STATE IDENTIFICATION METHODS FOR MV-GRID AUTOMATION WITH SPECIAL REGARD TO LV-INTERCONNECTIONS

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ABSTRACT

The utilization of power systems in Germany has changed considerably due to a fundamental shift in the variety of power generation during the last years. Since most of the renewable power plants are connected on distribution level, these grids are affected fundamentally. Smart distribution systems are one important element to handle the new challenges. Therefore the authors of the present paper are developing a decentralized automation concept for monitoring and control of MV-grids.

Considering such a smart distribution system for MV-grids, it is most important to get a detailed overview of the current grid state almost in real time. Therefore, a reliable grid state identification is the primary requirement for any continuative surveillance or control method within the grid. An additional challenge of grid state identification within the German electricity network is a specific topology on the LV-level, which may have an influence on an autonomous MV-distribution system. In some distribution networks, there is a strong interconnection of MV-substations on the LV-level, which could be leading to power flows through the LV-grid and therefore influencing the voltage and currents in the MV-grid.

The scope of the present paper is a comprehensive analysis of the impact of such LV-interconnections on the grid state identification for a decentralized MV-automation concept. A reasonable approach to enable an adequately accurate state identification in such cases has to be found. The superordinate scope of the research work is to develop an integrated automation system for LV- and MV-grids, which enables an integrated smart distribution solution.

I. INTRODUCTION

The power systems in Germany and their utilization have changed considerably during the past decade. More and more decentralized generation units have been integrated into the distribution networks, leading to new challenges for the distribution system operators [1]. Today, the installed capacity of renewables in Germany amounts to about 87 GW. So far, rural distribution grids are mainly affected, whereas the large scale integration of photovoltaic into urban distribution grids is just in its beginning.

An extensive enhancement of the grid structure would be a solution to these challenges, but it is a time-consuming and very expensive answer. An alternative solution to these challenges is the integration of automation devices and surveillance technology and the development of an autonomous smart grid system.

The scope of the present paper is to introduce such a smart grid system for MV-grids and to give a short introduction into the used grid state identification (GSI) methods. GSI is the first step in developing an autonomous automation system. The present paper presents the challenges in determining the grid state in general and with regard to a specific grid topology on the LV-level. In some grids, there are connections between one or more MV-substations on the LV-level, resulting in a power flow on LV-level. These connections may influence the accuracy of the GSI on the MV-level. Hence, the present paper also describes the influence and consequences of the mentioned LV-topology on the error of the GSI.

II. DECENTRALISED AUTOMATION CONCEPT FOR MV-GRIDS

To avoid a costly enhancement of the grid structure as a solution to the increased decentralized generation in the distribution networks, the authors of the present paper are developing a smart grid system, which enables the distribution network operator not only to overview the state of the network but also to respond to any violation of permitted voltage range or the exhaustion of the grid components' capacity [2]. After developing a decentralized automation concept for LV-grids [3], the current project focuses on the development of a smart grid system for MV-grids. The superordinate goal is the development of an integrated automation system for LV- and MV-grids as presented in Fig. 1, with a coordinated approach for surveillance and control of both voltage levels. Fig. 1 shows such an autonomous surveillance and control system located in the HV/MV-station, communicating with measurement and control technology situated within the MV-grid and communicating with LV-surveillance and -control systems placed in some of the MV/LV-stations.

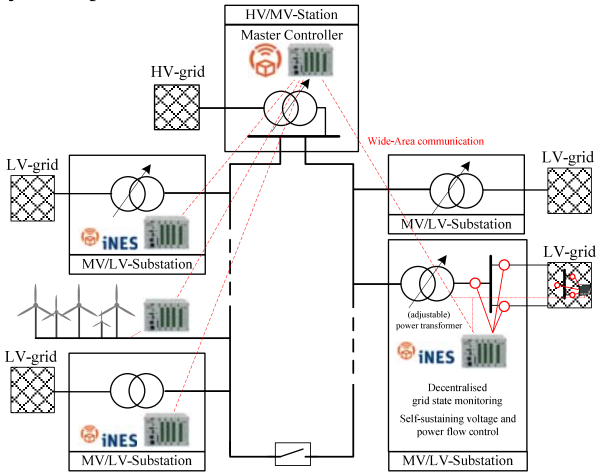

Fig. 1: Integrated automation system for LV- and MV-grids

The determination of the grid state is the primary requirement for such a surveillance or control method. Without knowing the grid state, no intelligent control method can be implemented to meet the before mentioned problems within the distribution grid. Therefore, GSI is the first step in developing a smart grid system. Unfortunately, determining the grid state in the MV-grid is a challenge, due to the sparse measurement topology in these grids.

