Practical Experience with Modal Estimation Tools at Swissgrid

Mats Larsson, Walter Sattinger, Luis-Fabiano Santos, Roland Notter

***Abstract*—This paper describes experience with modal estimation tools for monitoring oscillations in the ENTSO-E continental European power system. A brief description of the tools and the wide-area monitoring system (WAMS) used by Swissgrid is given. The most important use cases are described and illustrated using recordings from actual events. The main use cases for the information provided by the WAMS at Swissgrid for planning and daily operation are discussed.**

***Index Terms*--Power oscillation, wide-area monitoring and control, phasor measurement, PMU, small disturbance stability, power system dynamics, practical experience.**

I. Introduction

A large interconnected power system such as the ENTSO-E Continental European Synchronous Area (CESA), which spans from Portugal to Turkey in the East-West direction and from Denmark to Italy in the North-South direction. The characteristics of power oscillations is an important consideration in the operation of a large interconnected power system like the continental European one. The CESA harbors a large number of oscillatory modes. These modes range from local plant modes with relatively high frequency of 0.9-2 Hz to the slow dominant inter-area modes of 0.1-0.4 Hz that relate to the coherent speed variations of generators in entire network areas against those in other areas.

Since 2004, Swissgrid monitors the Swiss transmission grid using PMUs [1]-[4], [8] and employ modal estimation tools for the monitoring of power oscillations. The system has been successively extended and is now interconnected with WAM systems from the same vendor at Verbund, Austria and at HEP in Croatia, enabling real-time exchange of phasor data. Additionally, phasor measurements are exchanged with WAM systems from other vendors in Denmark, Slovenia, Italy, Portugal, Greece and Turkey. Phasor data is exchanged over a secure inter-TSO communication network. In total, the WAM system collects data from 22 PMUs with full time resolution of 10 Hz. The setup now has excellent capabilities for monitoring inter-area oscillations in the CESA. The architecture of the hierarchical WAM system at Swissgrid is illustrated in Fig. 1.

This paper describes some of the operational experiences and use cases for modal estimation tools at Swissgrid, illustrated by WAMS recordings from actual events.

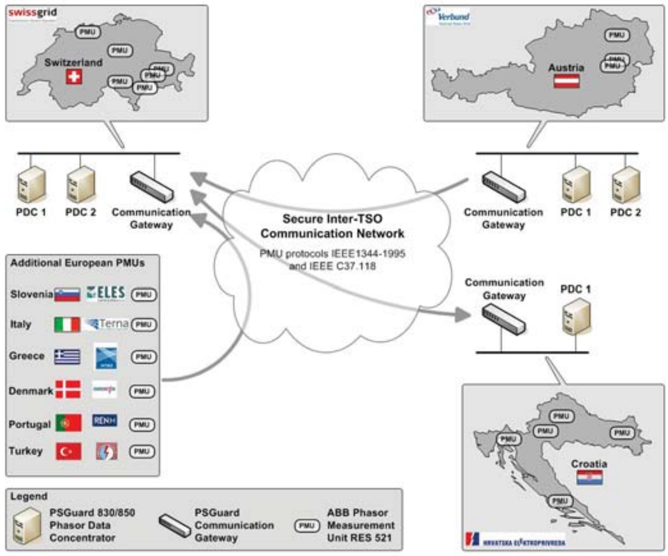

Fig. 1 - Architecture of the hierarchical WAM system at Swissgrid.

II. MODAL ESTIMATION TOOLS

As shown in Fig. 2, oscillations can occur in a power system as either *ambient* oscillations that arise from the interaction of the load variations with the dynamics of the power system, or *transient* oscillations that occur as a result of switching events or disturbances in the power system. Ambient oscillations are usually small in amplitude but are ever present. Transient oscillations have larger amplitude, but will decay within some tens of seconds as long as the damping ratio is adequate.

