Evaluation of syncrophasor use in distribution grids to estimate the regional grid state

Eberhard Waffenschmidt, Patrick Littau, Christian Pelikan
TH-Köln, Betzdorferstr. 2, 50679 Köln, Germany
correspondence to: eberhard.waffenschmidt@th-koeln.de

Abstract

It is known that synchrophasor (also "voltage angle") measurements in the transmission grid can retrieve information of the regional power grid state. This makes such measurements attractive for decentralized grid components. If they could share information about synchrophasor measurements, they could use the information about the regional grid state for independent operation.

However, most of the decentralized components are connected to the distribution grid in the medium voltage or low voltage grid. Therefore, we suggest to measure the syncrophasor (also "voltage angle") at the device's point of connection to derive such information. On the way to the connection point of a device in the low voltage grid, this syncrophasor may change. Therefore, this publication investigates, how the syncrophasor changes on this way. This is done by simulations. As a result, the voltage angle has a variation of about 1.5° in the medium voltage branch and 6° at the end of the low voltage branch. This is significant smaller than the anticipated syncrophasor variations in the transmission grid of up to 60°. Therefore, the simulations give an indication that syncrophasor measurements in the distribution grid might be used as an indication for a regional excess or demand of power.

1 Introduction

Adding more renewable generation to the power grid means more decentralized generation. At a certain level of renewable energy penetration this also requires a decentralized grid control. As a possible option, grid connected devices could be able to detect the state of the power grid by measuring physical parameters at their point of connection. They would then be able to react on such information with a suitable reaction. All devices together would be able to react beneficially for the grid as a "swarm" of devices.

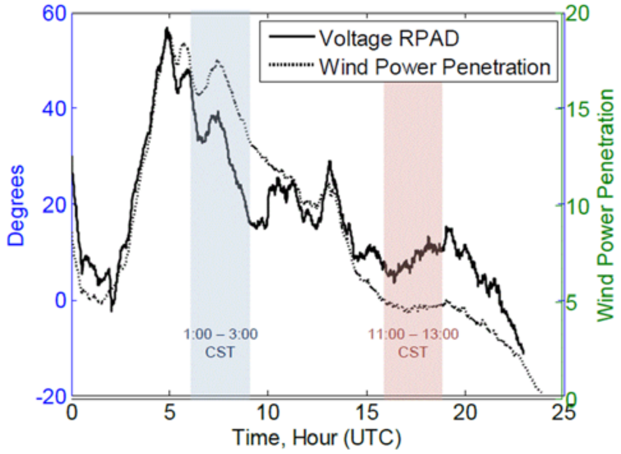

Figure 1 Relative phase angle difference (RPAD) between Austin and McDonald, Texas, USA during various wind power levels [3].

Measuring the grid voltage gives information about the grid state at this point and measuring the grid frequency informs about the state of the total grid (e.g. whole Europe). However, neither information about the grid state in the region (excess or demand of power), nor about the neighbourhood (overloaded line or transformer) can be obtained with these measurements. Therefore, we suggest to measure the syncrophasor (also "voltage angle") at the device's point of connection to derive such information. This contribution presents first simulation results, which indicate that such an approach might be suitable.

The syncrophasor measurement is the measurement of the phase shift of the alternating voltage against a fixed, precise time reference (details see e.g. [1]). It is becoming a tool in the transmission grid to detect the regional grid state [1][2][3]. As an example, the voltage phase angle can be attributed to the infeed of wind power energy in a region (see Figure 1) [3]. As can be seen from the figure, the voltage phase angle may change over a range of about 60 degrees. Other publications suggest similar ranges [1][2][4][5].

Measuring the voltage phase angle in the distribution grid is an evolving technique. Low cost phasor measuring units (μPMU) are recently proposed and presented in several publications. [6] proposes a network of high-precision phasor measurement units and their applications in the power grid. [7] gives an overview of their work. Another proposal for a low cost μPMU device with costs of approximately 350 US$ is presented in [8], where also details of the construction and timing are discussed.

The most relevant information about the regional grid state is present at the nodes of the transmission grid. On the way to the connection point of a device in the low voltage grid, this syncrophasor may change. Therefore, this publication investigates, how the syncrophasor changes on this way. This is done by simulations.

2 Simulation setup

For the simulations, a reference grid suggested by CIGRE has been selected. It is described by K. Rudion in reference [9] for the medium voltage and low voltage part. The medium voltage part is simplified to a single unmeshed branch. The used grid consists of a medium voltage branch and a low voltage branch as shown in Figure 2.

