21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE Moscow 2006

[a] **Approach to and Experiences with Wide Area Monitoring, Protection and Control Systems**

**P. Reinhardt, A. Suranyi, Dr. J. Bertsch**

ABB Switzerland Ltd., Power Systems, Baden, Switzerland

**SUMMARY**

In the light of increasing utilization and operational complexity of power systems owing to continuous growth in electricity consumption as well as cross-border trading without adequate power system extensions, the use of systems for the supervision and maintenance of power system stability has won significant attention.

The paper provides an introduction to the concepts of Wide Area Monitoring (WAM) systems and stability assessment solutions based on phasor measurement data. One such application to monitor power oscillations online is described in more detail.

Customer installations in Europe and Asia are described and the experiences gained are related. Special focus is given to the use of a WAM system during and after the resynchronization of the two synchronous zones of UCTE. This event can be seen as a parallel example to the progressing interconnection and meshing of power systems and serves to illustrate the support provided by highly accurate measurement and on-line monitoring.

The integration of WAM systems with SCADA will be described. Conclusions are drawn for system design requirements allowing the stepwise upgrading from monitoring to protection and control functionality. An outlook for the integration of Wide Area Monitoring, Protection and Control Systems with existing SCADA and innovative primary technologies such as FACTS will be given.

**KEYWORDS**

**Wide Area Monitoring, Protection & Control, Power system stability, Oscillations.**

## a 1 Introduction

Utilities and power system operators are faced with various needs and problems such as protecting their transmission system against major disturbances, counteracting cascaded line tripping, etc. These can be broken down to physical phenomena that can be mitigated by a management scheme making use of information from a WAM system. Such a system uses direct phasor measurements and enables more accurate algorithms for emergency control or protective actions.

Through the growing interconnection of national power systems, the resultant multi-national and highly meshed grids are often affected by high and partially also unscheduled transit power flows. The safe handling of the high demands and complexities posed, such as significant variations in power flow patterns and quick changes in operational conditions, calls for accurate monitoring of the dynamic behavior of the own power system and beyond. Data and information from the own as well as remote ends of transmission corridors may essentially improve the quality of power system operation and support operators with optimal utilization of available transmission capacities.

### System platform and implementation

Wide area monitoring systems (WAMS) are essentially based on the data acquisition technology of phasor measurement for current, voltage and frequency. The measured quantities include both magnitudes and phase angles and are taken by Phasor Measurement Units (PMUs) at selected locations in the power system. The data are time-synchronized via Global Positioning System (GPS) receivers with an accuracy of one microsecond and stored in a data concentrator every 100 milliseconds (see Figure 1). The phasors measured at the same instant provide snapshots of the status of the monitored nodes. By comparing these snapshots, not only the steady state, but also the dynamic state of critical nodes in transmission and sub-transmission networks can be observed.