The oscillatory components of the variations in the measured signals are commonly classified by the damping ratio ζ and natural frequency ω_n. Each oscillatory mode is associated with an eigenvalue $\lambda = \alpha \pm j\omega_n$ that can be derived either from a nonlinear simulation model or from models formed on-line based on real-time measurements. Modal analysis of these models can also reveal the activity and observability of these modes in each individual measurement signal. This information is important for root-cause detection related to oscillatory modes and for alarming purposes.

Swissgrid employs a time domain damping criterion based on the ratio between the amplitudes of two successive oscillations, which is related to the natural damping through

$$\zeta_{td} = 1 - e^{\frac{2\pi\alpha}{\sqrt{\alpha^2 + \omega_n^2}}}$$

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For poorly damped oscillations, the time domain criterion ζ_{td} gives a similar numerical value as the damping ratio, but for well-damped oscillations the ζ_{td} will be considerably higher. Throughout the paper, the time domain damping criterion is employed.

Swissgrid uses two different tools for monitoring of small-disturbance stability:

- Power Oscillation Monitoring (POM) – aiming at detecting and alarming when transient oscillations are visible in a specific measurement signal.
- Power Damping Monitoring (PDM) – aiming at identifying the oscillatory modes and their respective damping, frequency and modal observability in different areas during ambient conditions.

POM relies on a single carefully selected measurement. Key rules for the selection are to use angle difference measurements formed from measurements at either end of an a-priori known oscillation path, or flow measurements from lines known to be on an oscillation path. At Swissgrid, several instances of POM using different measurements are running in parallel using different measurements.

PDM is installed in a single instance that monitors the entire grid and requires multiple measurements from geographically dispersed PMUs. Recommended measurements are PMU frequency measurements or angle difference measurements [7]. Since the objective is also to identify mode shapes, which are easy to interpret in frequency measurements but harder with angle difference, the Swissgrid installation is using frequency measurements.

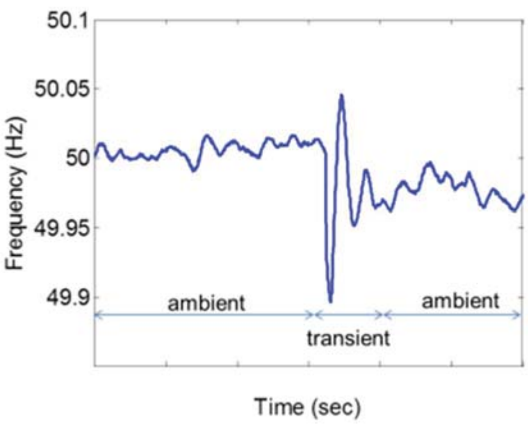

Fig. 2 – Illustration of ambient and transient oscillations.

A. Power Oscillation Monitoring -POM

Each instance of POM relies on a single selected PMU measurement or an angle different formed from two PMU measurements, a linear autoregressive model with time varying coefficients and Kalman Filtering techniques for identification of parameters characterizing critical oscillations. The information about oscillations and their progress in time is obtained from the estimated model for the actual set of its time-varying parameters. The theoretical background and performance validation has been previously reported in [6].

The logic for alarms and warnings indicating the presence of dangerous power oscillations is in practice built on estimates obtained in the frequency-domain (such as relative damping) and combined with the information obtained in the time-domain (e.g. the current oscillatory amplitude). In addition, to achieve a higher reliability, the actual as well as the past estimated values are used. Hence, before an alarm and/or warning are triggered, the minimal damping and/or maximal allowed oscillatory amplitude must occur (and persist) for a certain minimal period of time.

B. Power Damping Monitoring -PDM

The PDM application is based on a system identification procedure that is carried out using a sliding window. This yields a time-varying dynamic equivalent of the power system, which is analyzed using modal analysis, resulting in the desired information about the active inter-area modes in real-time. The information includes:

- The number of detected active oscillation modes.
- The frequency and damping of each mode.
- The amplitude of the oscillations in each mode and in each measurement signal.
- The modal observability, i.e., a measure of how well each oscillatory mode is visible in each measurement signal, as well as the relative phase in each measurement.