After screening available grid state identification methods and adapting these methods with respect to the use within an automation system for MV-grids, the authors of this paper have decided to implement two separate methods for GSI [4]. These two methods have proven to be the most accurate and reliable when facing a limited budget for measurement technology within a MV-network. The first method which will be used for GSI within the automation system on MV-level is the network partitioning method. It is an approach the authors have already put to use in the decentralized automation concept of LV-grids and which they adapted to the requirements within a MV-grid [1]. Additionally, a method called sensitivity analysis will be implemented in the MV-automation system [4]. Since its requirements on the measurement topology are different from the network partitioning's requirements, the automation system's flexibility and applicability in potential future grids are increased if both methods are implemented. Since the first method will be used for the analysis of the interconnections' influence on GSI-error, this method will be described in detail in the next section.

III. MV-GSI BY NETWORK PARTITIONING

From the mathematical point of view, GSI and thus the calculation of power flows in a power grid requires the solution of multiple nonlinear equations. The lack of measurement data due to sparse measurement equipment in the MV-gird, however, leads to an underdetermined system of equations [1]. Therefore, the lack of information has to be compensated by either using a mathematical algorithm which solves the problem of an underdetermined equation system or alternatively by determining all loads and the generation influencing the grid state. Appropriate methodologies are described in [5], [6], [7].

Using analytic load profiles as a substitute for missing measurements to determine the load and generation is an established method for grid planning purposes. However, since the actual grid state is required for a continuative surveillance and control system and the use of load profiles is only accurate as long as the grid state is in a typical load situation, an alternative approach for finding substitute values is necessary [8].

Grid - separation into load areas

To achieve an online calculation of the grid state, the network partitioning method uses the available measurements to divide the observed grid into separated and autarkic load areas [3]. A load area is limited by the end of a branch or a measurement of a terminal or nodal power, thus all powers at the borders of a load area are known. Fig. 2 shows the partitioning method for a single load area.

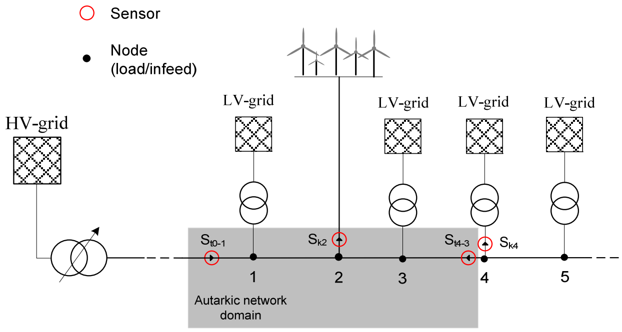

Fig. 2: Network partitioning with power sensor

With all borders of a load area under surveillance, the total amount of power entering or leaving the area is known. The sum of power is then distributed by a second algorithm with regard to the rated power of each substation within the area. With the acquired knowledge of the loads at all observed and unobserved nodes, the grid state can then be calculated using an ordinary power flow calculation.

It is obvious that by installing more sensors, the size of the load areas within an observed grid can be reduced and with that the error of state identification, as well. It is important to emphasise, however, that a generation on MV-level should be monitored in general to ensure an accurate estimation of substitute values. The total amount of sensors installed is bounded by the accepted maximum error of the grid state estimation on one side and economical considerations on the other side.

Calculation of estimation errors

The described GSI-methods have been applied to an 11-node, 10 kV-grid which represents a typical MV-grid topology in Germany. Fig. 3 shows the topology of the grid which has been used in the present paper to describe the error of the network partitioning method and the influence of LV-connections on MV-GSI.

