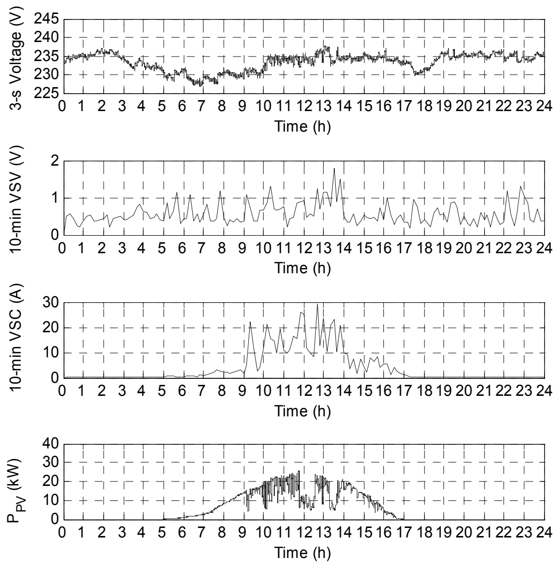

Figure 2. Analysis of VSV and VSC for a variably cloudy day (Scenario 1, 13/09/2004)

A similar analysis is shown for a sunny day (09/09/2004) on Figure 3. The effect of the PV generation can be clearly seen on the voltage plot. While the voltage decreases in the morning hours with the increasing consumption (minimum at about 7:00), it rises during the day (peak at about 13:00) and then decreases in the evening hours. As expected, the VSC level is very low during the whole day (lower than 5 A compared to the almost 30 A in Figure 2). The VSV profile exhibits a few spikes over 1 V which do not seem to correlate with the PV generation (with the VSC). Both voltage and VSV profiles are noticeably very similar for the two working days (Figures 2 and 3) in the morning and in the evening hours (before 10:00 and after 17:00).

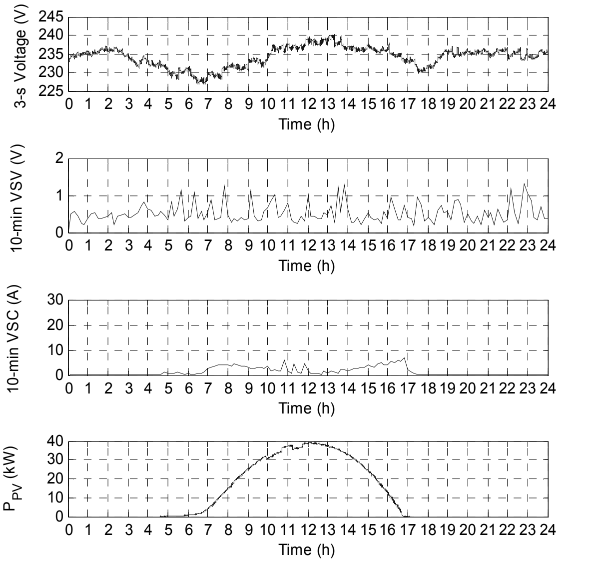

Figure 3. Analysis of VSV and VSC for a sunny day (Scenario 1, 09/09/2006)

This first analysis shows that PV power variations seem to be within the time scale relevant for very-short variations. However, the effect on the VSV is very limited: only a few spikes can be credited to the PV generation. A quantification of this impact for various days is presented in Table II.

Day/Period	VSC_{95} (A)	VSV_{95} (V)
Variably cloudy day	20,9	1,2
Sunny day	2,7	1,3
Cloudy day	2,3	1,2
Observation period (about half a year)	7,7	1,2

Table II. Comparison between various days – 95 %-percentile of the very-short current and voltage variations

This table shows that although the VSC level rises significantly for variably cloudy days (level about three times the "average" level for the whole observation period), the VSV level is virtually not affected by this increase. Moreover, the comparison between the VSC level for the selected day (variably cloudy) and the whole period shows that the selected day represents an "extreme case" not occurring very often. This day has therefore been selected for the rest of the study as *worst case*.

Figure 4 shows the correlation between VSC and VSV. The data correspond to Scenario 1 (original system), for the whole observation period (about half a year). Such correlations should be carefully interpreted since all the parameters such as load variations having an effect on the VSV are not considered. This figure however shows that very high VSC values (e.g. above 30 A) always result in higher VSV values (usually above 1 V). The points with high VSV and low VSC correspond to very-short voltage variations due to load switching or transformer tap-changer operation.

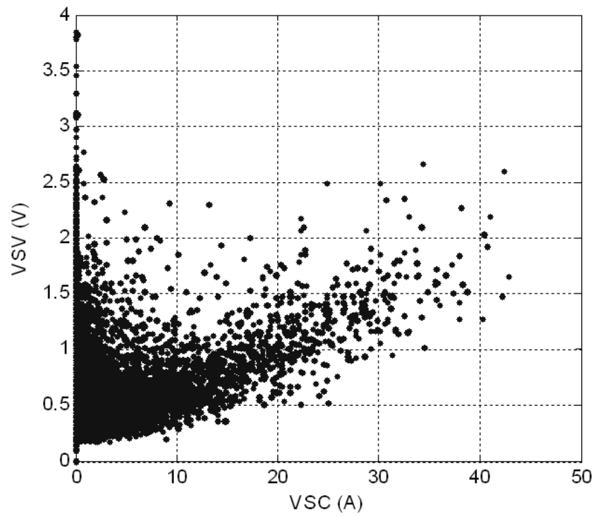

Figure 4. Correlation between VSV and VSC (Scenario 1)

Quantifying the increase of VSV level with growing PV penetration levels

As previously explained, further analyses have been made through simulations in order to investigate the effect of increased PV penetration on the VSV level. For this, simulations according to the scenarios described in Table I have been performed for the selected day (variably cloudy day: 13/09/2004). For each scenario, the VSV and the VSC have been computed. The 95 %-quartile has been used to quantify the very-short voltage variations (VSV_{95}).

