PROBABILISTIC SIMULATION FOR LV-GRID OPTIMIZATION WITH NEW NETWORK COMPONENTS

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ABSTRACT

Sustained integration of distributed renewable energy sources (especially photovoltaic generation in low voltage grids) has driven the need to expand grid capacities in recent years. Solutions to finding an economic justifiable approach for mains operation in an aging grid environment have become indispensable.

This paper highlights the design of a probabilistic simulation environment. Furthermore it provides the possibility to rate new grid technologies taking all conceivable grid states into account. Thereby the simulation is based on actual, measured field data instead of standardised profiles. The aim is to create a simulation environment where different grid situations can be simulated allowing DSOs to optimize their grid planning. Especially low voltage grid simulations with few grid participants lacking accuracy, when modelled by standardized profiles, will benefit from this approach.

INTRODUCTION

Due to the sustained integration of renewable energy sources (RES) into the distribution grid, more and more areas reach the critical point were locally generated power is fed back into the higher grid levels. This results in various fluctuations in the distribution grid which is already operated at its technical limits. To prevent a massive, cost intensive conventional grid expansion leading to overcapacities that are rarely used, new technologies summarized under the term of “smart grid technologies” can constitute a possible solution.

In order to benchmark different approaches and technologies a realistic simulation environment is created and based on actual measurement data. As a testing area, the low voltage (LV) grid of a small village in southern Germany (SONDERBUCH) has been equipped with a large variety of sensors providing a detailed view of the actual grid condition. With more than 60 independent renewable energy sources (RES) all based on photovoltaic (PV) systems and only 80 loads, a very high PV penetration is already present in this grid. As a result, the overall amount of about 1.2 MW_P can be generated at times facing only 0.2 MW_P of maximum load. The surveyed grid therefore provides excellent conditions in representing assumed future developments in other areas. Fig. 1 depicts Sonderbuch including all main bus bars and interconections. Grid section 2 with the installed CDT is highlighted in yellow.

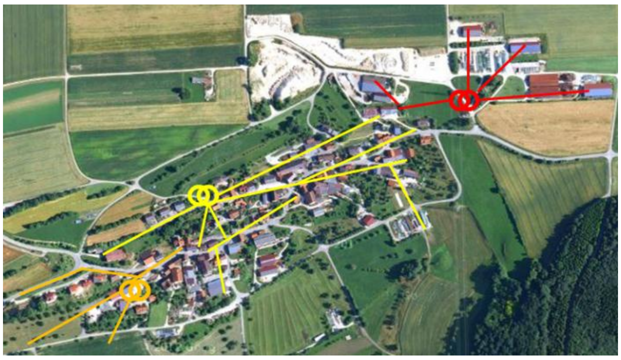

Fig. 1: Areal view of SOUNDERBUCH, Zwiefalten including main bus lines.

MOTIVATION

Today, according to standard rules, the complexity to design the LV-grids is reduced by assuming that the connected loads can be modelled by mean values based on experience. Only special loads with known behaviour like heat pumps and night storage heaters are added with a specific load profile. When RES are installed in the area, the grid stability is calculated using the two scenarios; “maximum infeed – no load” and “maximum load – no infeed”. This creates overcapacities that are rarely used. The approach for a better and faster integration of RES is to utilize these overcapacities and avoid unnecessary grid expansions.

When reducing the reserves in the grid design and improving the grid utilisation grade, the simplified assumptions made for the loads can become problematic, as they do not represent the actual behaviour of the customers. The procedure for emulating the loads in a simulation with a small amount of grid participants, by using scaled standard H0-profiles is not a sufficient option as shown in [1]. Especially the voltage band edges on each node in the grid are mainly influenced by the behavior of every single customer and source connected to the grid. Therefore it is important to model the grid participants more detailed then with a standard profile, if reliable statements on the voltage band edges are required. Considering this, probabilistic approaches offer a promising solution [2]. This paper will discuss one possibility for a probabilistic approach to emulate customer and source behavior in a simulation environment for a LV-grid. Furthermore it will show possible influences to and variations of the voltage bands which can be achieved by integrating a controllable distribution transformer (CDT) in the simulation as done in this grid in late 2012.

