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**Recent Advances and Experience with Power System Oscillation Monitoring and Control using Wide-area Phasor Measurements**

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## KEY WORDS

Power oscillation, wide-area monitoring and control, phasor measurement, FACTS/HVDC, PMU, small disturbance stability, power system dynamics, power system control

## ABSTRACT

Power oscillations are a growing concern among power system operators worldwide. Traditionally, the main countermeasure against dangerous power oscillations has been the installation of power system stabilizers (PSS). Essentially, the potential for inter-area power oscillations depends on the strength of the tie lines between different areas and the load on the ties. From a European perspective, with the anticipated integration of remote renewable energy sources such as offshore wind power from the North-sea region and solar power from southern Europe or Africa, we can expect the average transmission distances to grow and consequently also tie line flows. Unless tie lines are also reinforced we expect more oscillation events in the European grid in the future.

From an operational point of view, it is of high priority to be able to estimate the damping of oscillatory modes reliably in real-time in order to take appropriate and timely measures in case damping becomes poor. Recent developments in wide-area phasor monitoring have resulted in a new power oscillation monitoring algorithm that uses multiple measurements from different locations in the grid. An equivalent system model of the power grid is estimated in real-time and based on this model, the damping and frequency as well the activity of oscillatory modes can be determined from ambient process variations. As basis for this, a wide-area measurement system (WAMS) can provide time synchronized signals from phasor measurement units (PMUs) that can measure voltage, current and frequency with adequate accuracy and resolution in time. This paper shows results from pilot operation of the new application at swissgrid, including recordings from an actual and representative event in the continental ENTSO-E interconnected power system. This example demonstrates the performance of the new application as well as provides information about the oscillatory modes present in the continental ENTSO-E system today.

## 1.0 - INTRODUCTION

Wide-area monitoring systems (WAMS) offer the possibility of supervision of power system dynamic phenomena. They are based on phasor measurement units which are most often synchronized using a global positioning system (GPS) clock to provide time-synchronized voltage and current phasor, as well as frequency measurements with synchronization accuracy better than microseconds [1-4].

This paper describes a new damping estimation application that employs WAMS data to estimate the damping of oscillatory modes from ambient data before a disturbance [5-7]. This can give an indication of the damping of transient oscillations that will follow a disturbance, once it occurs. The application is based on a system identification procedure that is carried out in real-time using a sliding measurement window. If the transfer between two grid areas is limited by inadequate damping, the damping monitor can assist in maximizing the power transfer capability by providing a faster and more accurate view of the current situation than one obtained via off-line dynamic simulations. This is possible since the PMU measurements are not subject to modeling errors that are potentially present in the off-line simulation models. Such modeling errors could lead to definition of overly conservative or even inadequate transfer limits. The new damping monitoring application also identifies the parts of the power system that participate in a detected oscillation through modal activity information that can be used to determine the root cause of a poorly damped oscillatory mode, and serve as starting point for the definition of improvement measures.

Furthermore, any fast power electronic devices able to directly or indirectly modulate electric power flows (such as FACTS, HVDC or the excitation systems of synchronous generators), can be used as actuators to improve poor damping, provided they are equipped with appropriate controller extensions [8-10].

## 2.0 - DEFINITIONS OF MODAL DAMPING AND FREQUENCY

In the case of a single wide area electromechanical oscillation mode, the relationship between power flow, $y(t)$, and the unmeasured load demand, $u(t)$, can be modeled by a second order linearization

(1) $$\frac{d^2y}{dt^2} + 2\zeta\omega_n \frac{dy}{dt} + \omega_n^2 y(t) = u(t)$$

where $\zeta$ is the damping ratio and $\omega_n$ is the natural frequency of the oscillation. If $\zeta$ is positive and less than one, an impulsive change in $u(t)$ gives a decaying transient oscillating response. This response typically occurs after a fault or major system disturbance and is called a *transient* or *ring down*. On the other hand, random changes in $u(t)$ excite a persistent oscillation at the natural frequency, which may be of small amplitude and largely hidden in noise. This is called *ambient conditions*.

Eigenvalues are the complex roots, $\lambda_1$ and $\lambda_2$, of the characteristic equation arising from (1). There are also many ways to estimate eigenvalues from time series of measurements $y(t)$, including subspace identification which is used in this paper. If the eigenvalue is expressed in Cartesian form as $\lambda_i = \alpha \pm j\omega_t$, an the expression for *damping ratio* is $\zeta = -\alpha \big/ \sqrt{\alpha^2 + \omega_t^2}$ . Another common measure is the *time domain damping* which can easily be obtained as the ratio of two successive peaks in a recorded oscillation as illustrated in Figure 3, or from the eigenvalues as $\zeta_{td} = 1 - e^{\frac{2\pi\alpha}{\sqrt{\alpha^2 + \omega_t^2}}}$ . Throughout this paper the general term damping refers to the time domain damping $\zeta_{td}$ .