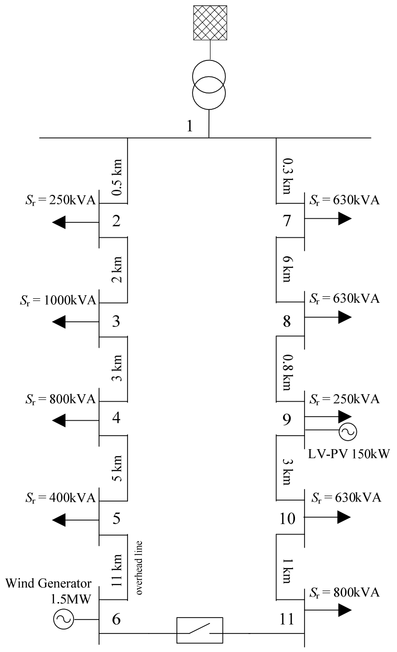

Fig. 3: MV-grid used for calculating estimation errors

The grid supplies nine MV/LV-substations and connects one wind generator on MV-level and 150 kW_p of photovoltaic on LV-level.

For the following calculations, a realistic load scenario for every minute of one year was used for each node of the investigated grid. These scenarios were generated by combining several household, industrial and commercial load profiles, as well as generation profiles for wind and photovoltaic generators, at each substation. The load scenarios were postulated as reference point for the following analyses.

IV. LV-INTERCONNECTION OF MV-SUBSTATIONS

The occurrence of GSI-errors in relation to the actual grid state is not only due to the sparse measurement equipment and thus missing information about the nodal loads. Another factor which may complicate the state estimation process is the topology of some distribution grids in Germany. Especially in urban distribution grids, it is not unlikely for MV-substations to be connected not only on the MV-level, but also through interconnections on LV-level. Some LV-grids are supplied by more than one substation and the connection of those substations on LV-level may affect the estimation error on MV-level. As an example, Fig. 4 shows the interconnection of two substations on LV-level within an MV-grid.

To investigate the influence of such an interconnection on the accuracy of MV-GSI, the following analysis was carried out.

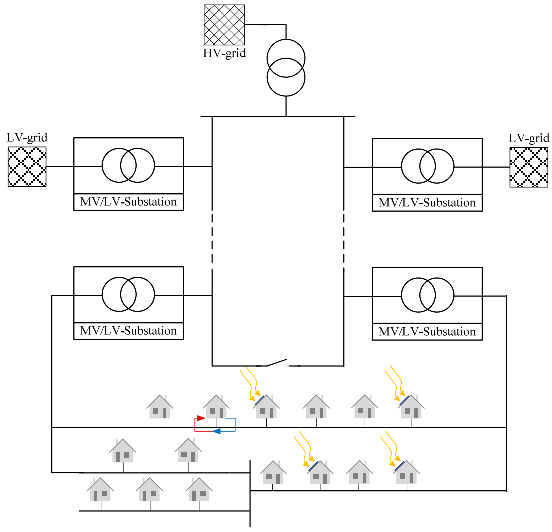

Fig. 4: Decentralized automation system for MV-grids with interconnections on the LV-level

Influence of LV-interconnections on GSI-error

To ensure that only the estimation error based on the interconnections is analysed, it is important to consider two influencing factors. First, the GSI-method contains an inherent error of estimation regardless of the grid topology. Second, the sensors' positions within the grid have an influence on the estimation error. Depending on the position, the network partitioning method differs in its accuracy to establish substitute load and generation values, which is why two measuring scenarios were compared during the calculations. The methodology to exclude the common estimation error and the error due to the sensors' positions is described in the following sections. An interconnection on LV-level between node 4 and 11 was assumed for the analysis.

Measurement topology scenarios

Since the position of the available sensors in the grid and specifically their position in relation to the interconnections has a high influence on the GSI-error, three measurement topologies can be distinguished. In all cases three sensor positions are used, one of them is the slack node 1. In the first case, both interconnected nodes 4 and 11 are unobserved with additional measurements at node 6 and 9. In the second case, the interconnected node 11 is observed, too, along with node 6 (see Fig. 5). The third case, in which both node 4 and 11 are additionally equipped with sensors, has not been further analysed. Due to the fact that both interconnected nodes are measured, the interconnection does not have any influence on the GSI-error. The load areas are the same, whether an interconnection exists or not. As a consequence, the third measurement topology is not being discussed in the further investigations.

Grid-Modifications for LV-interconnections

To separate the common GSI-error from the GSI-error due to the interconnections, three separate calculations were performed.

The reference calculation was performed using the grid shown in Fig. 3. The information about the load and generation at all nodes is available. Therefore a full power flow calculation can be used to calculate the grid state in the form of a vector with all nodal voltages.