APPROACH

In order to proceed with the probabilistic approach, a set of daily profiles with a 15 minutes time resolution is generated at each metering point out of the measured data. Smart meters at 30 customers and 45 photovoltaic devices were taken into consideration. An overview of the methodology can be seen in Fig. 2.

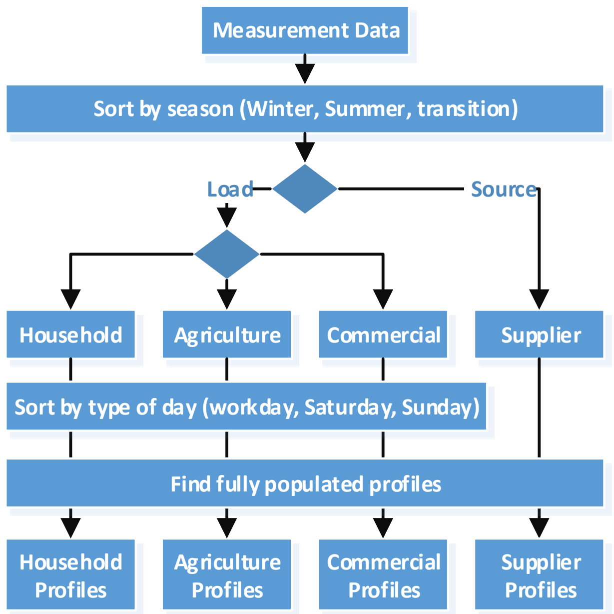

Fig. 2: Overview of methodology used for data processing.

In order to compensate seasonal characteristics, the data sets of all four groups were clustered into three seasons according to the VDEW: “summer”, “winter” and “transition”.
All grid participants which provided data were classified into two main-, and four subcategories. The load-category is further split into the three subcategories, households (16 meters), commercial users (two meters) and agricultural users (twelve meters). Five of the 75 meters are 2-way-meters allowing a consumption of the generated power directly at the customer’s site without utilization of the public grid. They account for one household, four agricultural loads and five suppliers.
In the same step measured load values were standardized to their recorded maximum, keeping in mind that the recorded maximum is a 15min average, not the actual value which might have occurred. Source values were standardized to the respective installed peak power.
Loads are further sorted in “workday”, “Saturday” and “Sunday” (including federal holidays as observed in Baden-Württemberg, Germany). Assuming weather conditions are not linked to specific days of the week, sources are not sorted any further. Only fully populated profiles with at least one value different from zero and no missing values were filtered to form the base of the probabilistic approach.

With all profiles scaled down to standardized values, they become interchangeable between meters of the same subcategory. This means profiles can be assigned at random within the same subcategory, even if this specific participant did not provide any measurement data.

Table 1: Fully populated profiles used as simulation input.

Summer Workday	PV	House-hold	Agri-culture	Com-mercial
Number of Profiles	**4185**	**881**	**817**	**147**

Meters from the source category need to stay within daily weather patterns. This is achieved by drawing a day for the sources at random, using only the profiles of that day as a base for one out of 10,000 simulation steps. In addition, sources need to compensate for installation parameters, e.g. their alignment. Therefore profiles are linked to their own meters compensating installation parameters. Meters with no directly measured profile get assigned one at random with no possibility to compensate for installation parameters.

From previous measurements done at the low voltage substations it was possible to determine an average resilience of the overlying grid to change in voltage levels varying with the load flow. This value was used to recalculate the voltage level of the overlying grid for every time interval.
After assigning the profiles, load flow calculations are done in 5 minute intervals for a whole day. Voltage levels were recorded at each terminal in the grid. The entire process was repeated 10,000 times. This yields 10,000 calculated voltage levels for each time interval and each terminal in the grid.