## 3.0 - DAMPING MONITORING OF POWER OSCILLATIONS USING AMBIENT DATA

The 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 and the relative phase in which each oscillatory mode is visible in each measurement signal.

The configuration of the application defines:

- The selection of measurements to use as input. Experience has shown that voltage angle difference measurements and frequency measurements are particularly useful for this purpose. A general rule is to select measurement from the edges of the system since they usually offer the highest observability of inter-area modes.
- The length of the sliding window which is typically around 10-15 min.
- The update rate which is typically once every 30 seconds.
- 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 and results from simulation experiments as well as measurements in the Scandinavian power grid are described in [5,6] and has been benchmarked against other damping monitoring algorithms in [7].

## 4.0 - WIDE-AREA MONITORING SYSTEM AT SWISSGRID

Since 2004, swissgrid has been monitoring the Swiss transmission grid using PMUs [2-4]. The system has been successively extended and is now interconnected with WAMS 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 WAMS systems from other vendors in Denmark, Slovenia, Italy, Portugal, Greece and Turkey. Phasor data is exchanged using the SynchroPhasor standard protocols over a secure Inter-TSO communication network. In total, the WAMS system collects data from 22 PMUs with the full time resolution of 10 Hz. The setup now has excellent capabilities for monitoring inter-area oscillations in the ENTSO-E Continental European Synchronous Area (CESA). The architecture of the hierarchical WAMS system at swissgrid is illustrated in Figure 1.

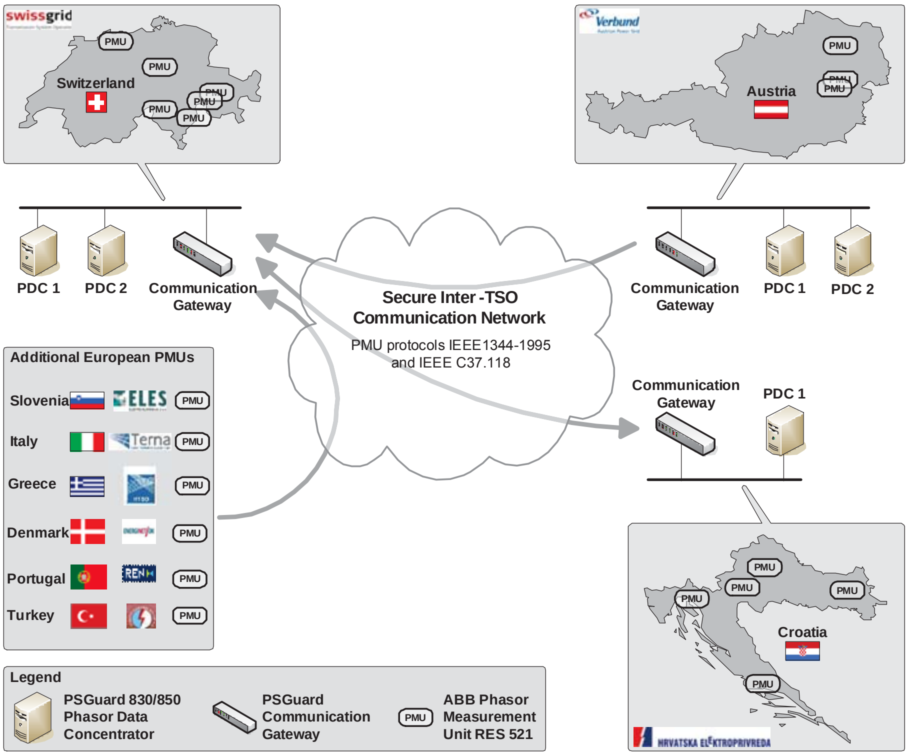


Figure 1 - Architecture of the hierarchical WAMS system at swissgrid.

## 5.0 - CASE STUDY: ENTSO-E CESA

A large interconnected power system such as the ENTSO-E Continental European Synchronous Area (CESA), which spans from Portugal to the West, Denmark to the North, Italy in the South and Greece in the East, 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 that relate to the coherent speed variations of generators in entire network areas against those in other areas. Although the damping monitoring application will detect also local modes, the investigation here focuses on the inter-area modes. Since September 2010, the Turkish power grid is connected to the ENTSO-E CESA system, currently in trial operation. As discussed below, the connection of Turkey resulted in a new dominant mode.