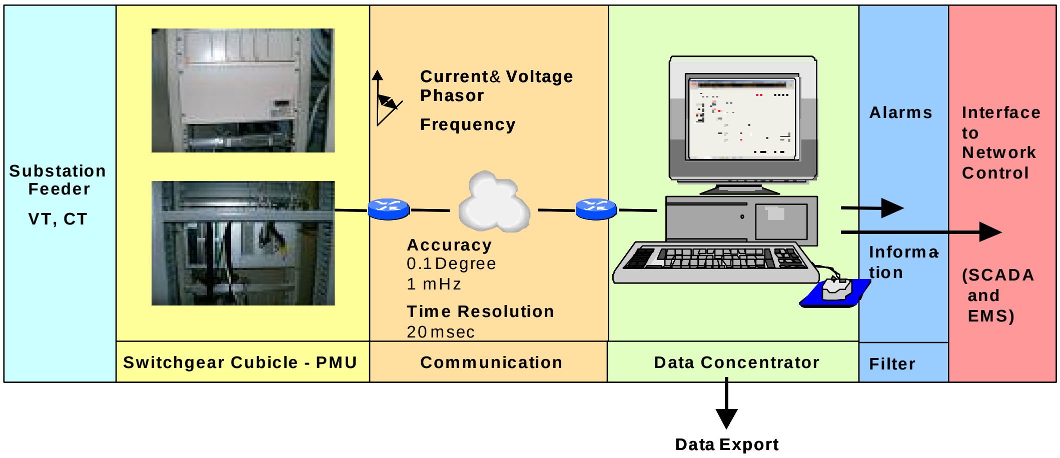



Figure 1: Configuration of a WAM system

### Defining power system phenomena

The physical phenomena underlying operational needs and problems in power systems such as counteracting major disturbances or cascaded tripping as well as intelligent load shedding can be mitigated by a management scheme making use of information from WAMS. Examples include angle, frequency or voltage instability and cascading outages. In order to address each of these phenomena, a reliable system has to be designed with respect to input variables, decision criteria and output actions. Phasor Measurement Units allow for direct and fast angle measurement, instead of indirect power measurement, and enable the development of more accurate algorithms for emergency control or protective actions such as:

§ Phase angle monitoring (PAM), see [1]
§ Line thermal monitoring (LTM), see [1]

§ Voltage stability monitoring for transmission corridors and entire networks with indication of margin to stability limit (VSM), see [2]

§ Power oscillation monitoring with amplitude and damping of the most dominant oscillation mode (POM), as described herein and in [1]

§ Frequency stability monitoring with amplitude and damping of the most dominant frequency (FSM)

**Example of an application: Power Oscillation Monitoring**

Power oscillation assessment is the algorithm used for the detection of power swings in a power system. The algorithm is fed with selected voltage and current phasors. The algorithm processes the input phasors and detects the various swing (power oscillation) modes. The algorithm quickly identifies the frequency and the damping of the least damped swing modes, which can e.g. lead to angular instability causing major power system disturbances or blackouts (see Figure 2). The algorithm employs adaptive Kalman filtering techniques. When the damping of any oscillation mode decreases below a predefined value, the operator's attention is drawn to the urgency of the situation with an alert followed by an emergency alarm. The indication of the frequency of an oscillation may be associated with the known existing mode of the power system, i.e. the operator may distinguish whether a local or an inter-area mode is excited.

Figure 2: Power oscillation monitoring with the graphical user interface

Furthermore, the stored data can be used for the collection of long-term statistics. Based on their evaluation, the system reinforcements can be planned and performed, such as retuning of Power System Stabilizers (PSS) to damp the frequencies appearing most often as dangerous ones.

**Use of WAM Systems by European and Asian grid operators**

The paper focuses on three utilities / transmission system operators (TSOs) that have implemented a wide area monitoring solution in their 400/220 kV power systems and the applications used, viz.

| Utility/TSO | PAM | VSM | POM | LTM |
|---|---|---|---|---|
| Austrian Power Grid (APG) | X | (x) | | X |
| Electricity Authority of Thailand (EGAT) | X | | X | |
| ETRANS (the coordinator of the Swiss grid & UCTE South) | X | | X | X |

Table 1: Utilities / TSOs and their use of WAM applications

**Austrian Power Grid - the Austrian TSO**

APG, the largest producer and distributor of electrical energy in Austria, operates and maintains the super-regional high voltage and extra-high voltage grids with ties to all neighboring countries. A production surplus of 1.900 MW in North Eastern Austria and a 1.400 MW deficit in the South of the country bring about heavy power transfers via the three 220 kV north-south line connections with a total capacity of 1.200 MW. Increasing congestion restricts electricity flows and reduces security of supply.

In summer 2003, APG has experienced a severe incident, when a trip on a heavily loaded neighboring 380 kV corridor between S/S Heviz (Hungary) and Tumbri (Croatia) immediately led to a redirection of large north-south power flows onto the weaker Austrian 220 kV corridors. A total collapse of the 220 kV system could only be avoided by performing emergency actions, i.e. tripping the infeeding 220/380 kV lines from the north. To maintain its n-1 criteria and better control power flows under all circumstances on the grid, APG decided to install three phase shifting transformers (PST) within its 220 kV system. These shall be commissioned end of 2006. Until then, the supervision of the operational condition of the critical corridor is of utmost importance to APG, leading to the initial installation of a WAM system (Figure 4) on the double line between the substations Vienna SO and Ternitz (see Figure 3). In a first step, this will help APG to determine the dynamic thermal limits of these 220 kV lines and to gain experience with the measurement of phase angles under all typical load conditions.