To investigate the influence of the interconnections on GSI-errors, in a second step, the network partitioning method was used to estimate grid states for all load scenarios. Using the grid as described above, the error includes the estimation error based on the GSI itself, as well as the estimation error which is due to the not yet considered interconnections on the LV-level.

In order to obtain the inherent GSI-error, some modifications to the grid were carried out in the third step. To begin with, an interconnection on the LV-level was added by including an extra line on MV-level between two substations. For this purpose, it was assumed, that substation 4 and 11 are connected on the LV-level. Therefore, a single branch, representing the connection on the LV-level, was added between these two nodes. The impedance of this connection is essential to the influence on the GSI, which is why it was calculated using an existing LV-grid of the project partner Mainova AG, in which the described LV-automation system was installed [3]. In general, distribution grid operators can use their geographical information system to calculate the interconnection's impedance in the LV-grid.

After adding the line to the existing grid, the next step is to modify the load distribution between the two connected nodes.

Auxiliary node in line 4-11

The loads of node 4 and 11 in each load-scenario are assumed to be the total load of the LV-grid being supplied by these two substations. As a result, the calculation with the modified grid can no longer be executed with a nodal load at node 4 and 11. The hitherto nodal power values are now values of branch power flowing into or out of the new branch. To perform correct calculations, an auxiliary node in the new line has to be constructed, which represents the total power entering or leaving the line from both sides (neglecting lines losses). The position of this auxiliary node is essential to an exact representation of the original load distribution. It is calculated using the total length of the added line and the proportion of the original nodal loads. By using eq. (1), an auxiliary node was added, replacing the added line for two new lines [7].

$$\frac{\text{length}_{4-N_A}}{\text{length}_{N_A-11}} = \frac{S_{11}}{S_4} \tag{1}$$

The total length and impedance of both lines are equivalent to the originally added line. The new grid topology between node 4 and 11 is shown in Fig. 5, including the described measurement topologies which have been analysed.

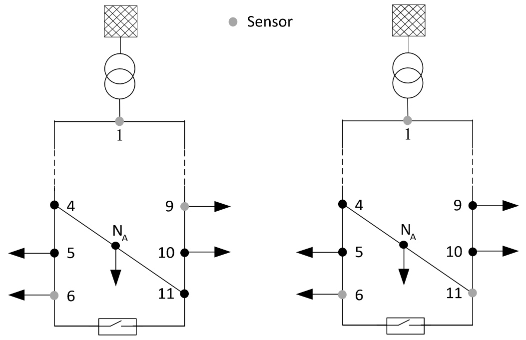

Fig. 5: Grid modification with auxiliary node N_A for the analysed measurement topology 1 and 2

Nodal power load at node 4 and 11 now is zero. The load at N_A is the total power load of the combined nodes 4 and 11. Of course, the positioning of node N_A had to be calculated separately for each load scenario.

With this new grid topology, the network partitioning method was performed for the two described measurement scenarios and the GSI-error was calculated in relation to the power flow calculation with full measurement information.

Results

The results of the described calculations are shown in Fig. 6 and Fig. 7. In contrast to what was expected, the maximum GSI-error is higher in most cases when the grid is modified and the interconnection between node 4 and 11 is taken into account. If the connection is neglected, the estimation error is considerably smaller at most nodes within the grid. As stated above, only when both interconnected nodes are observed with sensors the connection does not have any impact.

Nevertheless, these results can be explained by considering the nature of the GSI-method. By adding an extra line between the left and the right line section, the very essence of the network partitioning – the construction of autarkic load areas – is affected. The reason why the GSI-error is smaller even when neglecting the LV-connection is that the number of the load areas is increased or their size decreased, respectively.

With measurement topology 1 (Fig. 6), the size of the left load area is considerably increased when adding the line, leading to a higher error in the calculation of substitute loads and thus influencing voltage error at all nodes.

With measurement topology 2 (Fig. 7), the size of the left load area is increased, thus increasing the error as well.

Additionally, the power flow calculation performed with the substitute values of loads and generation is influenced by the additional line between both sections. The power flow on the line, combined with inferior substitute values explains the higher total error.