The new damping monitoring application has been in pilot operation at swissgrid since December 2010, and has continuously monitored the damping and frequency of inter-area modes in the CESA system. The application has been configured to use real-time frequency measurements with a time resolution of 10 Hz from the seven locations shown with circles in Figure 2. This figure also illustrates the inter-area oscillation modes that have been detected by the damping monitoring application 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. Prior to the connection, detailed simulation studies and measures were taken to ensure damping of this anticipated 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 STATCOMM and SVC with damping modules. The field recordings using WAMS indicate that those measures have been effective. The estimated time-domain damping ( $\zeta_{td}$ ) most of the time is in the interval 45-70% which we consider adequate.

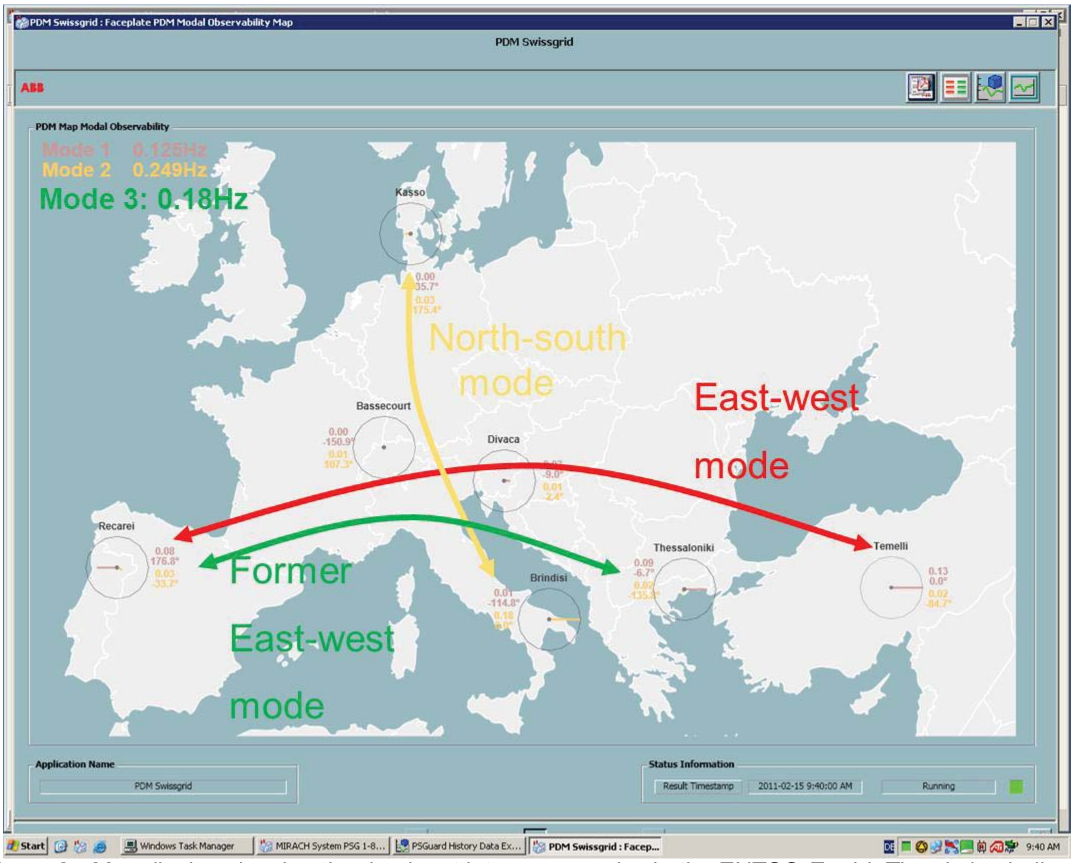


Figure 2 - Map display showing the dominant inter-area modes in the ENTSO-E grid. The circles indicate the location of the PMU frequency measurement used by the damping monitoring application.

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. Nowadays, this mode mostly also has good time-domain damping ( $\zeta_{td}$ ) 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. The WAMS recordings show that this mode typically exhibits the lowest damping of the three dominant modes, although a significant improvement can be seen during the second half of 2011.

The results 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.

## 5.1 - Huge Power Generation Loss in Turkey

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. As designed, a system protection scheme (SPS) in the Turkish grid executed around 270 MW of load shedding in the Turkish part of the system to protect tie lines to Greece and Bulgaria.