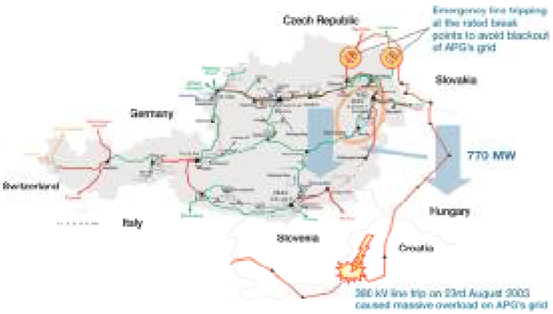



Figure 3: APG's Grid

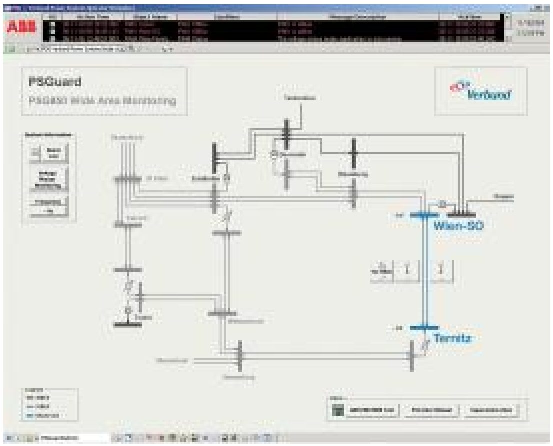



Figure 4: WAM system setup

In a next step, APG is considering to potentially install further PMUs in the Ernsthofen and Tauern substations. This with the aim to first assess the effectiveness and then optimize the use of the three PSTs for optimal utilization of the available transmission capacity without the risk of invoking critical situations. The initial Wide Area Monitoring system can then easily be extended further to a slowly operating closed-loop control installation e.g. by feeding back set-point values into existing SCADA systems.

At a later stage, APG might desire to use the WAM System to better supervise voltage stability on its north-south corridor as this becomes more important after the decommissioning of an outdated power plant in the south of Austria, or to monitor phase angles and average live line temperatures on more lines within its 220/380 kV system. Such system or functional extensions can easily be realized.

**EGAT - the Electricity Authority of Thailand**

EGAT has installed a WAM system in the south of Thailand on a long corridor to Malaysia (Figure 5). In the past, this corridor tended to be a source of power oscillations, limiting operational conditions, and potentially energy exchange with the southern neighbor via an existing DC link. EGAT decided to install the wide area monitoring system enabling it to continuously supervise damping, frequency and amplitude of potential oscillations (Figure 6). This can be seen as early warning for operators, to e.g. temporarily switch in capacitor banks or inductive loads for immediate stabilization of the power flows. As a next step, EGAT is considering to possibly automate these control actions in a wide area control installation.


Figure 5: EGAT's transmission corridor to Malaysia

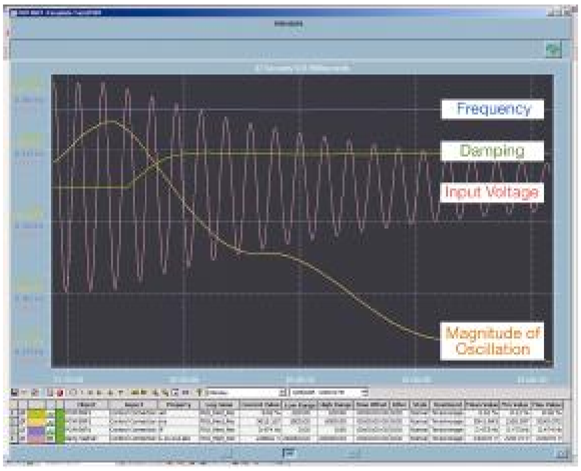



Figure 6: On-line display: Estimation of frequency, damping and magnitude of oscillation