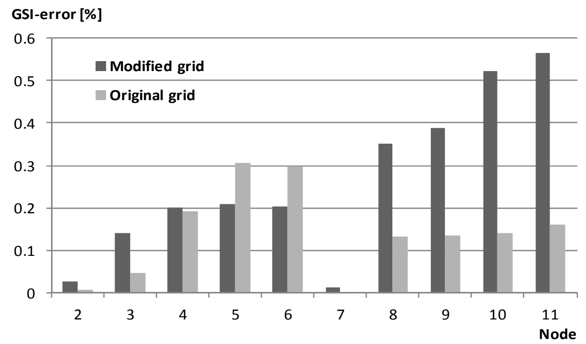

Fig. 6: GSI-error with no LV-connected node observed

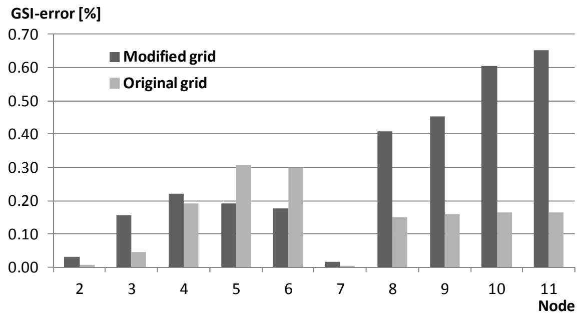

Fig. 7: GSI-error with one LV-connected node observed

The affected power flow calculation also explains why the error in the right branch of the test grid is considerably higher. With the substitute value of the auxiliary node being incorporated in the power flow calculation, the estimated voltage in the right branch is affected negatively, even when the load area in this branch is not altered.

V. CONCLUSIONS

The scope of the present paper was to give a review of the challenge of grid state identification on the MV-level. For the implementation of an automation system for distribution grids, the grid state has to be estimated with an appropriate method, which has been presented in this paper. With both the presented method of network partitioning as well as the alternative method of grid state identification, sensitivity analysis [4], a sufficient accuracy is achieved for a decentralized automation concept. Since both methods have some advantages and disadvantages regarding the measurement topology available, both methods will be implemented in the MV-automation system to obtain a sufficient flexibility. However, to ensure high enough estimation accuracy, generation units connected to the concerned MV-grid should be measured with sensors in any case to contribute to the state identification.

Furthermore, the scope of the paper was an analysis of the influence of interconnections on the LV-level on the GSI-error on MV-level. The results of the analysis indicate that a consideration of these interconnections in form of a representative connection on MV-level does not improve the accuracy. On the contrary, the error is increased due to the nature of the GSI-method. The influence of the electrical connection on the LV-level is too small to justify taking it into account using the described GSI-method.

MISCELLANEOUS

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REFERENCES

[1] N. Neusel-Lange, C. Oerter und M. Zdrallek, 2012, “State Identification and Automatic Control of Smart Low Voltage Grids“, *Proceedings 3rd IEEE PES ISGT Conference*, Berlin.

[2] C. Oerter, N. Neusel-Lange, P. Sahm, M. Zdrallek, W. Friedrich und M. Stiegler, 2013, “Experience with First Smart, Autonomous LV-Grids in Germany“, *Proceedings 22nd International Conference on Electricity Distribution (CIRED)*, Stockholm.

[3] C. Oerter und N. Neusel-Lange, 2014, “LV-Grid Automation System – A Technology Review“, *Proceedings IEEE Power & Energy Society General Meeting*, Washington.

[4] N. Neusel-Lange, C. Oerter, F. Dorsemagen, J. Meese und M. Zdrallek, 2014, “Real-Time State Identification for MV-grids on autonomous agent platforms“, *Proceedings 18th Power Systems Computation Conference (PSCC)*, Wroclaw.

[5] E. Manitsas, R. Singh und B. Pal, 2008, “Modelling of pseudo-measurements for distribution system state estimation“, *SmartGrids for Distribution. IET-CIRED. CIRED Seminar*.

[6] M. Wolter, 2008, “State Identification of Distribution Grids“, Shaker, Aachen.

[7] M. Wolter, 2009, “Grid reduction approach for state identification of distribution grids“, *Proceedings Power & Energy Society General Meeting. PES '09. IEEE*, Calgary, AB.

[8] T. Schlösser, A. Angioni, F. Ponci und A. Monti, 2014, “Impact of Pseudo-Measurements from new Load Profiles on State Estimation in Distribution Grids“, *Proceedings IEEE International Instrumentation and Measurement Technology Conference*, Montevideo.