Figure 5 provides a comparison between the voltage rise and the VSV level caused by the PV generation for increasing penetration levels. The x-axis ("penetration factor") corresponds to the multiplication factor used for simulating higher penetration levels; it is directly proportional to the computed voltage rise.

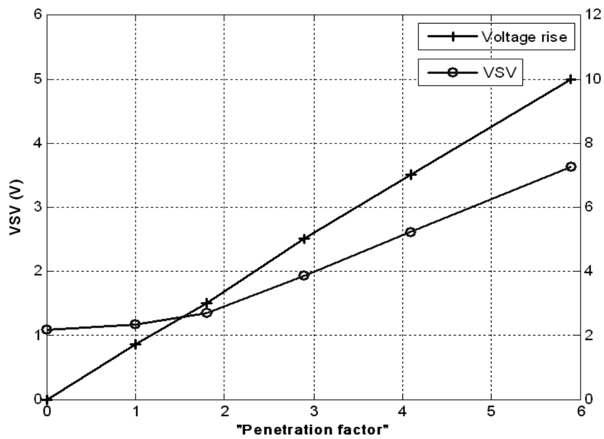

Figure 5. Comparison between voltage rise and VSV for various penetration levels (Scenarios 0-5, 13/09/2004)

Figure 5 shows that the increase of the very-short voltage variations (VSV_{95}) is slower than the increase of the voltage rise. Doubling the penetration factor from 1,5 to 3 leads to a doubling of the computed voltage rise (from 2,6 % to 5,2 %) but does not lead to a doubling of the VSV level (from 2,1 V to 3,3 V i.e. an increase of 57 %).

The VSV level corresponding to the voltage rise limit of 3 % for distributed generators connected to the LV network according to [7] would be 1,4 V, i.e. a small increase (0,3 V) in comparison with the VSV level of 1,1 V without PV generation. After this comparison between VSV level and voltage rise, a further quantification of the VSV level is done based on the limits specified in [7] for the connection of distributed generation. In [7], possible causes of voltage changes (switching of large loads, motor driven with fluctuating schemes and fluctuating distributed generators) are mentioned, and limits for both the magnitude and the "frequency" of such changes are specified. These limits are presented in Table III; voltage changes are defined in [7] as the difference between two consecutive 10-ms rms values.

Repetition rate (min^{-1})	Maximum voltage change (%)	
	LV	MV
0,1	3	2
0,01	6	3

Table III. Voltage changes limits according to [7]

For example, voltage changes occurring not more often than 0,1 per minute (6 per hours) shall not have a magnitude greater than 3 % for LV-connected distributed generation. As explained in [5], voltage steps result in a spike of the VSV level of about the half of the voltage step. Taking this into account, the 3 % limit for changes can be translated in a 1,5 % limit for the VSV. Table IV summarises the results from this analysis.

Scenario	0	1	2	3	4	5	Limit
Penetr. fact.	0	1	1,8	2,9	4,1	5,9	-
Voltage Rise (%)	0	1,7	3	5	7	10	3
VSV_{95} (V)	1.1	1.2	1.4	1.9	2.6	3.6	-
$N_{VSV>1,5\,\%}$	0	0	0	0	2	10	144
$N_{VSV>3\,\%}$	0	0	0	0	0	0	14

Table IV. Number of voltage variations during the selected day (Scenarios 0-5)

In the last two rows, the number of voltage variations ($N_{VSV>1,5\,\%}$: 10-minute intervals for which the VSV value exceeds the 1,5 % or 3 % limit) are indicated. The last column shows the value corresponding to the limits specified in [7]. This table shows that the number of 10-minute intervals with a VSV level above the limit is much lower than the computed limit (10 10-minute intervals compared to 144 for voltage variations greater than 1,5 %), even considering the worst case (i.e. variably cloudy day).

CONCLUSIONS

This paper has considered the effect of photovoltaic generation on voltage variations, on the basis of long-term measurements made at a large PV installation in Austria. It can be expected that the conclusions can be expanded to other geographical regions. The focus has been laid on very-short voltage variations (variations between 3 s and 10 min) since flicker is not relevant for PV.

The main results are briefly summarised.

- The VSV concept is a useful tool for quantifying voltage variations caused by *fluctuating* generation.
- Power variations resulting from irradiance fluctuations are in the time scale relevant for very-short variations.
- The analysis of measurements made at the PCC of a large PV installation does not show any noticeable increase of very-short voltage variations (VSV_{95} increase of about 0,1 V for a variably cloudy day).
- Investigations for scenarios with larger PV generation show that the voltage rise increase is faster than the increase of the VSV level.
- The rate of repetition of voltage variations is much lower than the values corresponding to the limit specified in current interconnection requirements (limit of 3 % for voltage changes with a rate of repetition lower than 0,1 min^{-1}).

These investigations have shown that PV generation variations are limited (both in magnitude and repetition) in respect of their impact on very-short voltage variations.

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