OBSERVABILITY OF THE DISTRIBUTION SYSTEM

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ABSTRACT
In this paper the approach of implementing the phasor measurement units (PMU) into the state estimation method in order to improve the power system monitoring at the distribution level will be presented. The possibility of using accurate synchronized measurement data for the simulation to enhance the calculation of the power system state will be presented. The simulation will be performed on an example network with dispersed generation (DG) and the results of the approach will be shown and discussed.

INTRODUCTION
In conventional power systems power generation takes place in big, centralized units and the electricity is transported through the transmission to the distribution level, where it is distributed to the customers. In recent years, more and more small distributed generating units have been put into operation in power systems in order to provide an energy supply near the consumption point covering the power demand in the region. This use of DG can minimize the losses of transport energy and take part in reducing CO2 emissions, which is an aim of governmental policy considering environmental issues. Because of government support and funding for the use of renewable energy sources (RES), like in Germany, the amount of energy coming from these units has achieved a significant percent of the overall energy produced and may cause changes in the structure of the power system. Those changes are only directly related to the power generation level, but make an impact on the whole system – transmission and distribution levels.

PROBLEM BACKGROUND
As already mentioned, in addition to conventional power plants dispersed generation now plays an important role in the generation of electric power, thereby becoming a common part of power systems. Taking into account the fact that dispersed generation units are strongly dependent on weather conditions, which can only be forecasted with limited accuracy, it is difficult to predict if the generated amount of power will cover the system need, and if it does not meet the need, it leads to unsafe operation of the power system. Additionally, the non-linear character of load in the distribution system requires a more precise measurement system to deliver the right values of voltage as well as active and reactive power for system state estimation issues. In order to be able to provide proper and stable operation of the “expanded” power systems, the current state of the system should be known, which requires the improvement of already existing monitoring systems. The new situations and scenarios, which did not occur in conventional systems, need to be recognizable. One of the examples of such a new disturbance in the power system can be a bidirectional power flow. Taking into account the fact that the DG is usually installed at the distribution level – and not the transmission level - this part of the power system monitoring should be taken into consideration. Because of the inadequate number of measuring devices at this system level, new techniques and methods for improving the system state calculation should be proposed and introduced.

PHASOR MEASUREMENT UNIT (PMU)
Nowadays it is possible to take advantage of the global positioning system (GPS) not only to calculate the exact position, but also to get highly accurate time information. Each of the satellites orbiting the earth has an atomic clock on the board, which produces the exact time and date. That information is sent to the earth with the GPS-Message. Some of the modern measurement devices, like phasor measurement units, can use this GPS-Signal to extract the time information and use it for measurement purposes. Fig. 1 shows the common elements of which a PMU is composed. As an input signal the three phase voltages and currents coming from the power system can be used. After conversion to digital signals the PMU can calculate the phasors taking into account the time information. The device uses the pulse per second (PPS) as a synchronization impulse to start performing the measurement and an internal phase-locked-loop to provide impulses for the measurements during one second, before the next PPS comes. Each of the measurements coming out of PMU contains the UTC-time and date of the performed measurement. This makes it possible to compare the measurements taken at exactly the same time at different places in the network, which was not possible using not-synchronised measurement. Additionally new parameters, like synchronised measured phase angle, can be implemented and used for the state estimation issue.
The IEEE standard [2] defines in which format and with which reporting rate (see Table 1) the measurement data should be sent from the PMU to the phasor data concentrator (PDC), where it can be saved and used for further calculation.

Table 1. PMU reporting rates [2]

<table>
<thead>
<tr>
<th>System frequency</th>
<th>50 Hz</th>
<th>60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reporting rates</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| (frames per second) | 10   | 25
| 10               | 12    | 15    |
| 20               | 30    |       |

This standard also includes and specifies the technical requirements, so the phasor measurement units coming from different manufacturers should fulfil the compatibility criteria and the expansion of the wide area monitoring system (WAMS) is ensured.

