IMPLEMENTATION OF PHASOR MEASUREMENT UNITS IN DISTRIBUTION SYSTEMS

Robert SCHMARANZ
Siegfried GEBHARD
Stephan BRANDL
KNG-Kärnten Netz GmbH - Austria
robert.schmaranz@kaerntennetz.at
siegfried.gebhard@kaerntennetz.at
stephan.brandl@kaerntennetz.at

Herwig RENNER
Graz University of Technology
Austria
herwig.renner@tugraz.at

ABSTRACT

Due to the changing requirements in sub-transmission voltage levels, new challenges arise for the on-line monitoring and the off-line assessment of the grid behaviour. These requirements can be met with new measurement and visualisation methods using phasor measurement units (PMU), which enable the assessment of current and voltage phasors in different substations in real time. In this paper, the implementation of a wide area measurement system (WAMS) in a 110kV grid is presented. The theoretical considerations will be supported by practical experiences during non-disturbed grid operation and islanded grid restoration tests within the grid of the KNG-Kärnten Netz GmbH (KNG), an Austrian DSO. Furthermore, off-line analyses of PMU-data are used to gain a better understanding of the dynamic behaviour of the grid.

INTRODUCTION

In the past, the implementation of PMUs was basically discussed for transmission grids. In these grids, the dynamic behaviour as well as the steady-state load flow was monitored. Due to the new challenges in distribution systems, PMU applications can be used to support the grid operation in the sub-transmission voltage levels.

These new measurements can be used for the visualisation of rotor angle instabilities, the dynamic visualisation of the frequency during grid restoration, the detection of islanding of parts of the grid, the improvement of the state estimation, the support during the synchronisation of separated grids, the implementation as fault recorders or the investigation of the dynamic grid behaviour. Many of these PMU-applications are available on-line and can support the operating staff in the control centre during critical system states.

INSTALLATION OF THE PMU SYSTEM

In the 110kV grid of the KNG three PMUs were installed in the first stage. The first PMU is placed next to large hydro pump-storage power plants in the west of the system. The second one is situated in the centre of the 110kV grid and the third PMU is placed next to the link to the 400kV transmission grid. Due to the positioning of the PMUs, the received data can give a good overview about the situation within the 110kV grid. The locations of the PMUs are shown in Figure 1.

![Figure 1: Grid topology in Carinthia](image1)

The monitored 110kV grid can simply be characterised as two circular sub grids, connected in a central substation. In the western 110kV grid, large hydro pump-storage power plants are situated, whereas the main loads are located in the centre and in the eastern part of the system. Both 110kV subsystems are linked to the 400kV transmission grid.

![Figure 2: Online visualisation of the PMU data](image2)

The PMU data are visualised online, as shown in Figure 2, in the control centre of the KNG to support the operating staff. As main information the voltage angle...
difference between PMU1 and PMU3, the voltage phasors and the frequency time course are provided.

**ROTOR ANGLE STABILITY**

The load flow situation in the 110kV grid is significantly affected by the operating point of the hydro power plants (generation or pump). Especially if the western connection to the transmission grid is not available due to maintenance work, a high power transfer on the 110kV overhead lines between the western part (power plants) and the eastern part (loads and remaining link to the 400kV transmission grid) will occur. The highest load transfer can be observed between PMU1 (hydro power plants) and PMU2 (middle of the 110kV grid, high loads). This high load transfer results in a rising phase angle difference, which can exceed predefined security levels.

In the past, the assessment of this situation was carried out by monitoring the predefined threshold values of the power and voltage measurements of the individual overhead lines and cables in SCADA. To assess this grid situation correctly and to avoid rotor angle stability problems, grid operators need an on-line visualisation of the grid angle difference. Within the KNG, PMUs are nowadays used to support the operator during these situations.

For the special grid situation outlined above, the rotor angle stability has to be observed since instability already occurred in the past [1]. The maximum transferable power between PMU1 and PMU2 can be estimated by the following equation [2]:

\[ P_{\text{max}} = \frac{E_G \cdot V}{X_T} \cdot \sin(\delta) \]

Where \( E_G \) is the internal voltage of a virtual generator representing the power plants and \( V \) is the constant voltage of the infinite bus, representing the transmission system. The reactance of the generator, the main transformer and the overhead lines are summarised as \( X_T \). The angle \( \delta \) is the sum of the machine angle \( \delta_G \) and phase angle difference \( \delta_L \) between the generator clamp and the infinite bus. The maximum transfer power is achieved at \( \delta = 90^\circ \).