**ETRANS (future Swissgrid) - the Swiss coordinator**

ETRANS has installed its first WAM system in the fourth quarter of 2003. It decided to use the phase angle on its important North South corridor as important additional information to determine actual loads and the impact of loss of power generation in neighboring countries on the reserve capacity of the interconnected European transmission system. Additionally, ETRANS used their WAM system installation to better understand and supervise the effects of wide area oscillations within the European Grid. This was of great value during the important UCTE zone 1 & 2 - resynchronization event on October 10, 2004, where potential critical oscillations had been expected. By installing an additional PMU in Greece and connecting it to the existing WAM system in Switzerland, a high-precision supervision of pan-European power and frequency oscillations became possible.

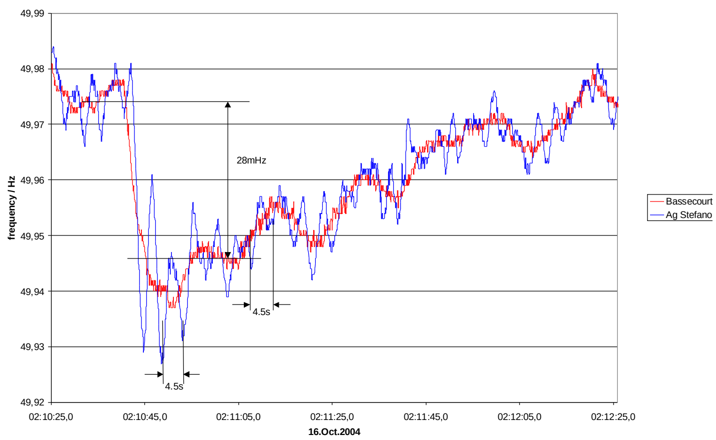



Figure 7: Loss of a power plant in Spain (1000 MW) recorded by WAMS

Figure (7) shows the impact of a power plant trip in Spain on the frequency in Switzerland and Greece. Since its commissioning phase in 2003, the system has given ETRANS the chance to record and analyze the impact of several similar events and to better understand their influences on the available transmission reserve capacity of major corridors and interconnections. This is an important input for the temporary release of reserve capacity on congested European transmission corridors.

The on-line phase angle measurements give ETRANS and the connected Swiss TSOs the chance to monitor the actual corridor loading. Moreover, the average line temperature calculated from the highly accurate phasor measurements gives operators an additional indication for better observance of the thermal loading of the line.

## Operational experience during UCTE grid reconnection

The resynchronization of the two UCTE zones that were divided as a result of the war in former Yugoslavia in 1991 has been a matter of highest priority to the Union for the Co-ordination of Transmission of Electricity (UCTE), which co-ordinates the interests of transmission system operators in 23 European countries [3]. Through the networks of the UCTE, 450 million people with a total annual consumption of about 2300 TWh are supplied with electricity. Coordination centers are responsible for the coordination of the scheduling and accounting process within the UCTE system, RWE for the North block and ETRANS for the South block [3]. The common objective of the UTCE members is to guarantee the operational security of the interconnected power system. Therefore, the physical re-integration of the South East European electricity markets with the remaining UCTE markets stretching beyond EU frontiers had a positive impact on the Europe-wide electricity sector. Preparation work for the process included the restoration and construction of crucial transmission infrastructure that was managed by the transmission system operators.


Fig. 8: WAMS, with installations in Switzerland, Croatia and Greece, is used for supervising of system stability and recording power system dynamics during and after the resynchronization.

