SAFE OPERATION OF PHOTOVOLTAIC SYSTEMS IN HOUSEHOLDS WITH SAFETY-PLUG CONNECTION

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Defining the load of a fused string in a household was the aim of this project. This is required for save operation of plug and play socket photovoltaic (PV) systems in the grid of households. The additional power of the PV-system could overload the wiring. First, the standardization of socket PV-systems in Germany is being checked. By measuring the grid impedance, the actual load situation should be indicated. To do so, different measurement methods are being examined. Grids reaction to a known load is being observed to calculate the grid impedance. Further, the phasor shift between different load situations will be metered to estimate actual loads. The measurements of the grid impedance didn't really indicate the loads. However promising correlations between voltage cracks, phasor shifts and loads in a string were found.

Keywords: plug and play PV, photovoltaic, grid impedance, measurement, safety pirate PV, socket PV, load define, voltage jumps, voltage cracks, balcony PV, PV, micro photovoltaic systems, facade PV, phasor-shift, impedance, grid analysis

1. INTRODUCTION

For the future of renewable energy socket PV-systems are becoming more and more import. They are mini PV-systems which can be installed via a standard shockproof socket. This is a great advantage, because every person can install such a system as it is just plugging in the PV-system. No electrician or approval procedure is required. These systems are used on balconies or facades. They offer a great potential because every tenant can install them and produce solar energy. Before such a device starts feeding-in energy some parameters need to be checked, especially the actual load, that runs over the wire that is connected to the PV-system. These systems are made for local self-consumption and not for feeding into the public grid. The investigations in this project aim for analysis methods to analyze the load in a string behind a fuse in a household, where the PV-system is installed. An exact analysis is important to guarantee the wires won't be overloaded, which could overheat them and cause fire.

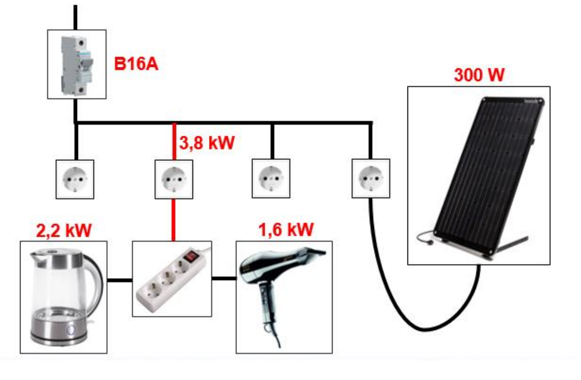

Figure 1: Overload caused by PV-system

Figure 1 shows by a simple example the principle of potential danger of feeding via safety plug. The fuse is supposed to safe the electric circuit from overload. If an electric kettle with an output of 2200 watts and a hairdryer with 1600 watts are connected to the grid the total power adds to 3800 watts. In such a scenario, the wires are overloaded (max. current 16A, i.e. 3600 watts) and – under normal conditions - provokes the fuse to trip. However, assuming the PV-system feeds its maximus power (300 watts), then the share of the power provided by the fuse reduces to 3500 watts which corresponds to 15,2 Ampere. The fuse won't trip, and the wire marked in red is being overloaded, overheats and, in an unfortunate event, causes fire. This problem can be solved by installing a fuse for lower amperes (overload becomes unlikely) or a fuse that communicates with the PV-system. For these solutions an electrician is involved which affects the simplicity of operating the system intolerably. If it is possible to define this load out of the PV-systems position in the grid, every consumer would be able to install a PV-system and run it safely.

2. EXISTING SYSTEMS AND STANDARDIZATION

In some countries it is already allowed to install these PV-systems without legal constraining. Thanks to their simple regulations, plug and play PV-Systems spread. A little survey illustrates that formal DIN VDE regulations complicate the use of plug and play PV-systems.

2.1 Existing regulations abroad

In the Netherlands, Austria and Switzerland regulations allow to install plug and play PV-systems to a certain level of summarized power. In the Netherlands more than 200.000 mini PV-systems are installed. Regulations only limit the maximum installed power to 500 watts per household. So far, the Netherlands haven't made negative experience with this regulation. Households with higher installed PV-power need to comply other standards, which for example imply changing to lower fuses in the PV-systems string [1].