The configuration of the application defines:

- The selection of measurements to be used as input signals. Experience has shown that voltage angle difference and frequency measurements are particularly useful for the detection of inter-area modes. A general rule is to select measurement from the edges of the system since they usually offer the highest observability.
- The length of the sliding window which is typically around 10-15 min.
- The update rate which is typically once every 30 seconds.
- The maximum number of modes to detect and strategy for selection and sorting of the identified modes. The different strategies include ranking by lowest damping, proximity to certain known oscillation frequency and sorting by absolute mode frequency.

The mathematical background of the algorithm, results from simulation experiments and measurements in the Scandinavian power grid are described in [6]. It was benchmarked against other damping monitoring algorithms in [7].

III. USE OF MODAL ESTIMATION AT SWISSGRID

A. Detection and Characterization of Oscillatory Modes During Ambient Conditions

The PDM application used for ambient data analysis has been configured to use real-time frequency measurements with a time resolution of 10 Hz from the seven locations shown with circles in Fig. 3. This enables the detection of known oscillatory modes as well as discovery of new modes when they appear. This figure also illustrates the inter-area oscillation modes that are typically detected by PDM during normal, ambient, conditions.

Fig. 7 shows the output of PDM during normal conditions. Three clusters of dominant modes can be seen which correspond to the main inter-area modes in the CESA system.

- The *East-West mode* involves coherent movement of generators in Portugal and Spain against those in Turkey. This mode typically shows a frequency of 0.13-0.15 Hz and appeared following the connection of Turkey. Under normal operating conditions, this is the dominant mode with the most oscillatory energy. The time domain damping (ζ_{td}) around 60% is also typical.
- The *Former East-West mode* involves coherent movement of generators in Portugal and Spain against those in Greece. This mode typically exhibits a frequency of around 0.17-0.2 Hz and is best visible in frequency measurements from Greece and from Portugal. This mode mostly also has good time-domain damping around 40-50 %.
- The *North-South mode* involves coherent movement of generators in southern Italy against northern Germany and Denmark. This mode typically exhibits a frequency of around 0.23-0.27 Hz. Good measurement signals for observation of this mode are frequency and voltage angle measurements from southern Italy or Denmark, or active power flow measurement on the cross-border lines between Italy and Switzerland.

Because of the significantly lower combined rotating mass of generation units in southern Italy, the amplitude in the frequency measurements is there much higher here compared to the measurement from Denmark. This is confirmed by the modal activity and observability estimates provided by the PDM application. The result of the damping monitoring application correspond well with anticipations from system studies and engineering expectations regarding the dynamic characteristics of the ENTSO-E CESA system, and thus serves as an indirect partial validation also of the models used in those studies.

Swissgrid has constructed detailed dynamic power plant models in the past in order to be used as a basis for power system restoration studies. In normal operation these power plants deliver ancillary services. With the help of accurate wide-area measurements (WAM) the conformity of additional active power delivery during frequency drops could be verified.

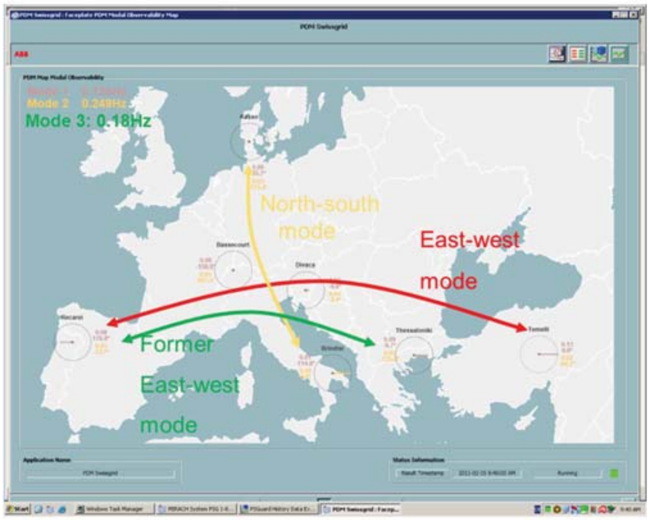

Fig. 3 - Map display showing the dominant inter-area modes in the ENTSO-E grid. The circles indicate the location of the PMU frequency measurement used by the damping monitoring application.