**SYSTEM OBSERVABILITY AND STATE ESTIMATION ISSUE**

The power system can be controlled properly only when the actual system state is known. Proper control makes it possible to predict what can happen in the next step and make a correct decision. To know the electrical power system state, it is necessary to know all of the complex node voltages (the magnitude and phase angle). It is impossible to install measurement devices on all of the nodes of the power system due to economical and technical issues [3][4]. Secondly, the amount of data coming from those devices would require an enormous computation power to handle and process it. Therefore, the measurement devices are only installed at special chosen places. The optimal placement of those devices can depend on many issues, for example economical factors, the character and structure of the network and the power consumption. The mathematical model of the power system can be built based on the knowledge about the topology of the network and the data of elements like lines, transformers and loads. Because of the complexity of some elements in the power system, i.e. the static and dynamic character of load, non-linear characteristic of work or the distortion coming from the power electronic devices, the modelling of a power system needs to be simplified on some levels. This makes it possible to create the equations that will be used to estimate voltages that were not measured. This procedure is known as state estimation (see Fig. 2) and it is used worldwide in order to provide the data for the proper operation of the power system.

The vector $\mathbf{z}$ represents the measurement performed in the network and consists of active and reactive node powers, the active and reactive power flows and the voltage magnitudes. The matrix $\mathbf{h}(\mathbf{x})$ represents the non-linear functions between the unknown voltages and the measured values. The measurement error $\mathbf{v}$ is included in the system model equation and can be affiliated with three main categories like measurement device error, operating uncertainties and incompleteness of the model. Calculation of the unmeasured voltages is done by minimization and solution of Eq. (2) (the method of least squares [6][7]).

$$J(\mathbf{x}) = (\mathbf{z} - \mathbf{h}(\mathbf{x}))^T \mathbf{R}^{-1} (\mathbf{z} - \mathbf{h}(\mathbf{x}))$$

The measurement devices have only a limited accuracy, so the measurement data is affected by errors. Only data with the best possible accuracy should be used for calculation to get the results closest to the real values. In order to have an influence on which data should have more importance in the estimation process, the $\mathbf{R}$ matrix was introduced [8]. As shown in Eq. (3) this is a diagonal matrix, where the dimension of the matrix is equal to the number of measurement data placed in vector $\mathbf{z}$.

$$\mathbf{R}^{-1} = \begin{bmatrix} \frac{1}{\sigma_1^2} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \frac{1}{\sigma_n^2} \end{bmatrix}$$

The elements are fraction numbers, whose denominators contain the standard deviation to the second degree - variance of the measurement device error. The standard deviation can be calculated from the Eq. (4).

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (z_i - \bar{z})^2}$$

The standard deviation can provide information about the difference between the measured data from the expected data. The higher the value of the standard deviation, the greater the dispersion of the measured values from the expected value. In the $\mathbf{R}$ matrix one is divided by the variance of the measurements, so the data with the smaller variance, which is equal to the smaller error of the measurement, will give the bigger value and will have more influence on the results of the estimation process.
APPROACH

The aim of the approach was to implement the measurement data coming from the phasor measurement units into state estimation algorithm and compare the results of calculation with and without PMU implementation. The example network shown in Fig. 3 was chosen for the simulation.

Fig. 3. Simplified structure of the example network

The nominal voltage of all of the nodes is 20kV. The nominal voltage of the load is 6kV with an active power consumption of 10MW. Additionally, node 2 is connected to a wind power plant (DFIG) with a nominal power of 1.5MW and nominal voltage of 575V. The network feeder is represented by a 3 phase source with the short-circuit power of 100MVA at the 20kV base voltage. The length of line 1 and line 2 is 10km each.

The first step before the simulation was to create the equation used further for the state estimation algorithm. The Line 1 was described as a $\pi$ element using schema shown in Fig. 4.