2.2 Power meters

Another important regulation in Germany concerns power meters. Most power meters turn backwards, if power goes in the opposite direction, i.e. into the grid. This may happen in the unlikely event that the PV-system produces residual power. A turning back of power meters is prohibited, thus running a plug and play PV-system may inflict an exchange of the meter.

2.3 Further DIN-VDE-standardization

The DIN-VDE 0100-551 (low voltage installation) has recently been extended to regulate technical requirement of low-voltage-feeding-devices. New rules are made for PV, wind and other feeding-devices. It requires that functionality of residual current devices (RCD) must not be adversely affected by DC-current percentages in the grid. Since DC-AC couplers are used in small feeding devices, this could be a consequence. Therefore, a special RCD is required. This standardization refers to DIN-VDE 0100-420 and -430 (saving utilities against thermic influence and overcurrent). Subsuming, one is allowed to connect a PV-system to an existing grid, yet, a change of the fuse is required. Further no safety plug must be used [2]. The standardization committee claims to release new requirements in 2019, in which a new plug is intended particular for PV-systems [3]. This will not improve the legal situation of operating a plug and play PV-system, because still some electric installation will be required.
Besides the issue of residual power being fed into the grid, potential overloads of the wires make permitting a simple usage of the PV-systems difficult. Therefore, this investigation focuses on load detection in existing grids.

3. MEASUREMENT

Two different kinds of measurements have been examined to determine the load situation in a fuse-string. First, voltage and current were recorded while activating different loads to calculate the grid impedance. Second, precise recordings of the voltage sine-waves have been analyzed.

3.1 Measurements of voltage fluctuations due to load varieties

Impedance, or impedance change can be a significant indicator for the actual load situation in a grid. If a string is simplified to a circuit with loads being connected parallel, the impedance lowers if a load is turned on. Due to impedance of the grid in a household, the voltage drops when a load is being activated. The voltage drop is constrained to the current that flows through the conductor, i.e. the activated load. By measuring the voltage changes, it is possible to conclude how much a string is being loaded. To get more precise information about the load situation in the string, it can be loaded with a known load (or shunt resistor) to determine a typical voltage jump. The measurements for these investigations were placed in two different households using the existing local grid in each apartment. In order to generate loads, devices with high power were activated. Those were electric kettles, toasters or hairdryers. These high loads affect as ohmic loads.

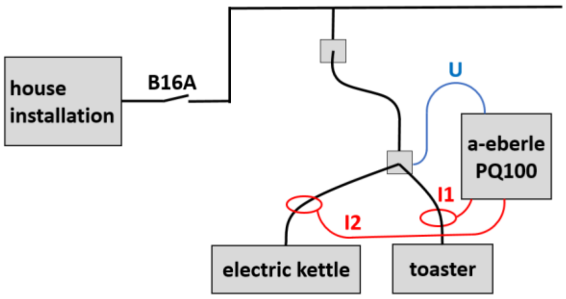

Figure 3: measurement structure

A network-analyzer (a-eberle PQ-Box 100) was used for logging the trend of the voltage fluctuations. Two multiple sockets were modified such that current measurements could take place by putting a current clamp around the life-conductor in the wire. Current and voltage values were recorded as effective values with a 1Hz sample rate. A PV-system could only meter at one position. For analysis it was required to place a second load into the grid to take calculable effect onto the grid, i.e. to simulate a realistic load-situation. For analysis, the current trend of the second load was recorded as well. A PV-system could analyze the effect it takes by feeding in some power into the grid, instead of straining it. This would cause a voltage ascent – the opposite effect – but it would still be in the same way dependent on the grid impedance. Therefore, the PV-system was substituted by a known load. The absolute grid impedance was calculated by generating a delta U and delta I generated by turning on or off the load and solving this equation:

$$Z = \frac{\Delta U}{\Delta I} \tag{1}$$

If the second load effects the grid, a change of the grid impedance occurs. The lower the impedance, the higher the load that affects it. This change should be detectable with the first resistor and the method shown above. Further, it is possible to calculate the exact load of the second resistor by the simplification of the grid being a parallel circuit and assuming that the impedance caused by the rest of the grid's loads stays constant or differs in a lower dimension. See results below in chapter 4.