Using the gained data distribution a statistical analysis was done to show how often specific voltage levels (maximum, minimum, 1^{st}, 5^{th}, 95^{th} and 99^{th} percentile) occur at certain nodes. Analyzing these values, the critical nodes in the grid and the possible upper and lower voltage confidence belt can be identified.

Comparing the voltage distribution function with and without CDT installed [3], offers reliable statements on the effectiveness and benefit of a CDT. The CDT controller in this simulation is programmed to measure the load flow at the substation bus bar and tries to hold the voltage level to 1.0 p.u. by changing tap-changer positions.

RESULTS

Based on previous work [1] the combination of interest is a typical summer workday. During noon hours this combination is expected to yield the largest generation with relative low load. This results in the highest net load flow in the grid and large voltage fluctuations.

In this paper, grid section 2 of the low voltage grid of Sonderbuch was observed because of the three transformers supporting the separated grid parts, only this substation is equipped with a CDT since late 2012. In addition grid section 2 is by far the largest of the three sections covering approx. 60% of the overall LV-grid.

In order to monitor the development of the voltage levels in the grid section 2 a special point of interest (POI 1) was selected on preliminary simulation results. This special node will be center of discussion in this paper as it is the most likely to be in violation of the EN 50160, hence this node undergoes the highest voltage fluctuation.

To gain an impression on how effective the CDT is at controlling the voltage level, the grid was first simulated using a static transformer. These static results are then compared to a control method adjusting the tap depending on load flow conditions as described in detail in [4]. Former results showed promising effects for this approach.

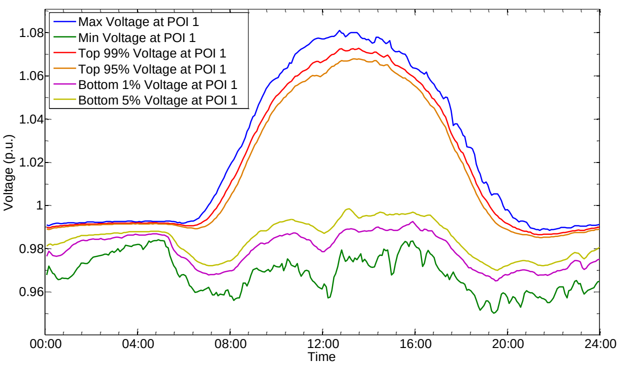

Fig. 3: depicts the absolute maximum and minimum voltage curve observed during conditions of a "summer, workday". In addition the 99^{th} / 1^{st} voltage percentile and the 95^{th} / 5^{th} voltage percentile at POI 1 are shown over 24 hours based on 10,000 iterations.

Because of the controller behavior of the CDT, the simulation step size of 5 minutes and the CDT dead time of 10 minutes (for flicker prevention), it makes sense to evaluate the 95_{th} and the 5_{th} voltage percentile. This excludes special cases of situations in which the controller was confronted with weather conditions that changed faster than the resolution of the simulation, such as fast moving clouds. These cause large voltage fluctuations in both directions which the CDT had no opportunity to react to, due to lack of time resolution. None of these fluctuations however violated any terms of the EN 50160 as simulation results showed.
The 95^{th} percentile depicts the curve not including the top 5% of all values that occurred; hence the 5^{th} percentile shows the curve without the top 95% of all values.
Fig. 3 shows the simulated voltage bands. In early morning hours voltage levels are below 1p.u. due to lack of solar generation. Starting around 06:00 the 5^{th} percentile dips as expected due to an increase in loads. As soon as solar generation kicks in, the voltage bands spreads. This is the result of the randomly assigned profiles which simulate anything from sunny to fully clouded weather conditions. The absolute minimum voltage levels are reached during evening hours and the spread slowly diminishes as the night progresses.