B. *Detection of Large Poorly Damped Oscillations*

The dominant modes depicted in Fig. 3 are permanently monitored by performing on-line modal analysis and related parameter identification. If the system damping for one of the significant modes becomes too low together with a high oscillation amplitude for longer than a few oscillation cycles specific alarms are transmitted from the WAM system to the SCADA environment. The operators are then notified through a red box that pops up on one of the main SCADA overview display illustrated in Fig. 4.

One of the latest critical inter-area oscillation occurred on Feb. 19th 2011 [9] when during Sunday morning the Italian power system mainly oscillated against the rest of the Continental European system. This large oscillation was successfully detected by both the POM and PDM modal estimation tools.

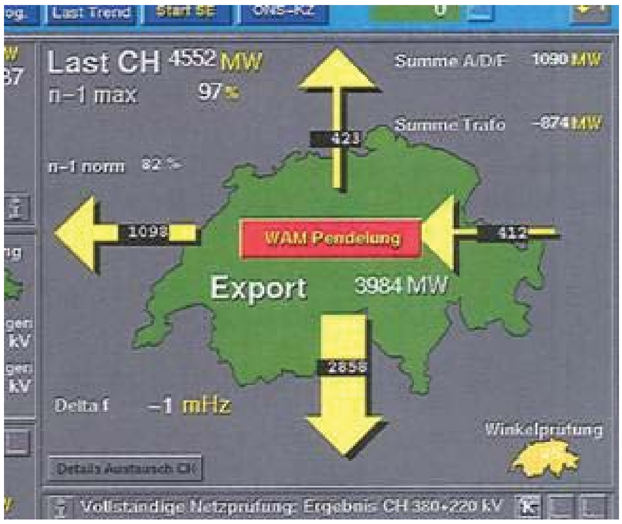

Fig. 4 - SCADA system screenshot during a detected inter-area oscillation. The red box containing the text “WAM Pendelung” notifies operators that the WAMS has detected a poorly damped and active oscillation mode.

C. Use of WAMS to assist synchronization of network areas

One of the first use cases for WAMS in Swissgrid was the usage of the wide-area measurements to supervise the synchronization of network areas. In year 2004 this tool was used during the resynchronization of UCTE synchronous zone 1 with synchronous zone 2. Fig. 5 shows the WAM recording from the more recent first trial connection from the first connection of Turkey to CESA in 2010. Before the decision to close the tie-lines was taken, it was ensured that the difference in frequency in the different areas is acceptable from the PMU measurements. From the figure, it is also clearly visible how immediately after synchronization, the new 7-second-mode became visible as predicted by system studies. This mode is currently carefully monitored in order to ensure that all damping measures within the Turkish system are sufficient. A detailed discussion is provided in the next section.

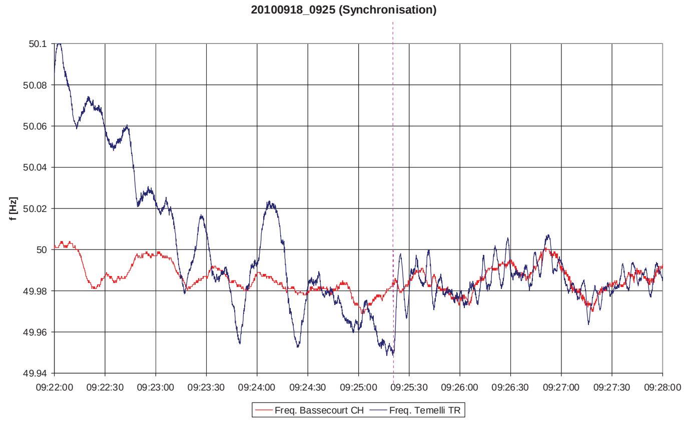

Fig. 5 – WAM frequency recording from connection of Turkey on September. 18th, 2010.