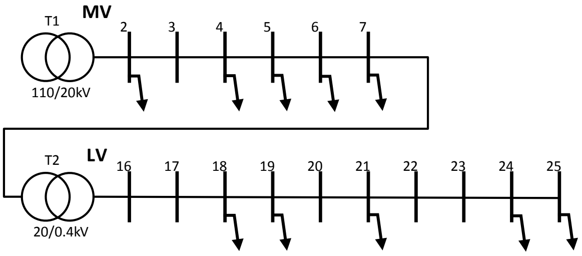

Figure 2 Modelled power grid. Based on CIGRE reference grid [9] and simplified.

Table 1 Characteristic of the transmission lines. X': inductive reactance, B': capacitive admittance, medium voltage data adopted from [9] and low voltage data based on [10].

Line	R'[Ω/km]	X'[Ω/km]	B'[µS/km]	l [km]
2-3	0.4	0.7	1.75	2.82
3-4	0.253	0.203	73.83	4.42
4-5	0.253	0.203	73.83	0.61
5-6	0.253	0.203	73.83	0.56
6-7	0.253	0.203	73.83	1.54
16-17	0.163	0.136	314.2	0.035
17-18	0.163	0.136	314.2	0.035
18-19	0.163	0.136	314.2	0.035
19-20	0.163	0.136	314.2	0.035
20-21	0.163	0.136	314.2	0.035
21-22	0.163	0.136	314.2	0.035
22-23	0.163	0.136	314.2	0.035
23-24	0.163	0.136	314.2	0.035
24-25	0.163	0.136	314.2	0.035

The characteristics of the lines between the nodes are listed in Table 1. The first line between nodes 2-3 is an overhead line, while all others are cables. The line lengths in the medium voltage grid ranging from, 0.5 km to 4.4 km are significantly longer than in the low voltage grid with 35 m between the nodes. This corresponds to reality, where medium voltage lines are used for longer distance and low voltage is used to distribute energy locally.

Table 2 shows the number of households connected to the busbars indicated in the figure. An amount of 65 different electric load profiles for households taken from [11] and [12] are connected randomly to the busbars. The different profiles are generated with a load profile generator using a behavioural model [13]. The large number of individual profiles allows a statistical analysis of the simulation results. Figure 3 shows an exemplary plot of the superposition of load profiles as used in this work. The loads are assumed to be distributed symmetrical among the three phases.

Table 2 Number of households connected to the busbars and related power factor.

Busbar	Amount of Housholds	cos(φ)
2	18742	0.98
4	2084	0.97
5	539	0.97
6	909	0.97
7	541	0.97
18	6	0.85
19	60	0.85
21	26	0.85
24	6	0.85
25	26	0.85

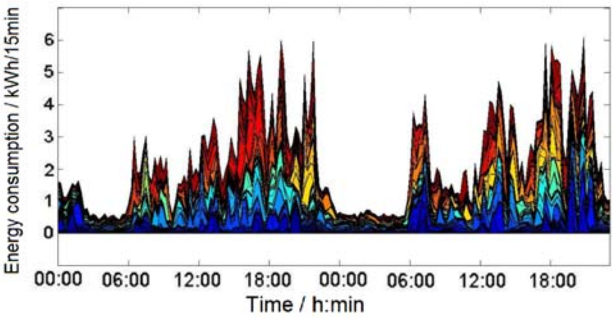

Figure 3 Exemplary plot of superposition of load profiles [12] as used in this work.

For each line a π-equivalent circuit as shown in Figure 4 is used as the line length is much shorter than the wavelength. For the low voltage lines, a line capacity of 1 µF/km is assumed. The line capacitances cannot be neglected. A comparison showed an error of at least 0.08%/kW regarding the computed power angle, which may add up to more than 1° for realistic use cases.

A schematic of the whole branch of the grid is shown in Figure 5.

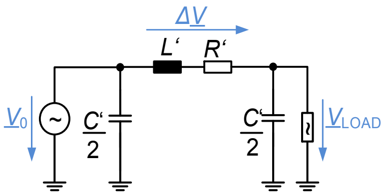

Figure 4 Applied line's equivalent network.

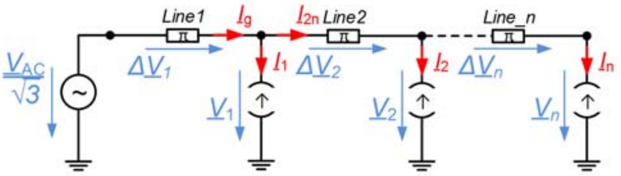

Figure 5 Schematic grid model with 1 source and n drains.

