IMPLEMENTATION OF PHASOR MEASUREMENT UNITS IN DISTRIBUTION SYSTEMS

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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 phasor 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.

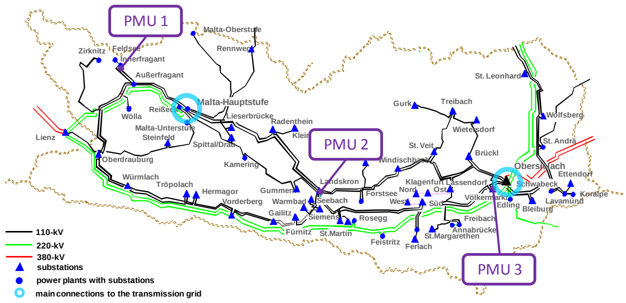

Figure 1: Grid topology in Carinthia

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 load s are located in the centre and in the eastern part of the system. Both 110kV subsystems are linked to the 400kV transmission grid.

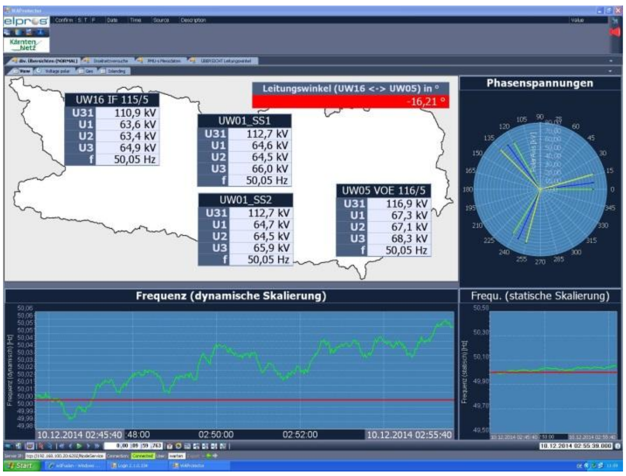

Figure 2: Online visualisation of the PMU data

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 STABILTY

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]:

$$P_{max} = \frac{E_G \cdot V}{X_T} \cdot \sin(\delta)$$

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 δ is the sum of the machine angle δ_G and phase angle difference δ_L between the generator clamp and the infinite bus. The maximum transfer power is achieved at $\delta = 90°$.

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 $\delta_G = 55°$. 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.

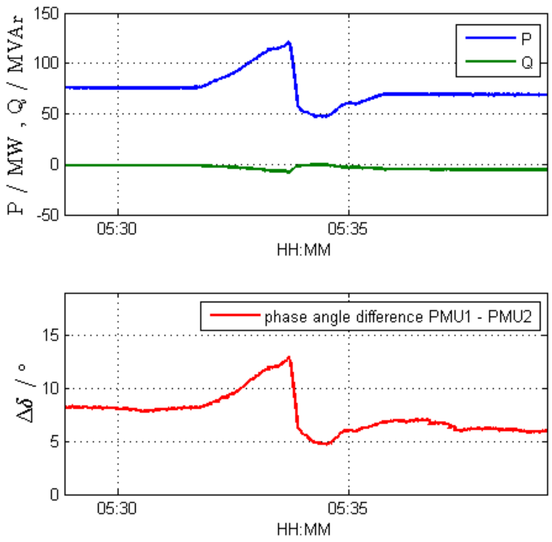

Figure 3: Rise of the voltage angle

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.

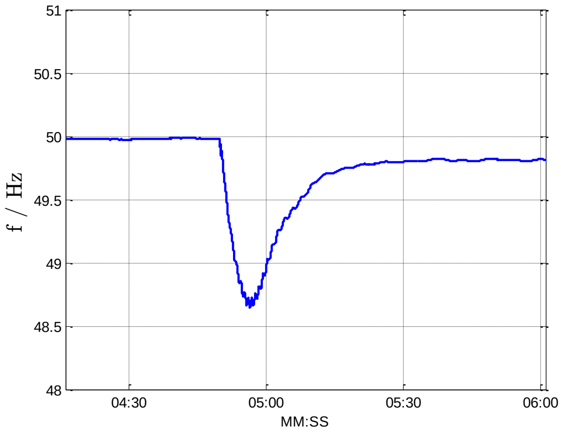

Figure 4: Frequency drop in islanded operation following a 15 MW load connection

In Figure 4 a frequency drop after a load connection of 15 MW during grid restoration test, recorded by PMUs, is shown. As the minimum frequency value of 48.7 Hz was expected, the next load connections were executed according to the restoration plan.