D. Use of PDM to Confirm Adequacy of PSS Retuning Efforts

Prior to the connection of Turkey to the CESA described in the previous section, detailed simulation studies and measures were taken to ensure adequate damping of the East-West mode. Those measures included for example retuning power system stabilizers to damp this new inter-area mode and the addition of active shunt compensation such as STATCOM and SVC with damping modules.

On October 25, 2011 five units of a major hydro generation plant were tripped due to a nearby busbar failure. The result was the loss of around 1300 MW generation in the Turkish part of the interconnected grid, which as expected excited the East-west mode. According to design, a system protection scheme (SPS) in the Turkish grid also executed around 270 MW of load shedding in the Turkish part of the system to protect tie lines from Greece and Bulgaria from disconnection due to overloading.

This event provided the opportunity to confirm the adequacy of the measures taken to improve damping as well as to validate the output of the PDM application during ambient conditions.

Fig. 6 shows the frequency response in Temelli, Turkey, following the generation loss as recorded by the Swissgrid WAMS. Following the trip there is a rapid decline in the local frequency of around 100 mHz followed by a well damped oscillation. From the figure, the time-domain damping (ζ_{td}) of the transient oscillation can be determined to be approximately 70%.

Fig. 7 shows the estimated modal damping and frequency during half an hour *before* the event, illustrated by red asterisks, and half an hour *after* the event, illustrated by blue crosses. Clusters corresponding to the known oscillatory modes are clearly visible. The cluster to the bottom right in the figure corresponds to the East-west mode with frequency 0.13 Hz and average damping of 60% before as well as after the disturbance. Thus, we can conclude that the plant trip appears not to have significantly changed the damping of this mode, and that adequate damping resources were available even though the lost generation units were equipped with power system stabilizers tuned to damp out this mode.

An interesting observation is that the power damping monitoring application was able to determine the post-disturbance damping of the East-west mode close to its true damping using only the ambient pre-disturbance data. This gives additional confidence in its effectiveness as an early-warning system against poorly damped oscillation that may arise also due to transient events.

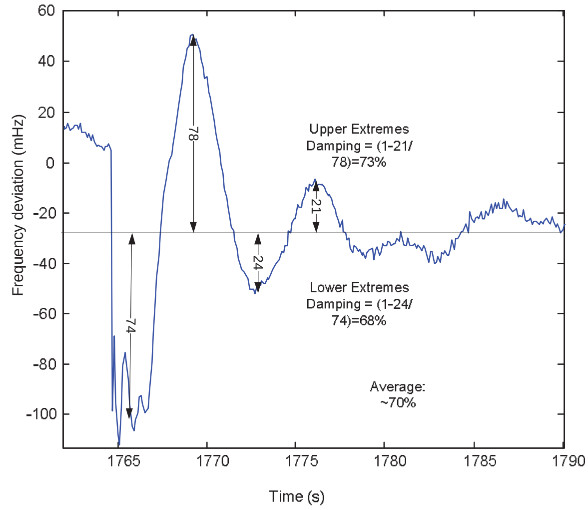

Fig. 6 - Frequency response in Temelli following the hydro generation plant trip October 25, 2011 recorded by the Swissgrid WAMS. Time axis is in seconds after 15.00 CET.