3.2 Oscilloscopic measurement

Information about the load situation in a grid can also be gained by analyzing the phasor-shift of two complex alternating voltages. One would take place before activating the load, the other in an activated situation. The phasor-shift occurs due to the inductive share in the impedance of a wire next to the ohmic. This can be seen in the following figure 5:

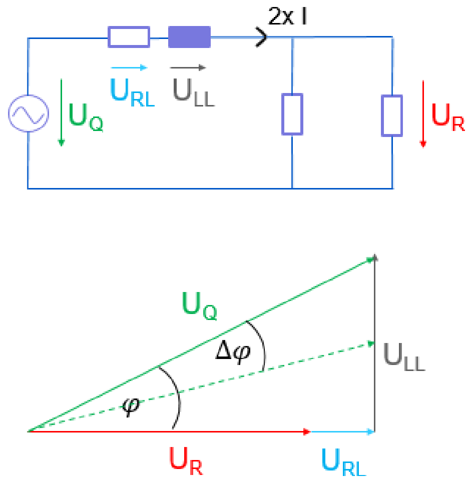

Figure 5: phasor-shift caused by extra load

For these measurements, the network-analyzer mentioned above was set to a sample rate of 10 kHz. The setting of these measurements was the same as in 3.1. The recording was triggered by the loads current ascents and descents of a preset level (5A). In this measurement, the exact sine wave was recorded. For the following analysis of the measurement, the recorded discrete values of the sinewave had needed to be fitted into a sine function with several parameters, namely: amplitude, frequency and phasor.

$$U_Q(t) = \hat{u} * \sin(\omega * t + \varphi) \qquad (2)$$

3.2.1 Data analysis

For investigations a simple linear regression of the data near the voltage zero-crossings was used. Due to the sines close to linear trend in this part of the function, this approach was precise enough to get a good determination of the times of zero-crossings. With this approach, frequency and phasor were calculated. The amplitude though can be approached with a non-linear regression. For this investigation, phasor and frequency played the most important role. For this simple fitting, Excel was used.

3.2.2 Comparison of two sinewaves

For predicting the next zero-crossings of the sine-wave before the load activation, the mean half-cycle duration was calculated. It was then added to the last measured zero-crossing of the old sine-wave every half-cycle. These time values of zero-crossings where then compared to the actual times of zero-crossings of the sine wave after activation of the load. This is a very simple way of fitting the sine-wave. However, it was precise enough to see the sine-waves are delayed by an activation of load.

4. SIMULATION

Simulations were made in LTspice IV and Mircosoft Excel. In these simulations real resistance and inductance per unit length were used. Our simulated system was connected to a power source with 400 meters long NAYY 4x150 cable with 0,206Ω/km and 0,26mH/km [4]. Two grid topologies were worked out both with NYM-J 3x1,5 in different length (20 and 50 meters). A specific resistance per unit length of 12,1Ω/km and an inductance of 0,343mH/km was taken. For the loads a specific resistance of 23Ω was chosen.

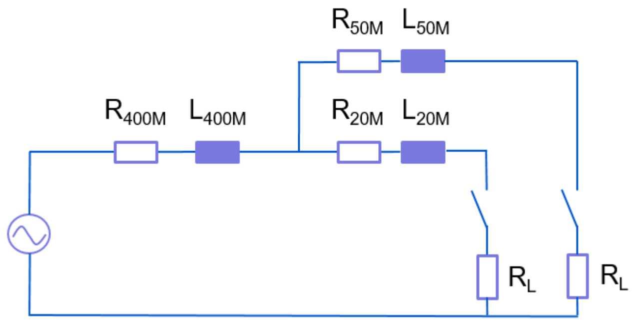

Figure 6: Two-string topologic (top. 1)

Figure 6 shows two different strings. They are connected to different fuses but the same phasor. This topologic was used to simulate the phasor-shift and voltage cracks at different points.

