ESTABLISHING TRANSPARENCY FOR DISTRIBUTION GRID PLANNING AND OPERATION USING METHODS OF STATE ESTIMATION

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ABSTRACT

The integration of distributed energy resources in distribution grids leads to new challenges for planning and operation as uncertainty about the grid state is increased concurrently. State estimation can identify the grid state in distribution grids with little measurements in place. In this paper a low voltage grid in Germany was analysed. It was found that the estimates of the grid states in a high temporal resolution are of suitable accuracy and can be used for deriving relevant cases to be considered in grid planning. The three-phase implementation allows the analysis of both the voltage magnitude and the differences in phase voltages.

INTRODUCTION

Due to the integration of new distributed energy resources, such as photovoltaic systems, distribution grids are facing new challenges. These are mainly related to higher loading of assets and operation at the voltage limits defined by grid codes and national standards [1]. Two implications of these changes for distribution grid planning and operation are addressed in this paper. First, even with a higher amount of uncertainty due to volatile feed-in, grid planning still has to be done economically, i.e. grid reinforcement should only be done where it is necessary. Second, new control mechanisms in grid operation have to be in line with a safe and reliable operation.
Since measurement equipment is scarce in distribution grids, the momentary grid state, especially in the low voltage level, is typically not available to the grid operator. Therefore, the identification of problems is done in simulations assuming different load and feed-in scenarios, which involves security margins and serves as a worst-case assessment. In this paper it is investigated how methods of state estimation (SE) can improve the knowledge of typical situations arising in the specific distribution grid for deciding on reinforcement measures, deployment of innovative assets and parametrization of control approaches.

METHODOLOGY

State estimation based on weighted-least-squares (WLS) algorithms calculates the most likely system state by minimizing the estimation error and is well established in transmission grid operation [2]. Equation (1) shows the objective function that minimizes the sum of squared deviations between the measurement value z and the estimate $h(x)$ resulting from the state vector x for every measurement i, weighted with W.

$$\min J(x') = \sum_{i=1}^{m} \frac{\left(z_i - h_i(x')\right)^2}{W_{ii}} \qquad (1)$$

Equation (1) can be rewritten to

$$\min J = \frac{1}{2}[z-h(x)]^T[W^{-1}][z-h(x)] \qquad (2)$$

Where W is the weighting matrix associated with the measurements. Generally, the elements of W correspond to the variances of each measurement and therefore reflect the uncertainty of the respective measurement.
This optimization problem can be solved iteratively using the delta of the state vector from iteration k to $k+1$

$$\Delta x = [G(x_k)][H^T\, W^{-1}][z-h(x_k)] \qquad (3)$$

where H is the Jacobian matrix

$$H(x_k) = \left[\frac{\partial h(x_k)}{\partial(x_k)}\right] \qquad (4)$$

and G is the Gain matrix

$$G(x_k) = [H^T(x_k)\, W^{-1}\, H(x_k)]^{-1} \qquad (5)$$

If the increment Δx is smaller than a predefined convergence level, the final estimate for the given situation is achieved [3].
Three-phase current-based SE has proven to be a suitable solution for the estimation of the grid state in the low-voltage (LV) level including unbalanced loads and distributed energy resources [4]. The implemented system state vector x_φ comprises the complex currents I_{1-n} of every branch in the grid and the complex slack bus voltage U_{slack} for every phase φ [5]:

$$\overline{x_\varphi} = \begin{pmatrix} U_{slack,\varphi} \\ I_{1,\varphi} \\ I_{2,\varphi} \\ \vdots \\ I_{n,\varphi} \end{pmatrix} \qquad \varphi = 1,2,3 \qquad (6)$$

The implemented algorithm accepts four different types of measurements:

- Nodal Voltage and Power
- Branch Current and Power Flow

In order to solve the WLS problem, missing measurements are compensated using pseudo-measurements providing the solver with the required information of active and reactive power per phase of the unmeasured nodes. These pseudo-measurements are of high uncertainty and have a low weight in the estimation process [6]. Therefore a precise estimation can only be based on a sufficient number of real measurements with little uncertainty.
Since the performance of SE is dependent on the measurement position, measurement placement is done using an optimization algorithm [7].

FIELD TEST REGIONS

In total two low voltage grids in Germany, 'Wertachau' and 'Kisselbach', serve as the test case for the investigation. These grids are home to the research project "Smart Operator" [8]. Since a high number of measurement devices have already been installed in these grids, the quality of the estimation can be assessed by comparing measurements that were not used in the estimation with the estimate. Thus, the evaluation criterion for estimation quality is the deviation between estimated voltage and measured voltage at the smart meters spread throughout the grids.
In the following analysis the results for the grid in Kisselbach will be shown. The low voltage grid comprises seven feeders with approximately 150 loads and 14 photovoltaic installations. In total over 150 Meters are available, of which only 18 were used as input for the SE.
Although the SE algorithm is capable of processing other types of measurements as well, only the line to earth voltage magnitude and the active and reactive power at the respective node are used for the estimation.