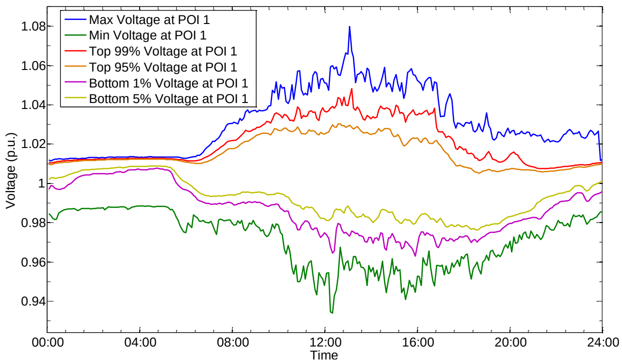

Fig. 4: shows the same voltage curves at POI 1 with the CDT installed.

Comparing figure 2 and 3 the effect and the benefit of the CDT can be identified. While the effect of the CDT on the upper voltage bands is small in the early and late hours of the day, a significant lowering of the voltage bands between 10:00 and 16:00 hours can be identified. During this time the CDT detects an increasing reversed load flow and changes the tap position to compensate for rising voltage levels. Table 2 shows the change in characteristic measurements taken from the results.

Table 2: Changes in 5^{th} and 95^{th} percentile.

	No CDT	CDT
Minimum of 5^{th}	**0.9985 p.u.**	**0.9761 p.u.**
Maximum of 95^{th}	**1.0678 p.u.**	**1.0304 p.u.**
Spread of 5^{th} and 95^{th}	**0.0693 p.u.**	**0.0543 p.u.**

Fig. 5 and 6 depict the voltage distribution with and without a CDT over time.

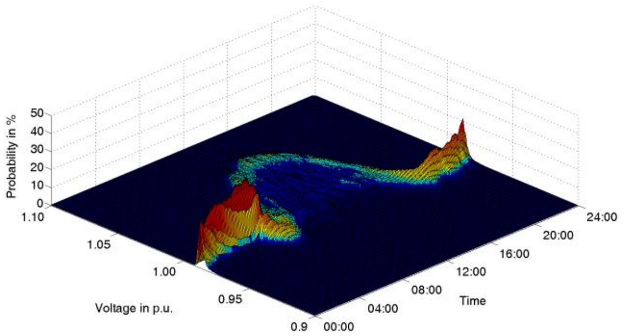

Fig. 5: depicts the voltage distribution for POI 1 over 24 hours in the category "summer, workday" without a CDT installed.

As figure 3 shows selected percentiles, in fig. 5 the z-axis shows the probability of occurrence over all voltage levels at any time slice of the day in percent. The small spread between the 5th and 95th percentile observed in Fig. 5 during morning and evening hours forms a high peak of probability around the respective values. Starting 10:00 till 16:00 hours there is only a very low peak on the z-axis. The result are wide spread voltage values. This is caused by the various possible grid states and the different generation states of the PV units mirroring real PV generation states. This is coherent with the large distance between the minimum and maximum voltage band of Fig. 3.

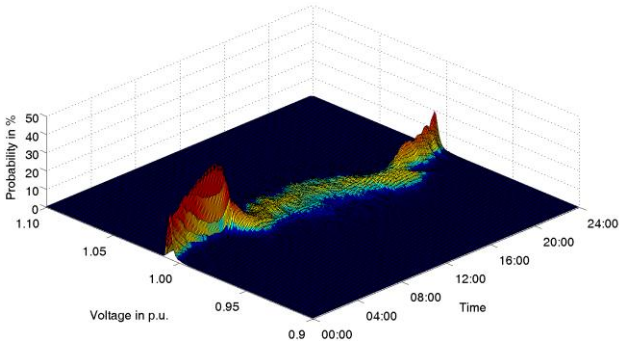

Fig. 6: shows the voltage distribution for POI 1 over 24 hours with a CDT installed in the category "summer, workday".

Depending on the input parameters for the CDT controller, the peak in the early and late hours of the day shifts to 1.01 p.u. resulting in reduced grid losses. The wide spread of voltage values between 10:00 and 16:00 hours is reduced to form a small bump in the area about 1.01-1.02 p.u.. This reduces on the one hand dispersion to any extreme values and on the other hand it is more likely to reach a reduced voltage peak value while maximum PV generation as a result of the CDTs intervention. The voltage band seems significantly compressed and shifted to a given target value.