Figure 3 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 ( $\zeta_{td}$ ) of the transient oscillation can be determined to be approximately 70%.

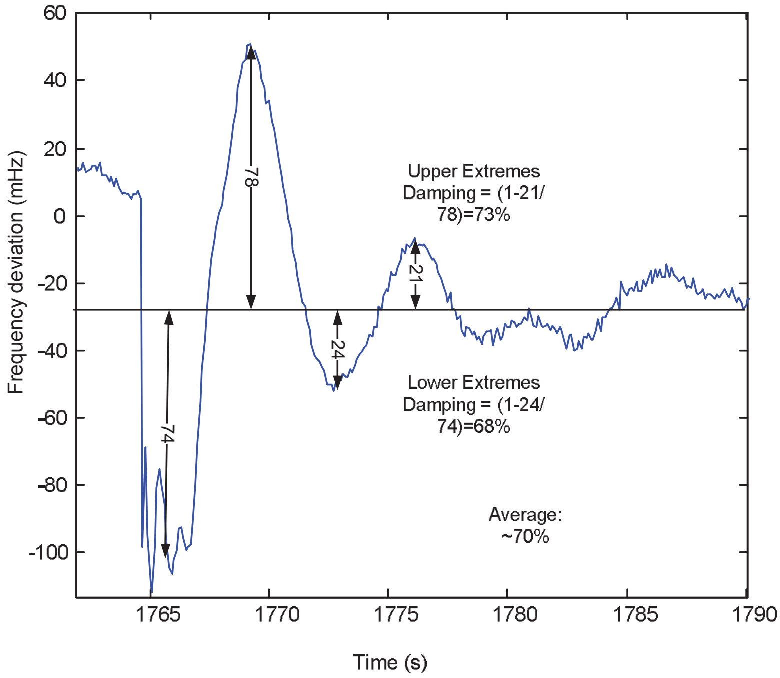


Figure 3 - Frequency response in Temelli following the hydro generation plant trip at 14.59 on October 25, 2011 recorded by the swissgrid WAMS. Time axis is in seconds after 14.30 CET.

## 4.2 Results of the Damping Monitoring Application

Figure 4 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. In the top left of the diagram the cluster corresponding to the North-south mode with a detected frequency of around 0.25 Hz, and average damping of 30% is visible. The clusters from before and after the disturbance are mostly overlapping. Thus we can draw the conclusion that the event had no significant effect on the damping or frequency of the North-south mode.

The cluster around 0.18-0.19 Hz corresponds to the Former East-west mode. The average damping before the disturbance was around 60% and around 50% after. This indicates that the event has caused a reduction of the damping of around 10%. However, the damping of this mode is still to be considered adequate after the disturbance. The reason for the reduction in damping is not yet clear, but a plausible explanation is that the load that was disconnected by the system protection scheme was mostly of an industrial nature, and may have been contributing to the damping of this mode. Another explanation could be that the flow patterns in the grid changed in a way leading to lower damping of this mode.

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 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.

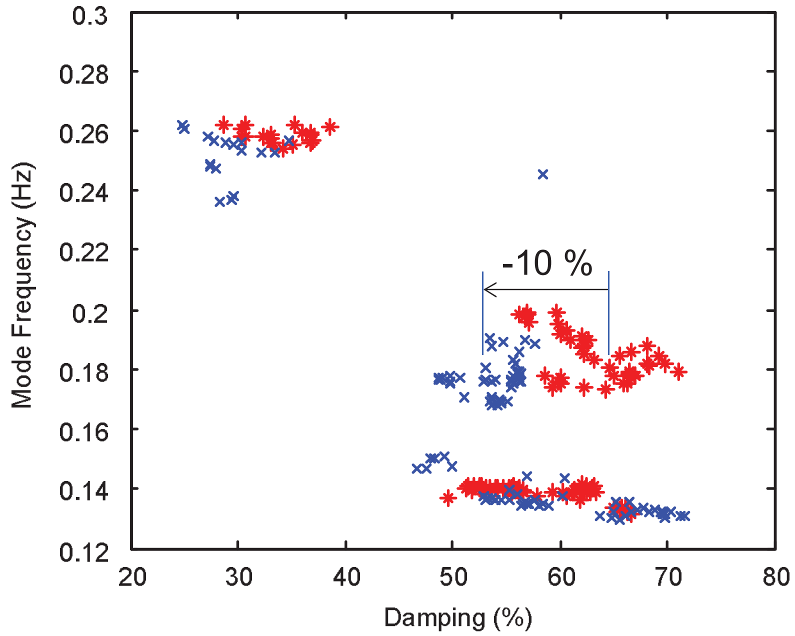

Figure 4 – Scatter plot showing the output of the damping monitoring algorithm for 59 executions of between 14.30 CET and 14.59 CET marked with red asterisks, and for 61 executions between 15.00 CET and 15.30 CET marked with blue crosses.