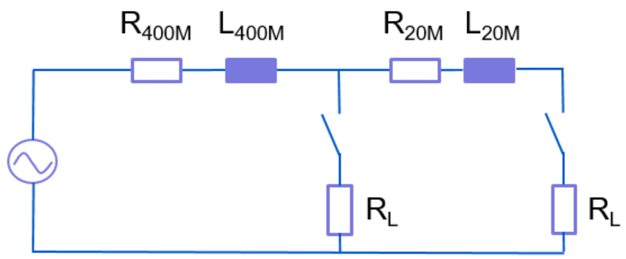

Figure 7: One-string topologic with two loads (top. 2)

In figure 7 only one string with two loads was used. Here the relation between voltage and different loads and the phasor was analyzed.

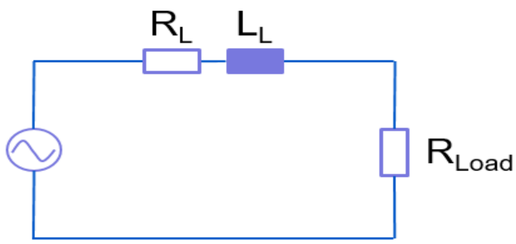

Figure 8: Easy phasor analytic

With electric circuit above, different loads were tested focusing on the different occurring phasor angles. For every specific load, a different phasor angle is attributed. The simulation as executed in Excel and allowed a calculation between phasor angle and height of the load. The results are shown in chapter 5. This simulation again used the specific parameters of two standard cables (400 meters NAYY 4x150 and 20 meters NYM 3x1,5). This specific data was set to the resistor and inductive in the electric circuit.

5. RESULTS

5.1 Voltage fluctuations and grid impedance

In chapter 3.1 the measurement of voltage fluctuations and the resulting grid impedance was described. Different measurements were recorded to identify the influence of a load in different positions in a household. The grid impedance at every voltage jump (induced by a load) was determined. In this measurement no relationship could be found impedance-change due to the load. The grid impedance rises or falls randomly. Theoretically it should decrease with higher loads. This method gives no solution to the problem.

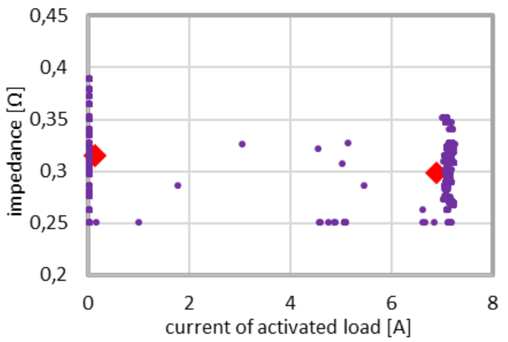

Figure 9: Impedance depending on load

Figure 9 shows the grid impedance depending on the load. A known load was turned on and off and for every voltage-jump the impedance was analyzed. The impedances range alters between 0,25Ω and 0,4Ω. The two clouds indicate there is a change in impedance caused by added load (the rectangle boxes indicate the arithmetic mean of the clouds). Calculations showed that the expected resulting change of impedance above is too high to be induced only by the known load that has been turned on and off. Occasionally, the impedance even raised, after activating the load – which is only explainable by natural impedance fluctuations of the grid. That means, no absolute load is reconstructable. Only qualitative assessments about a load are possible.
Hence, we analyzed other measurement with different places of load in the household. Important for this was that the same phase was used for the position of measurement and load. The two topologies shown in chapter 4 were analyzed and the length of the wires had been varied. Both, measurement and simulation result in similar manners (according to voltage trends, instead of absolute voltage differences). If a measurement was located close to the grid, the following relation was proven: The closer the load to the position of the measurement, the higher is the voltage drop. This means the impedance was higher.