To calculate the system state, the current iterative method is applied. For each iteration step currents I_1 to I_n are calculated from the load power at the nodes and the node voltage V_1 to V_n, starting with setting all node voltages to the nominal voltage. With these currents the voltage drop is calculated and a next set of node voltages

$$\Delta \underline{V}_n = \underline{Z}_n * \sum \underline{I}_n \qquad \underline{V}_n = \frac{V_{AC}}{\sqrt{3}} - \sum_{i=1}^{n} \Delta \underline{V}_i$$

This is repeated until the node voltages converge. To simplify the calculations, the low-voltage level components were transferred to 20kV by the transformer's transfer ratio:

$$Z_{MV} = \left(\frac{V_{MV}}{V_{LV}}\right)^2 * Z_{LV}$$

where Z_{LV} are the impedance values related to the low voltage grid and Z_{MV} the values related to the medium voltage grid. The transformer T2 is considered by its longitudinal components Z_K resulting from the nominal short circuit voltage ratio v_k and R_k resulting from the nominal power loss P_{loss} at nominal current I_N:

$$Z_K = \frac{v_k * V_N}{\sqrt{3} * I_N^2} \qquad R_K = \frac{P_{loss}}{3 * I_N^2}$$

The simulation is performed by a script written in MATLAB® and further post-processing with EXCEL®.

3 Simulation results

As a result Figure 6 shows the time dependence of the voltage angles between the main connection point and node 7 (Medium Voltage Grid) and node 25 (Low Voltage Grid). In all cases the voltage angle has a negative value, because the inductive reactance of the lines dominates. Clearly, the voltage angle changes much less in the medium voltage grid than in the in the low voltage grid. Also the scattering is lower in the medium voltage grid.

Figure 7 shows the occurring maximum range between occurring angles at each node. In the medium voltage grid, only a small range between 0° and -1.8° appears. The voltage angle doesn't change much from the beginning to the end. In the low voltage grid the range becomes larger: at the last busbar it varies between -0.5° and -10°. In addition, the voltage angle increases from the beginning to the end. In the medium voltage grid the variation is smaller than in the low voltage grid due to much lower currents for the same power transmission.

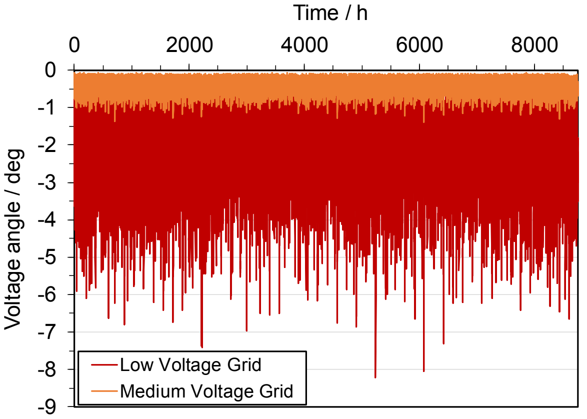

Figure 6 Time dependence of voltage angles between main connection point and node 7 (Medium Voltage Grid) and node 25 (Low Voltage Grid).

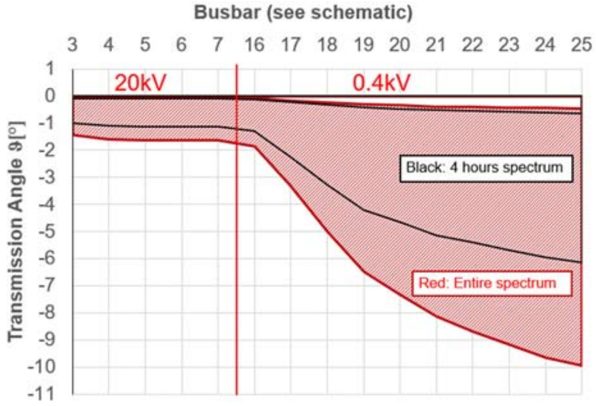

Figure 7 Occurring Transmission Angles over busbars 3-25 (Black: Occurring spectrum over 4 hours mean)

Figure 6 indicates much less scattering of the voltage angle in the medium voltage part of the grid. To quantify this, histograms of the voltage angle in the medium voltage grid and in the low voltage grid are calculated. Figure 8 shows the distribution of angles in the medium voltage part and the low voltage part. The figure confirms the assumption. In addition, it shows that especially in the low voltage part, extreme values with more than -6° are very seldom.