Fig. 4. Admittance representation of power system elements [5]

In order to represent the elements in the admittance form Eq. (5) was used, which describe the relation between the voltages and currents in the matrix form.

$$\begin{bmatrix} L_{ji} \\ L_{ij} \end{bmatrix} = \begin{bmatrix} Y_{ji} & Y_{jj} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} U_{ji} \\ U_{jj} \end{bmatrix} = Y_{j-i} \begin{bmatrix} U_{ji} \\ U_{jj} \end{bmatrix}$$

(5)

Secondly, the coherences between the measured values and the observed voltage values were describe. For that aim Eqs. (6) and (7) were used as a point of origin.

$$P_{ij} = \text{Re} \left( U_i^* L_{ij} \right)$$

(6)

$$Q_{ij} = \text{Im} \left( U_i^* L_{ij} \right)$$

(7)

Applying Eq. (5) to (6) and (7) the model of the example network was created.

SIMULATION AND RESULTS

The simulation was performed in MATLAB®/Simulink® software with usage of the SimPowerSystems Toolbox. All of elements present in the network were taken from the existing toolbox library. There was one generally simulated scenario, where the load was supplied by energy coming from the 20kV Network and DFIG wind power plant, where at the beginning of the simulation DFIG produces about 20% of the nominal power, and during the simulation raised the power production to about 100%. The following was measured: magnitude of the voltage at node 2 and the active and reactive flows from node 1-2. The assumption was that the voltage at node 1 has the magnitude of 20kV and the phase angle of 0 degrees.

There were three cases investigated in the simulations. First, the state estimation using the normal measurement devices without consideration of the measurement accuracy ($R$ matrix – all variance values were equal to 1). Second, the phasor measurement units were implemented as a measured device at node 2 to measure the voltage amplitude, but the diagonal elements of the $R$ matrix was still set to 1. In that case, possible improvement was only because more accurate data was expected to come from the PMU. Third, the second case was expanded because of implementing the correct values of the $R$ matrix, so the more accurate data were privileged in the estimation. In order to get the value of the variance, the routine according to Eq. (4) was created and, as a result, the values were saved in the 2 dimensional matrix, where one dimension represents the expected value, which should be measured (nominal voltage level) and the second one was the class of the accuracy (see Table 2). The accuracy of the measurement transformers was not taken into account.

Table 2. Example of the measurement variance calculations

<table>
<thead>
<tr>
<th>Nominal voltage level [V]</th>
<th>Accuracy [%]</th>
<th>Variance [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.2</td>
<td>0.0133</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.0838</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.3341</td>
</tr>
</tbody>
</table>

The simulation was performed with an accuracy of 1% for conventional measurement devices and 0.2% for PMU. Two points of system were chosen from the whole simulation period and state estimation was performed for them. In Fig. 5 the main characteristics of the wind turbine taken from the simulation are shown. The wind speed changes the amount of active power produced, which then affects the voltage value. After the pitch angle was set to the new value, the active power production was limited, the voltage profile was stabilized and the network was in stable state.
The first point of the power system work chosen for calculation was before wind speed increased ($t_{sim}<5s$). The second point was after wind speed increased and a steady-state value of the pitch angle was reached, where the produced active power was constant ($t_{sim}>20s$). The accuracy class of the measurement device was added to the values measured during the simulation according to the random error. Such data was taken as input for the estimation calculation. The results of the performed calculation are shown in Table 3.

The smallest errors have achieved the Case 3 in both points of operation of the power system. Because of the input of accurate data coming from the phasor measurement units and taking into account the $R$ matrix, the state estimation gave the best results. Usage of PMU in Case 2 without consideration of the weight $R$ matrix only led to partial improvement of the method.

### CONCLUSION

In this paper the influence of performing the measurement of power system parameters using PMUs on the accuracy of state estimation algorithm was investigated. It was shown that by using the standard state estimation algorithm with the measurements from PMUs it is possible to significantly improve the accuracy of the state estimation results. The best results were achieved with case 3, where not only the measurement data was used instead of normal data, but also the accuracy of the measurement devices was taken into account in the estimation algorithm. A further possibility to improve the power system state estimation procedure considers the extension of the standard estimation algorithm taking into account the advantage of synchronised measurements, which offer an additional system parameter, namely the voltage angle. The test simulations providing the input data for state estimation (measurements) as well as verification information were carried out using MATLAB®/Simulink® with the SimPowerSystems Toolbox.

### REFERENCES