## 6.0 - DAMPING OF POWER-OSCILLATIONS USING WAMS AND FACTS/HVDC

The most common practice today, is to use power system stabilizers (PSS) applied as an auxiliary input to the voltage set-point of the automatic voltage regulator (AVR) of large synchronous generators. However, any fast power electronic devices that can modulate directly or indirectly electric power flows (such as FACTS or HVDC), can be used as actuators to deal with the problem of poorly damped electromechanical oscillations in large electric power systems [8-10]. However, the effectiveness of the actuators for damping control, be it FACTS/HVDC or synchronous generators, largely depends on the tuning of the damping extensions and on the location of the actuator. Furthermore, generators and transmission network often belong to different entities with different interests. Thus, network operators are increasingly considering network components such as HVDC and FACTS devices to be equipped with damping controllers having the functionality equivalent and in some respects surpassing that of power system stabilizers [8,9].

There is no unique way of tuning a damping controller extension for a FACTS/HVDC or a synchronous generator; however, in the industry have been created appropriate tools for tuning of standardized structures of PSS for synchronous generators [11]. This PSS tuning procedure aims at fulfilling the following three goals:

- Local mode oscillations, i.e., those with the frequencies above 0.7Hz, must be well damped.
- The PSS should also provide adequate damping for inter-area mode oscillations.
- The PSS should not over-modulate the control signal.

The idea behind the wide-area approach to power system stabilizers is in principle very simple: Extend the number of signals, which can be considered as a feedback for control (i.e. including the remote signals available through WAMS), and select between them carefully those with the highest observability of the oscillatory modes to be damped. Hence, the selection of the proper feedback signal is herewith the first and very important step in the stabilizing controller design. In practice, one can use as a starting point the measured signals collected from the installed PMUs and identify this model. And, this is exactly what is happening when running the same algorithm as used in the damping monitoring applications described in the previous sections - however, extended with input channels corresponding to the considered actuators [12].

Applying the above mentioned concept to the identified power system model for the selected input and output channels and the critical modes, one can get the information which measurements should be ideally used as feedback signals in the damping control loops. In all cases investigated so far (see e.g. [9],[10],[12]), the remote signals were in the analysis classified as superior to the local ones. And, the resulting controllers (having the same structure but using remote signals) outperformed the conventional local ones.

Based on the collected experience, due to high modal observability of the critical oscillatory modes in the selected remote feedback signals one can observe the following tendencies:

- With wide-area controllers, the damping of all critical modes can be more easily achieved and demonstrated in both frequency domain (for linear or linearized system model) as well as in the time domain.
- In addition, the wide-area controllers have smaller gain across all frequencies, and therefore, they are inherently more robust and require less control energy those based on local feedback signal, to achieve the same damping.
- The price to be paid for the wide-area solution is higher investments into communication infrastructure to enable a reliable transfer of all required measurements from the remote place where they are captured to the generator excitation system. In general, the local measurements are still more reliable.
- Another advantage of the local approach is that only basic data and less information about the power system are required for the proper controller tuning, whereas the wide-area design requires an equivalent linear power system model, which can be created using a power system tool or through system identification.

## 7.0 - CONCLUSION

The paper demonstrates the use of a new multivariable damping monitoring algorithm for the purpose of supervision of inter-area oscillations in power networks. The application results are validated against the measured response following a generator trip in the Turkish power network that caused an oscillation visible along the East-west direction in the entire ENTSO-E continental Europe grid. The application was able to determine the damping of various oscillatory modes accurately using only the pre-disturbance data from ambient conditions. That is, the true damping of the post-disturbance transient oscillation in the East-west mode agreed well with the damping estimated by the damping monitoring application prior to its occurrence.

It is a common practice for the power system stabilizers to be designed using local measurements and synchronous generators only. Similarly, HVDC and FACTS devices can be used to improve damping. The use of properly selected feedback signals and actuators yields a superior performance and robustness of the designed controllers to damp the critical oscillatory modes, thanks to higher modal observability and controllability which leads to lower gains and better robustness of the feedback control loops. It is however, important to realize that the solution based on remote feedback has also a higher technical complexity and cost. Hence, the cost/benefit ratio shall influence the decision on which solution will be applied in practice on a case to case basis.

## 8.0 - ACKNOWLEDGEMENT

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