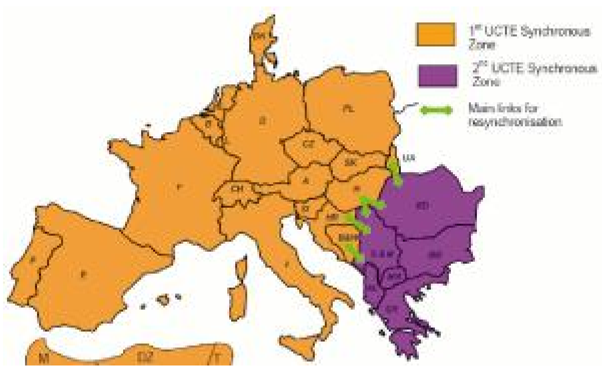


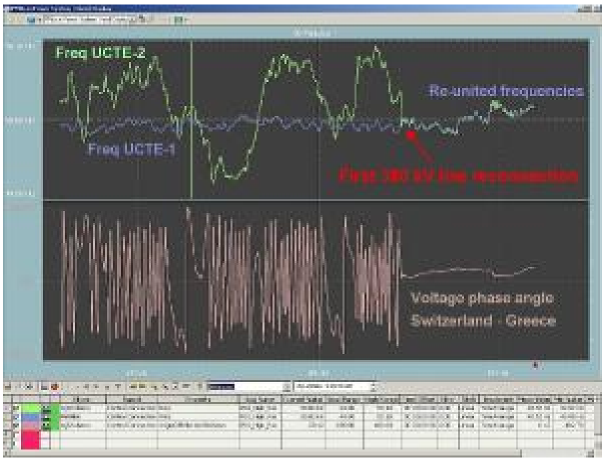

Fig. 9: 1st & 2nd UCTE synchronous zones with the five reconnected 380 kV lines

## Reintegrating UCTE-1 and -2

On 10th October 2004, the UCTE power system has been reconnected by reintegrating the second synchronous zone comprising most of the Balkan countries, Romania, Bulgaria and Greece and representing a load of 21 GW with the remaining UCTE area, i.e. the first zone with 223 GW of load (see Figure 8). As shown in Figure (9), relatively few lines connect the two zones.


Fig. 10: WAM on-line systems in the dispatching center during the reconnection process

Besides its contribution to the resynchronization as UCTE South coordinator, ETRANS provided on-line measurements of frequencies and voltage phase angles in Switzerland and Greece and so monitored the power system dynamics continuously. The Croatian TSO HEP also provided on-line grid data from its substations Zerjavinec and Tumbri recorded by its WAM system. See Figure 10.



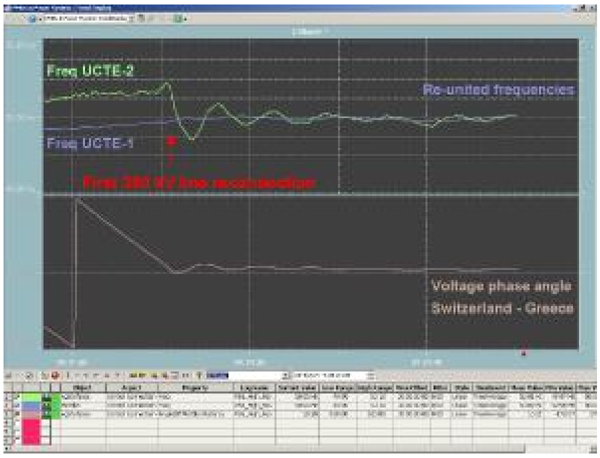




Fig.11: WAMS on-line trend display: UCTE-1 and -2 voltage phase angle difference and frequencies during the historical resynchronization process

Fig. 12: Zoom functionality (1 minute) to display the behavior of the power grid dynamics after the 1st 380 kV line reconnection (Arad–Sandorfalva)

The on-line monitoring helped the resynchronization team during the crucial phase and would have enabled early detection and reaction to unforeseen events (see Figures 11 and 12). All data could be exported for documentation [4] as well as off-line analysis and grid modeling enhancement (see Figure 13). Such transient behavior analysis is very important for network planning.

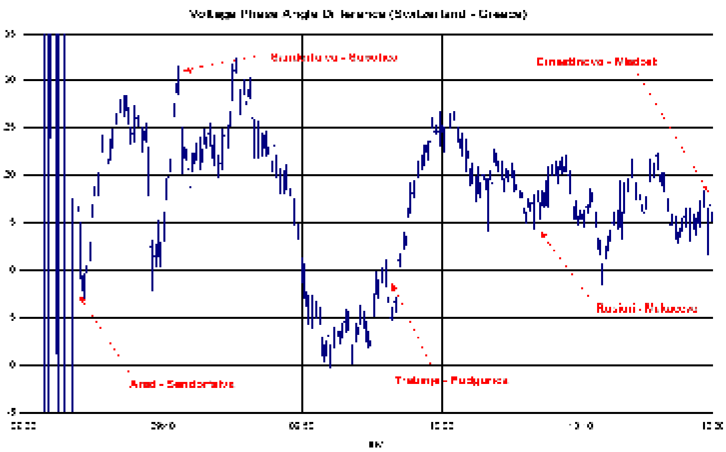


Fig. 13: WAMS data storage and export: off-line analysis of the angle difference during the reconnections of the five 380 kV lines