Another relevant topic during grid restoration is the load characteristic after re-energisation, in literature described as "cold load pick-up" [5, 6]. Reconnecting a shed load usually leads to an increased power demand at power-on time – depending on various factors as e.g. the outage time – than it was previous to black out. This unavoidable raise of load on pick-up can have a significant impact on the frequency stability in the early grid restoration stage.

Furthermore, dispersed generation influence the frequency of the restored grid. These generation units have protection systems monitoring several parameters like frequency or voltage level. If one of these parameters is not within certain limits, the generation unit is automatically disconnected from the grid. When voltage and frequency return to predefined limits, the dispersed generation units are reconnected automatically. Once these generators are reconnected they start to feed electrical power into the system, thus complicating frequency control with conventional generation units.

These two effects have also to be taken into account during the implementation of the grid restoration plan but cannot be evaluated in a sufficient accuracy. Therefore, to support the grid operator in his decision after each load connection, an on-line visualisation of the dynamic frequency time course in the control centre with an adequate timely resolution is essential.

Using measurements of the installed PMUs, the origin of a mysterious frequency oscillation (Figure 5) during the tests was detected. The first assumption that this was a local rotor angle oscillation with poor damping was rebutted. In fact, the observed oscillation was caused by the capacitive interference of parallel circuits belonging to the islanded test system and the interconnected rest of the grid. The difference in frequency of the islanded test system (51.5 Hz) and the interconnected system (50 Hz) was visible as beat frequency. The obviously undamped behaviour was due to automatic adjustment of the Petersen coil in the test system, thus altering the mutual coupling.

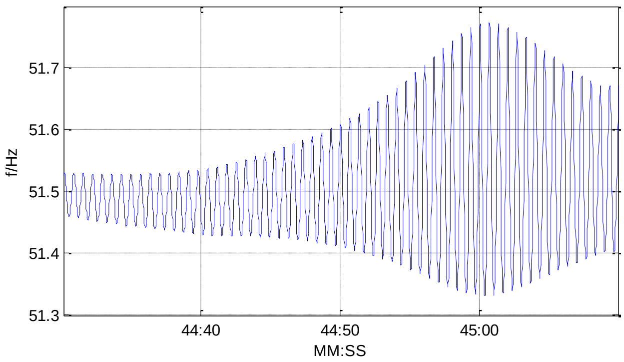

Figure 5: Frequency oscillation in islanded operation

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 this 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 $\Delta\varphi = 20°$
- synchronous monitoring time = 3 min

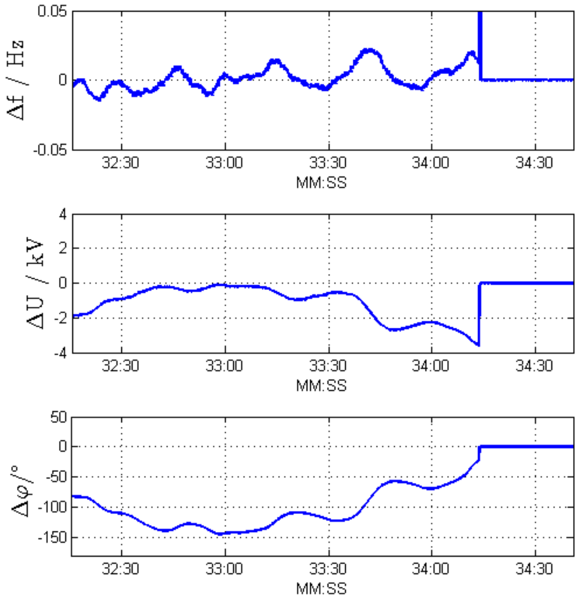

Figure 6: Synchronising process during grid restoration test

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.

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