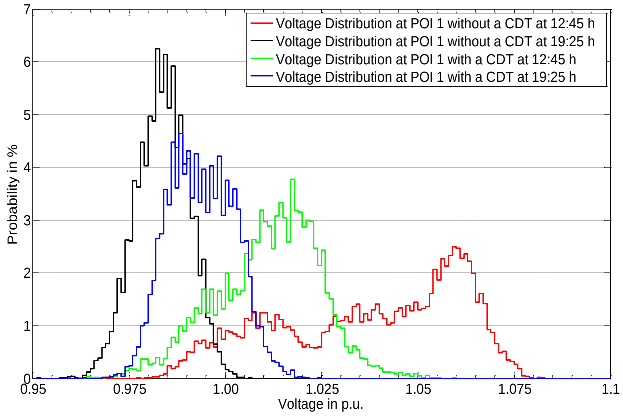

Fig. 7: shows the distributions of the voltage values at POI 1 during the time intervals at which the maximum and minimum voltage readings occurred without a CDT. Maximum and minimum voltage values occurred at POI 1.

Fig. 7 depicts the voltage distributions during the time intervals when the minimum and maximum voltage occurred without a CDT. This is compared to the same time intervals with a CDT active. Table 3 compares characteristic points of these distributions.

Table 3: Characteristic points of voltage distributions.

	No CDT	With CDT
Average, 19:25h	**0.982 p.u.**	**0.992 p.u.**
Average, 12:25h	**1.036 p.u.**	**1.001 p.u.**
Max. probability, 19:25h	**0.982 p.u.**	**0.988 p.u.**
Max. probability, 12:25h	**1.059 p.u.**	**1.017 p.u.**

Asserting the voltage curves in fig. 7 with and without a CDT installed it can easily be seen that the voltage distributions changed their shape, location and their probability respective their height. Comparing these figures the CDT with its implemented controlling method depending on the load flow condition is able to shift the average maximum voltage (12:45h, red curve) to lower levels (12:45h, green curve) and lift the average minimum voltage (19:25h, black curve) level to higher values (19:25h, blue curve). As a result the voltage spread is significantly reduced. The most probable values moved closer to the specified target of 1.00 p.u. and both the absolute minimum and maximum voltage levels could be influenced positively.

The narrower spreading of voltage values is a measurable and quantifiable effect of the CDT and a real benefit to the DSO. The monetary value is hidden in the conventional grid expansions which can be delayed or maybe avoided by implementing a CDT.
These simulation results allow parameterization of the controlling method used by tap changer controller depending on the height of the reversed power flow caused by the RES.

Furthermore it is possible to determine the effectiveness of a proposed controlling method in the created simulation environment without any risk to the DSO.
It is also possible to change the grid topology using the simulation environment to other specific grids with any voltage band problems and predict the usability of a CDT in this specific grid.

CONCLUSIONS

As shown by this paper, probabilistic simulations are a viable tool for grid analysis and validation of new technologies. It is possible to simulate the expected voltage and power distributions on every node in a given topology, also including effects of new technologies and components. For the presented situation the simulation was able to show that a CDT will ease the critical gird condition in the village SONDERBUCH. The reduction of the peak voltage band caused by the CDT also allows for additional integration of RES without additional grid expansion needed.
The huge advantage compared to prototype testing is that all possible grid states are taken into account in addition to a prediction how often certain situations will occur. With the simulation results, different grid enhancements can be tested, ranging from classical grid expansions to new innovative components like the CDT. Furthermore it is possible to determine the effectiveness of each approach and prove the benefit to the grid before the actual hardware installation. The flexibility of the simulation thereby allows compensation for different grid topologies and RES allocations with all season and day characteristics.
The next steps for this research project will include a detailed analysis of different control algorithms for the CDT as well as a field test to verify the simulation results.

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