### Integration with Network Control Systems (NCCs)

For integration to e.g. a SCADA/EMS system, only specific information is extracted, converted and transmitted. When used to generate alarms and alert operators to overload situations or evolving disturbances, additional time might be won to take remedial actions for maintaining system integrity.

### Outlook to Wide Area Protection and Control

In using PMU technology, topological information from different substations could be gained and used e.g. for state estimation and calculation as well as Wide Area Protection (WAP) concepts. For instance, operational intertripping schemes could be used to avoid pre-fault constraints for the following possible post-fault problems:

- Thermal capacity limits
- Stability of power generation
- Low local system voltages
- Potential overloading of parts of the power system

As a consequence, Wide Ares Protection systems pose more demanding requirements as compared to monitoring in terms of reliability, security, redundancy and processing speed. Therefore, these need to be based on a well-proven and universal high-level automation platform with high performance. An example of a system set-up for Wide Area Protection and Control [5] is shown in Figure 14.

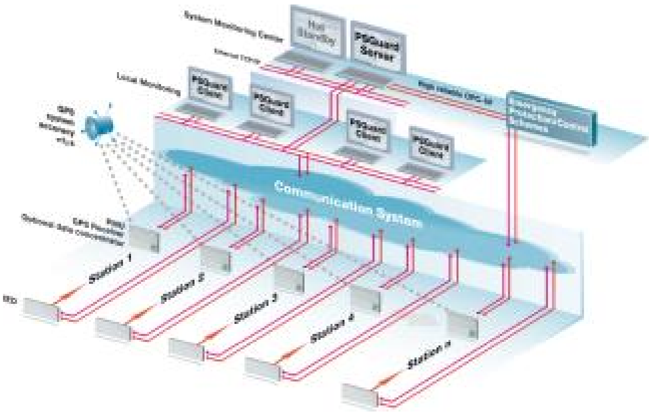



Figure 14: Wide Area Protection and Control System set-up

**Conclusions**

WAM systems have, in several installations and since 2003, proven the value of additional on-line stability information for use in the control room and to better understand dynamic power system behavior as well as fine-tune system parameters, e.g. in power system stabilizers.

As WAMS offers the possibility to see the own power system and beyond, secure interconnected system operation can be ensured. Applying this technology on a larger scale can significantly increase the benefits of wide area applications.

WAM systems have so far been mainly been used to provide information for manual process interaction. In a next step, these are seen as appropriate means to feed information back to, for instance, closed-loop control installations, using existing SCADA or other systems' process interaction.

**BIBLIOGRAPHY**

[1] J. Bertsch, M. Zima, A. Surányi, C. Carnal, N. Singh, W. Sattinger, "Experiences with and Perspectives of the System for Wide Area Monitoring of Power Systems", "Developments in Power System Protection", Amsterdam, The Netherlands, 5th-8th April 2004

[2] M. Zima, P. Korba, G. Andersson, "Power Systems Voltage Emergency Control Approach Using Trajectory Sensitivities", *2003 IEEE Conference on Control Application*, CCA, Istanbul, 23rd – 25th June, 2003

[3] UCTE homepage: www.UCTE.org

[4] P. Reinhardt, C. Carnal, W. Sattinger "Reconnecting Europe", Power Engineering International, January 2005, www.peimagazine.com

[5] C. Taylor D. C. Erickson, K. E. Martin, R. E. Wilson, and V. Venkatsubramanian "WACS-Wide-Area Stability and Voltage Control System: R&D and Initial On-Line Implementation," To be published in a special issue of the Proceedings of the IEEE, scheduled for March 2006.