STATE ESTIMATION QUALITY

In order to interpret the results of the state estimation, i.e. in the presented application primarily the voltage, in a first step the accuracy of the estimated has to be assessed. Only if the quality of the estimate is sufficient, the SE results will reduce uncertainty in planning and operation. The results show a good estimation quality, even when applying only very little measurements, resulting in deviations between (unused) voltage measurements and estimated values of typically below 1% (Figure 1). The average deviation is 0.49% and in the range of the measurement uncertainty. Also the 90% quantile of 1.34% and the average over the maximum deviation for every time step of 1.65% are tolerable. Previous analyses have shown similar behavior [6], [7].
However, both the comparison and the estimate itself are sensitive to bad data. The maximum deviation between measurement and estimate can range up to 9%. On the one hand low estimation accuracy can be caused by a wrong reference value and on the other hand a faulty input will lead to a wrong estimate. In the field trial this was observed at some places where the phase assignment was not consistent, e.g. the values for phase 2 and 3 were switched.

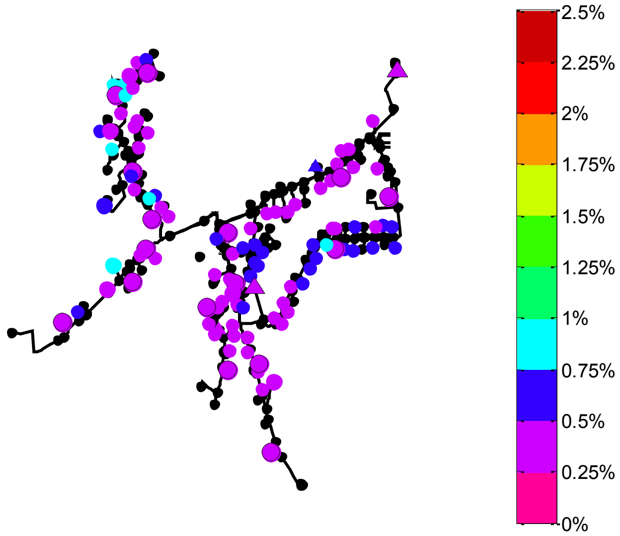

Figure 1: Relative Deviation between Measurements and Estimated Voltage

Apart from the discussed outliers the estimation quality is suitable for the application in planning and operation of low voltage grids. However, further research on how to overcome the issues of bad data in distribution grid state estimation is necessary.

RESULTS

In the following section, the results of the SE in Kisselbach in August 2015 are presented. The Results were calculated in a temporal resolution of one minute. Figure 2 shows the voltage distribution for the month for all three phases as line-to-earth voltage. In the histogram it can be seen that the majority of values is in the range between 230 and 240 V. During the considered period the voltage thus was characteristically above nominal voltage.

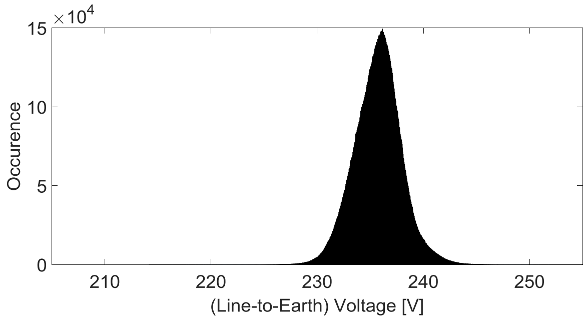

Figure 2: Histogram of Estimated Voltages

Table 1 provides an overview of the voltage behavior in the investigated period of time in Kisselbach. The results are given separated for every phase and the information about minima, maxima, median, average and quantiles provide an understanding of the distribution of occurred voltages. Both decreased and increased values for the voltage can be found. With the minimum value in the one minute resolution at 214 V. However, only 5% of the values are below the nominal voltage of 230 V. Simultaneously only 5% of the values are above 241.7 V. The average value of approximately 235 V reflects the observed shape from Figure 2.
It can clearly be seen that the maximum value for phase L3 is above the 10% margin defined in DIN-EN 50160. However, it has to be noted that the value estimated is only valid in one minute whereas the norm is based on 10-minute mean values. The respective 10 minute average including the maximum value of phase L3 is 246.25 V and therefore significantly below the limit of 253 V. For the other phases all one minute values have a maximum of 250 V.

Table 1: Overview of Estimated Voltages [V]

Phase	L1	L2	L3	Overall
Minimum	214.6	219.3	214.2	214.2
5% Quantile	230.0	230.4	230.4	230.2
Mean	235.5	235.7	235.9	235.7
Median	235.8	235.8	236.0	235.9
95% Quantile	241.4	241.7	242.0	241.7
Maximum	250.6	250.3	255.9	255.9

With respect to the temporal and spatial distribution of extreme values, i.e. maximum and minimum, the results show two characteristics:
First, all extreme values occur at different points of time for the different phases. Thus, six different points of time show a limit for the voltage in one of the phases. However, these extreme values can only be found in four different places. The maximum voltage arises at the same position for Phase L1 and L3. For phase L2 the maximum and minimum voltage are found at the same place.