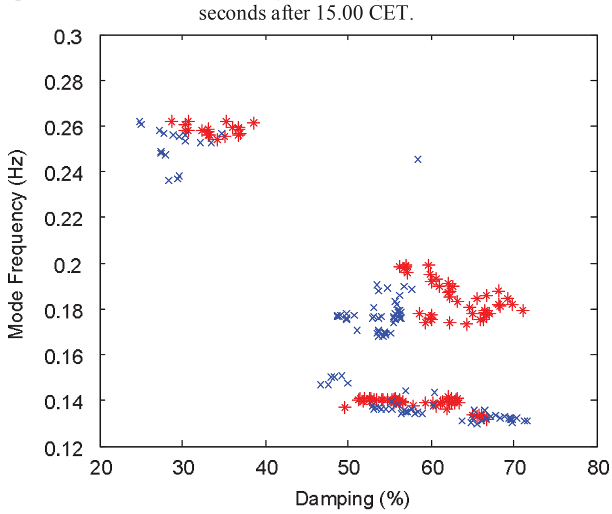

Fig. 7 – Scatter plot showing the output of the damping monitoring algorithm for 59 executions of between 14.30 CET and 14.59 CET marked with red asterisks, and for 61 executions between 15.00 CET and 15.30 CET marked with blue crosses.

E. Use of POM for discovery of a new mode

On July 7th, 2012 a new local plant mode, not seen before, suddenly appeared in the Swiss part of the network. Although the modal estimation tools have their measurement selection and tuning based on the a-priori known modes shown in Fig. 3, it is possible to detect also previously unknown modes provided the observability of such modes is adequate in the used measurements.

Fig. 8 shows the output of two instances of the POM modal estimation tool during this oscillation event. As seen in the figure, one of the POM instance detects the new mode. In this case, the automatic alert from the POM application prompted a more detailed manual examination of the recorded phasor data by the TSO which linked the new local mode to a particular power plant. Discussions between the TSO and plant owner then revealed the source of the problem, which was a result of a power system stabilizer being out of service following maintenance work. The PSS was put back into service and the new local mode disappeared.

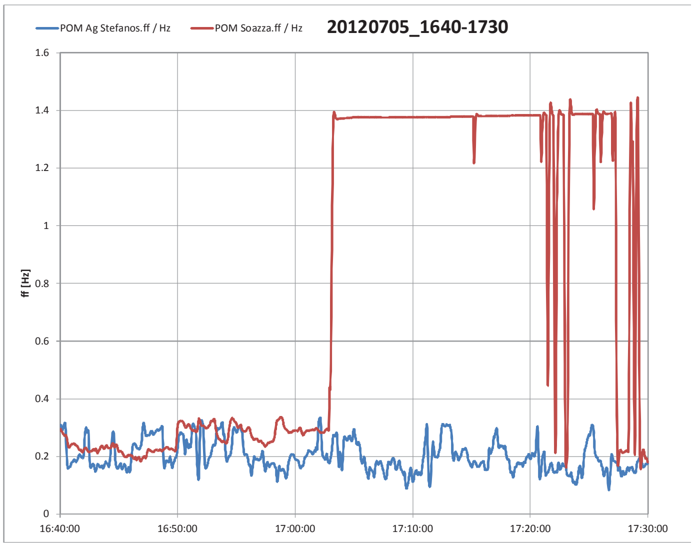

Fig. 8 – Modal frequencies estimated by two POM instances. The appearance of the new mode is clearly visible as the step of the estimated frequency as the poorly damped local modes becomes dominant.

IV. CONCLUSIONS AND FUTURE OUTLOOK

Swissgrid and ABB now have close to a decade of experience of the use of modal estimation in the daily operation of power systems. On numerous occasions, the modal estimation tools have provided information that has been useful to profile the dynamic performance of the ENTSO-E Continental Europe grid, allowed the detection and correction of problems as well as supported the operations in the synchronization of network areas.

From the vendor perspective, the validation of the modal estimation tools in a real-grid situations like studied here is of critical importance for continuous verification and enhancement of the underlying algorithms. The experience so far shows that the modal estimation tools are robust and reliable and have already been validated over a wide-range operating conditions. Within the near future these tools can be further enhanced to be used as basis for closed-loop damping control and for automated emergency control actions.

From the Swissgrid perspective, the next steps are to create a closer link between the WAM system and the SCADA system by setting up simple and comprehensive MMIs for a comprehensive visualization of system dynamics for the use of the power system operators.

V. ACKNOWLEDGMENT

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