Calculations show, that the inner rotor angle at rated power between the internal voltage of the virtual generator and the connection point in the 110kV level is around \( \delta_G = 55^\circ \). Taking into account a required security margin of 20° (to handle situations like a line outage due to a fault) the maximum allowed phase angle difference for the mentioned congestion between PMU1 and PMU2 is defined with 15°. This value is the pre-set threshold value for the alarm in the PMU application of Figure 2.

In Figure 3 the active and reactive powers transfer and the phase angle difference between PMU1 and PMU2 is shown. Due to the increase of the transferred power the phase angle difference rises. With the information of the new PMU application the operator was able to keep an eye on this event. If a further rise of the phase angle difference would have been occurred, the grid operator would have been able to take action on time.

![Figure 3: Rise of the voltage angle](image)

**GRID RESTORATION**

KNG successfully provided islanded grid restoration tests in 2005, 2009, 2010, 2011 and 2014 [3, 4] in collaboration with power plant operators, the Austrian TSO and Graz University of Technology. The first critical steps of the grid restoration plan have been practically exercised by switching pumps of a pump storage power plant to a designated generator configuration in an islanded part of the regional 110kV grid.

During grid restoration, the operator needs on-line information about the dynamic behaviour of the restored island. Especially during the first steps of the restoration, this island is very instable. The ratio of the rotating energy at rated speed to the switched consumer load determines the rate of change of frequency. The drop in frequency must be compensated by the units operating in primary frequency control mode. The frequency drop after each load-switching as well as the following oscillation is therefore an important information for the operating staff in the control centre to decide on the subsequent steps.
SYNCHRONISATION OF TWO GRIDS

The synchronisation of a generator to the grid is a well-known topic and automatically performed by the generator’s synchro-check relay. Synchronising two separate grids after a major disturbance during grid restoration is a more complicated case, due to the participation of several generation units or generation parks in both involved grids.

In this case, PMUs can be used to support the synchronising process by visualising the voltage phasors of both grids in the operation centre. The grid operator can therefore monitor the voltage magnitudes and phase angles as well as their frequency. If one or more of these values are not within predefined levels, specific manual actions can be set by the responsible dispatcher.

This process can be shown in an example from the islanded grid restoration test at the KNG in 2014. In this test nine synchronising attempts were successful carried out using the online visualisation of PMU data. On-site, the synchronism check function of distance protection relays is used for this purpose. This function ensures, when switching a line onto a busbar, that the voltage of the feeder is in conformance with the busbar voltage regarding predefined tolerances of magnitude, phase angle and frequency. For this functionality, the following threshold values are defined within the KNG:

- frequency difference $\Delta f = 0.5$ Hz
- voltage magnitude difference $\Delta U = 17$ kV
- angle difference $\Delta \phi = 20^\circ$
- synchronous monitoring time = 3 min
Figure 6: Synchronising process during grid restoration test

Figure 6 shows the voltage magnitude, the phase angle and the frequency difference between the island and the ENTSO-E grid in a substation during a successful synchronisation. It can be seen, that during this synchronisation process the two voltage vectors were nearly in phase opposition. All other release conditions were fulfilled. Due to the visualisation of this information, the responsible operator could intervene by arranging an acceleration of the reference machine, which results in a successful connection of the two grids.

FURTHER DEVELOPMENTS

An additional application of PMUs, forming a WAMS, is the analysis and support of protection systems. Distance protection relay performance during small disturbances can be analysed with the help of PMUs [7].

Although the fault location in case of phase-to-phase or 3-phase faults can be determined rather precise by distance protection relays, the accuracy can be improved by the use of PMUs.

The 110kV grid in Carinthia is operated resonant grounded. Therefore, the location of earth faults is a challenging job prone to uncertainty. Even in that case, the utilisation of PMUs can improve the performance. Especially the transients at the beginning of an earth fault slightly affect the voltage phasors. First tests with three PMUs installed in the system as described in Figure 1 came up with promising results. The region of the fault was detected correctly and the comparison of the amplitudes of the recorded disturbances could be used as indicator for the distance relative to the PMU locations. Further tests to improve the accuracy of the method are going on.

CONCLUSIONS

The installation and operation of PMUs in the 110kV sub-transmission system of Carinthia has definitely proved itself so far. There is a clear benefit in the assessment of security margins during congested operation. Also during islanded operation and grid restoration tests, the PMUs support decision making in the control centre. Further tests to utilise the PMUs in earth fault location detection are going on.

REFERENCES