Table 1: Results by simulation in topologic 1:

	voltage-drop gird to string 1	voltage-drop grid to string 2
string 1 load turned on:	6,2 V	1,78 V
string 2 load turned on:	1,65 V	12,58 V
both loads turned on	7,79 V	14,17 V

Table 2: Results by simulation in topologic 2:

	voltage-drop grid for near load	voltage-drop grid for distant load
distant load turned on:	17,46 V	23,53 V
near load turned on:	17,78 V	17,78 V
both loads turn on	33,42 V	39,17 V

The determined impedances ranged between 1,27 Ω and 1,63 Ω in the second topologic. In the first topologic they are between 0,62 Ω and 1,26 Ω. Measurements in real households showed impedances between 0,3 Ω and 0,4 Ω.
The result of topologic two displayed the following relation: The closer the distance to gird, the lower the voltage drops. The influence of the load is way smaller than the influence of the cables in the grid. No estimation of the load can be performed. Nonetheless due to the given impedance in the grid, a voltage drop indicates a load that turned on.
If an estimation via known voltage drop is made for unknown loads, the voltage drop is highly dependent on how far the load is away from the metering position. This likely leads to an underestimation of the load situation and therefore, to unsafe (risk of overload) or too cautions operation (too early safety shutdown of the PV-System).

5.2 Phasor-shift

The same simulation setting but with focus on phasor-shift and different loads achieves the following results:
In the topologic with two strings (figure 6) it is not possible to define the load of one electric string. The influences on the phasor-shift are nearly the same, no matter in which string a load is placed. The main reason for this is the high inductive share of the long cable from the transformer unit to the house. In contrast, the inductive influence of the house wiring is very low. Nevertheless, an estimation about a load can be made, because it produces a shift of the phasor. In comparison to the complex output voltage of the transformer, it can be well seen. Yet a PV-system would only be able to record the voltage at one safety-socket before and after a load was added. The phasor differences at that position aren't significant enough to perform a load estimation. For measuring the phasor shifts, time differences of microseconds must be evaluated. Besides the high requirements a build-in meter must meet to do so, a great uncertainty is given by the slight frequency changes in the grid, which affect the durations of the sine half-cycles in the microsecond dimension.

Table 3: Results from the simulation in topologic 1:

	phasor-shift gird to string 1	phasor-shift grid to string 2
string 1 load turned on:	4,98 µs	4,70 µs
string 2 load turned on:	4,556 µs	5,236 µs
both loads turned on	9,476 µs	9,889 µs

Table 4: Results from the simulation in topologic two:

	phasor-shift gird to near load	phasor-shift grid to distant load
distant load turned on:	5,13 µs	5,43 µs
near load turned on:	5,248 µs	5,248 µs
both loads turned on	9,856 µs	10,14 µs

Further, measurements for the second topologic have been recorded. Because the transformer was far away, no reference voltage values from the transformer could be recorded. They only allow to compare the complex voltages before and after a load activation (same conditions for the PV-system).

Table 5: Phasor-shift with load

half-cycle	load	real zero-crossing point	calculated zero-crossing point	phasor-shift
0	0 kW	25,6335 ms	25,6335 ms	0 µs
1	1,8 kW	35,6307 ms	35,6307 ms	0 µs
2	1,8 kW	45,6279 ms	45,6363 ms	8,4 µs

For this measurement a hairdryer with a power of 1800 watts was activated. The phasor-shift has the same dimension than in the simulation. Based on that, a load could be estimated, but the position of the load is unclear. In fact, this load could be turned on in a neighboring house (which would be irrelevant for the PV-system) and the phasor would still shift in the same dimension because the long wire from the transformer would still have the same highest influence for both houses.

These calculations are based on comparing the half-cycle durations of the half-cycles around the event that the load is being activated or turned off. A measurement of the half-cycle durations shows that there are natural fluctuations in the dimension of the phasor-shift, affected by a load. Therefore, the results of comparing the neighboring half-cycles hold some uncertainty. In addition, it is possible, that the delay takes place in more than one half-cycle, see figure 10:

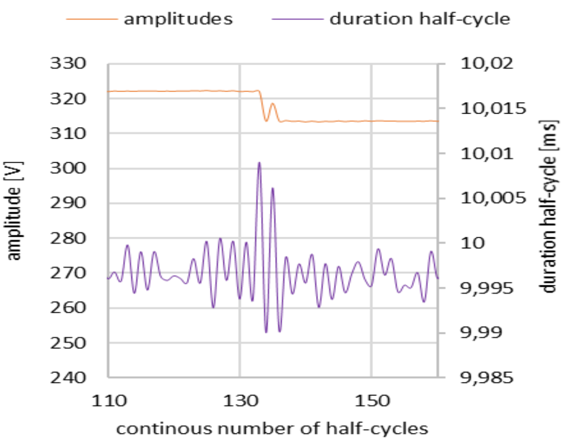

Figure 10: Half-cycle duration variation

5.3 Phasor-angle under different load levels

The circuit in figure 8 was affected with different loads (R_{Load}). The following diagram shows the results of the simulation:

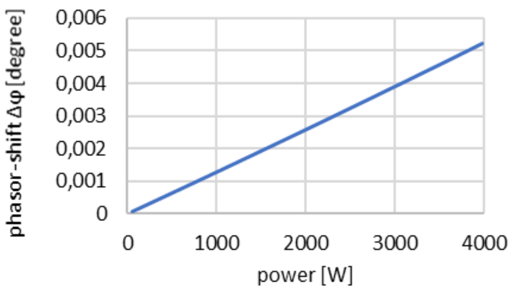

Figure 11: Phasor-shift due to load

The simulation was made until the maximum power a phasor with 16 amperes can provide (3,6 kW). A quasi linear relation between phasor-angle and power can be clearly seen. The following can be concluded by this simulation: The higher the load, the higher the phasor shift. A simulation of higher power (50 kW) showed, this relation turns out to be nonlinear for very high loads. If this nonlinearity would already occur in the range of the diagram above, an estimation of the actual load situation would be possible. In this case, thanks to the nonlinearity, the phasor shift, after activating a known constant load, would reach various voltage differences, depending on the surrounding load situation.

6. CONCLUSION AND FORECAST

A relationship between load and grid impedance was found. However, the influence of loads was too low, to do accurate load estimation. This is due to the dimension of measured grid impedances was extremely low. Even in cases where an influence on the impedance can be seen, the grids natural changes of impedances are higher. Accordingly, no certain determination of the load situation can be done via the grid impedance.

The phasor-shift investigations showed that a load has a reproducible influence on the phasor shift. This can also be shown by simulation. For measurements, a very precise detection of the zero-crossings is necessary to distinguish the small time- and therewith phasor-shifts between loaded and unload situations. Here, uncertainty comes due to the frequency changes the grid. Therefore, precise approaches and fittings must be done to overcome uncertainties. Because the impendency of the long wire to the house is higher than the one of the households wiring, every load shows the same phasor-shift dependency, regardless its position. It can’t be figured out in which house the load was activated.

Because the resistance of household wirings is higher than the resistance of the grids cable, voltage jumps can help to estimate how distant a load has been activated from the point of measurement. This relationships occurs: A high load that is connected via a long wire to the string, in which the measurement takes place, will show the same voltage jump than a small load located close to the string. This has a potential of underestimating the load. Therefore, a safety factor is necessary, if the PV-system should decide on basis of voltage jumps.

For good load determination a combination of phasor measurements and voltage drop analysis seems to be helpful. In this scenario, phasor-shifts are used to determine the height of load (thanks to the linear relation of phasor-shift and P_{Load}: Figure 9) and voltage jumps to estimate the distance to the load. Then, with some uncertainty, it will be possible to determine whether a load is in the string of measurement (this would be, where the PV-system is) and how high the load is.

For this, further investigations are needed: an exact acquisition of the influence of frequency changes in the grid to the detection of phasor-shifts must be made. In addition: voltage jumps that come naturally from the grid must be considered to determine how high a security factor needs to be (as mentioned above). Therefore, a data-logger needs to record for a longer term. Further, the PV-system needs a shunt-resistor to analyze the effects this takes onto the grid in terms of phasor-shift and voltage jump. Even though this could be theoretically done by observing the grids reaction when the PV-system starts and stops feeding into the grid, the power difference needed for certain analyzes must be several dimensions higher.

The results showed, that no measurement of the current is needed to estimate the load situation if the shunt-resistor in the PV-system is known. In fact, in this investigation, current-metering was only needed to indicate whether a load was activated or not.

Above all, it is interesting how standardization committees will change regulations for PV-systems with safety plug in the beginning of 2019.

8. SOURCES

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