Table 1 suggests that the values, especially the considered quantiles and average, are similar for all phases and that the voltage is symmetrical. The three-phase SE allows a detailed analysis of the voltage asymmetry in the grid. However, since the measured values only include voltage magnitude, the accuracy of the estimate of phase angle is unclear. Therefore the asymmetry analysis is based solely on the absolute value of the difference in voltage magnitude between the three-phases. Accordingly, three different deltas between phase voltages are calculated: L1 and L2, L1 and L3 as well as L2 and L3.
The resulting values cannot be compared directly with the asymmetry margin given in DIN-EN 50160, but provide an insight on the difference in voltage in the three-phase low voltage grid.

Figure 3 displays the histogram of the calculated phase differences for all three cases. The peak value can be found close to zero and the majority of values is below 4.6 V, which corresponds to 2% related to nominal voltage.

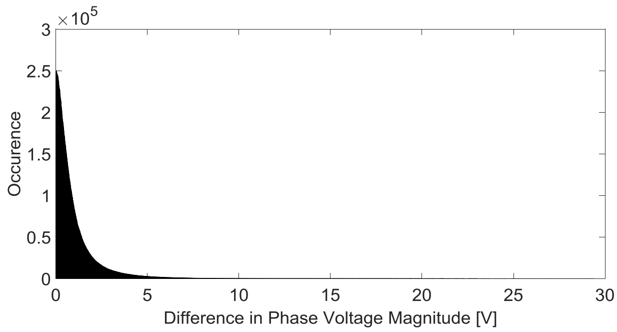

Figure 3: Histogram of Voltage Magnitude Deltas

In Table 2 an overview of the distribution of voltage differences in the investigated period of time in Kisselbach is provided. The results are given separated for every case and the information about minima, maxima, median, average and quantiles provide an understanding of the distribution of occurred voltage deltas. The average value of below 1 V reflects the observed shape from Figure 3Figure 2. However, for safe operation only the upper limits are of interest. 95% of the values are below 6.38 V. The maximum difference between phase L1 and L3 amounts to 29.36 V, which corresponds to approximately 12.8% related to nominal voltage. For the other two cases the maximum differences between the phases are also above 20 V. As described above, this is not comparable to the limits provided in the norm, but suggests that in few points of time a significant amount of voltage asymmetry can be found in the grid.

Table 2: Overview of Voltage Difference [V]

Phase	L1-L2	L1-L3	L2-L3	Overall
Minimum	0.00	0.00	0.00	0.00
5% Quantile	0.02	0.02	0.02	0.02
Mean	0.95	1.06	0.95	0.99
Median	0.65	0.67	0.60	0.64
95% Quantile	5.25	6.79	6.76	6.38
Maximum	25.17	29.36	21.54	29.36

The temporal and spatial distribution of the maxima shows that the maximum difference in phase voltages for all the cases occurs at the same node in the grid. However, the point of time varies for the different deltas in phase voltage magnitude.
The SE results provide a comprehensive picture of the grid state in the considered period of time. The gained insight can be used both for planning and for operational purposes.

BENEFIT FOR PLANNING AND OPERATION

Based on the results above, 9 points of time with extreme values either for voltage magnitude or the voltage difference between the phases have been identified.
For those points of time the respective power at all nodes is known as a result of the SE and thus the relevant load cases for planning can be derived. Therefore no assumptions for coincidence factors of load and generation are necessary in the planning process. However, a safety margin can still be applied, which is suggested in order to allow for the uncertainty in the estimate. It should be noted that the considered period of time of one month is as seasonal influences are not visible. The resulting load cases can be applied in short-term planning such as the assessment of connection requests of new generators.
In addition to this, the grid state can be automatically monitored, enabling smart grid approaches. For example the application in a control scheme such as Smart Operator [1], where it can be used for improved training cases [9] and for the real-time operation as such [10].

CONCLUSION AND OUTLOOK

The implemented SE algorithm shows a suitable accuracy in the field test grids. However, bad data is especially critical in a distribution grid setup with little measurement devices. It has been found, that the implemented SE can provide valuable information on the actual situation in the grid that can be used for planning and operational applications.
The analysis of the grid in Kisselbach has shown that both the extreme values of voltage magnitude and the maximum of phase voltage difference serve as potential cases to be considered in the planning process.
The gained data can be applied in further investigations such as the integration potential for new generators, e.g. photovoltaics, or loads, e.g. electric vehicles.
The impact of the newly generated load cases on the reinforcement requirement needs to be further investigated, since the grid expansion demand is highly dependent on the assumed load scenario.

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