Voltage phasor changes in the transmission grid are anticipated as rather slow (compare also Figure 1). Averaging measurements at the point of connection should therefore less affect the contribution of the transmission grid. However, it may improve the angle variation in the medium and especially in the low voltage grid.

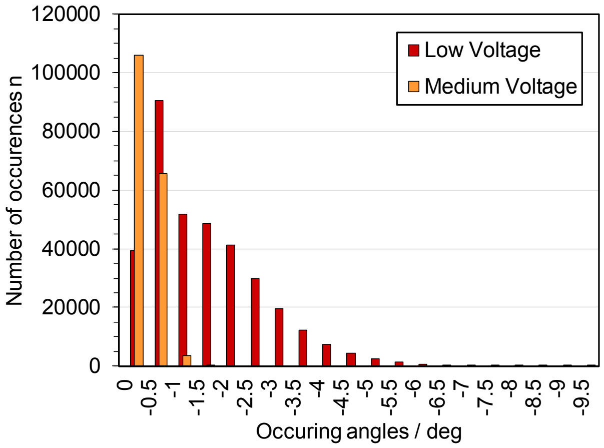

Figure 8 Absolute number of occurring values for the voltage phase angle.

Therefore, the values at the far end of the branch at node 25 are averaged over time. As a result, the time dependence of the voltage angle between main connection point and node 25 (Low Voltage Grid) with different averaging periods is shown in Figure 9. Comparing one hour averaging with the raw data (see Figure 6) shows no significant benefit. But compared to a measurement frequency of 4 times per hour, this is not astonishing. However, a 4 hour averaging apparently reduces the variation of the voltage angle significantly. The maximum spread is now less than 6°, as also indicated by the black curve in Figure 7. A daily average would even reduce the scatter, but such a high averaging would also affect the voltage phase change value of the transmission grid. Therefore, such an average interval would not be suited for the intended application. For comparison, the total average of all values is shown in the figure as well.

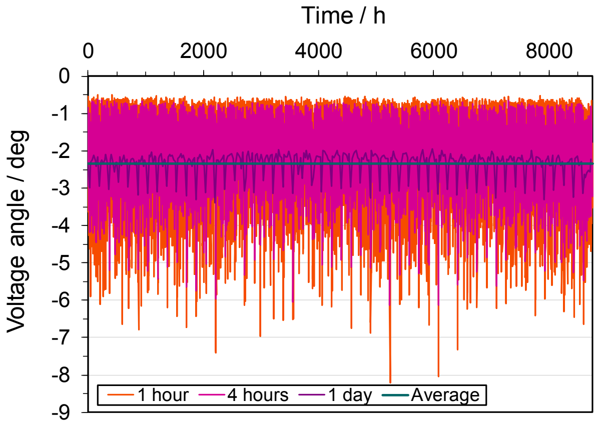

Figure 9 Time dependence of voltage angle between main connection point and node 25 (Low Voltage Grid) with different averaging periods.

Figure 10 shows the voltage phasor in the low voltage grid related to the one in the medium voltage grid. The different colours relate to different averaging times, which are applied, with similar colours as in Figure 9. This figure shows that the averaging does not only reduce the scattering of the values in the low voltage and in the medium voltage part of the grid. It also visualizes a linear dependence of the voltage angle change in the medium voltage on the voltage angle in the low voltage grid. Averaging improves this relation significantly. This may help in predicting voltage phase changes in the distribution grid.

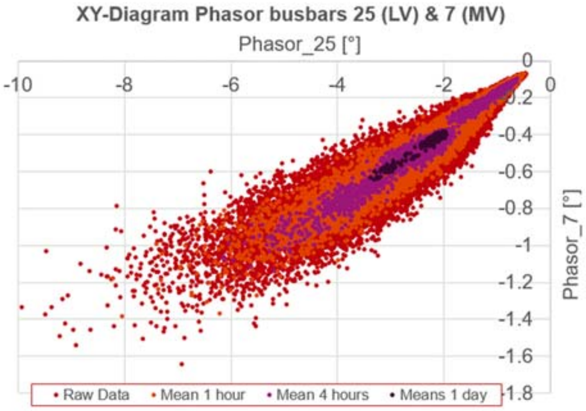

Figure 10 Data points of busbars 7 and 25 compared for various averaging periods

4 Conclusions

Concluding, such variations of 1.5° in the medium voltage branch and 6° at the end of the low voltage branch are significant smaller than the anticipated syncrophasor variations in the transmission grid of up to 60°. Therefore, the simulations give an indication that syncrophasor measurements in the distribution grid might be used as an indication for a regional excess or demand of power.

5 Literature

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