EUROPEAN TRANSACTIONS ON ELECTRICAL POWER
Euro. Trans. Electr. Power 2011; **21**:2098–2111

Survey on power system stabilizers control and their prospective applications for power system damping using Synchrophasor-based wide-area systems

Yuwa Chompoobutrgool, Luigi Vanfretti*,† and Mehrdad Ghandhari

Electric Power Systems Division, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm SE-100 44, Sweden

SUMMARY

Power system oscillation damping remains as one of the major concerns for secure and reliable operation of large power systems, and is of great current interest to both industry and academia. The principal reason for this is that the inception of poorly-damped low-frequency inter-area oscillations (LFIOs) when power systems are operating under stringent conditions may lead to system-wide breakups or considerably reduce the power transfers over critical corridors. With the availability of high-sampling rate phasor measurement units (PMUs), there is an increasing interest for effectively exploiting conventional damping control devices, such as power system stabilizers (PSSs), by using these measurements as control input signals. In this paper, we provide a comprehensive overview of distinct elements (or ''building blocks'') necessary for wide-area power system damping using synchrophasors and PSSs. These building blocks together shape a tentative methodical framework, and are disposed as follows: (1) fundamental understanding of the main characteristics of inter-area oscillations, (2) wide-area measurement and control systems (WAMS and WACS) and wide-area damping control (WADC), (3) advanced signal processing techniques for mode property identification, (4) methods for model-based small-signal analysis, (5) control input signals selection, and (6) methods for PSS control design. We also describe the latest developments in the implementation of synchrophasor measurements in WAMS and WACS as well as their prospectives for WADC applications. This paper serves both to abridge the state-of-the-art in each of these elements, and to accentuate aspiring ideas in each building block. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: Phasor measurement units; power system stabilizers; wide-area measurement; wide-area monitoring and control; wide-area damping control

1. INTRODUCTION

The occurrence of low frequency inter-area oscillations in power systems is one of the main concerns for system operation and control [1]. As power systems continue to be interconnected and more power is transmitted over capacity-constraint power transfer corridors, adequate damping of inter-area oscillations is necessary to secure system operation and ensure system reliability. The damping of these oscillations is also crucial for maintaining maximum power transfer within transmission corridors.

One of the most common applications of phasor measurement units (PMUs) is power system monitoring, especially for monitoring wide-area disturbances and low frequency electromechanical oscillations [2–4]. PMUs are a solution to increase observability in traditional monitoring systems and provide additional insight of power system dynamics. In recent years, the introduction of synchrophasor measurement technology has significantly improved observability of power system dynamics [4] and is expected to play a more important role in the enhancement of power system controllability [5].

---

*Correspondence to: Luigi Vanfretti, Electric Power Systems Division, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm SE-100 44, Sweden.
†E-mail: luigiv@kth.se

Power system stabilizers (PSSs) are the most common damping control devices in power systems. The PSSs of today usually rely on local information (such as generator rotor speed or electric power) and are effective in damping local modes. Carefully tuned PSSs may also be able to damp some inter-area oscillations; those which can be observed in the monitored input signals. By appropriately tuning available PSSs, together with wide-area measurements obtained from PMUs, it is expected that inter-area damping can be effectively improved.

The aim of this paper is to discuss the different elements that make possible the use of PMUs in PSS control to improve damping of inter-area modes. We discuss the use of wide-area measurements, generators selection for controllability, and PMU signal selection for obtaining the highest observability of dominant inter-area modes. Tuning methods for PSS are also discussed. It is expected that real-time monitoring and control using synchrophasor measurements could help enhancing system stability and security, particularly by enhancing inter-area damping control.

The remainder of this paper is organized as follows. Section 2 describes the main characteristics of inter-area oscillations. Section 3 describes recent applications of phasor measurement technology: WAMS, WACS, and WADC. In Section 4, identification and monitoring of inter-area oscillations is discussed. Methods of small-signal stability analysis are described in Section 5. Section 6 is devoted to control input signal selection while Section 7 summarizes PSS controller design methods and placement. In Section 8 conclusions are duly drawn.

2. INTER-AREA OSCILLATIONS

2.1. Characteristics

Inter-area oscillations are a part of the nature of interconnected power systems. Large power systems being connected by weak ties transmitting heavy power flows tend to exhibit such modes. These oscillations are a result of the swing between groups of machines in one area against groups of machines in another area, interacting via the transmission system. They may be caused by small disturbances such as changes in loads or may occur as an aftermath of large disturbances. This type of instability (small-signal rotor-angle instability) in interconnected power systems is mostly dominated by low frequency inter-area oscillations (LFIO). LFIOs maybe result in small disturbances, if this is the case, their effects might not be instantaneously noticed. However, over a period of time, they may grow in amplitude and cause the system to collapse [6].

Incidents of inter-area oscillations have been reported for many decades. One of the most prominent cases is the WECC breakup in 1996 [7]. Mode properties of LFIO in large interconnected systems depend on the network configuration, types of generator excitation systems and their locations, while load characteristics largely affect the stability of inter-area modes [1]. In addition, the natural frequency and damping of inter-area modes depend on the weakness of inter-area ties and on the power transferred through them. Characteristics of inter-area oscillations are analyzed in Ref. [8,9] using modal analysis of network variables such as voltage magnitude and angle; these are quantities that can be measured directly by PMUs. The study gives a deeper understanding of how inter-area oscillations propagate in the power system network and proposes an alternative for system oscillatory mode analysis and mode tracing by focusing on network variables.

2.2. Damping of inter-area oscillations

Power system oscillation damping has always been a major concern for the reliable operation of power systems. To increase damping, several approaches have been proposed; the most common ones being excitation control through PSS and/or supplementary damping control of HVDC, SVCs, and other FACTS devices. In this paper, we focus on PSS excitation control using control input signals derived from PMU data.

3. WIDE-AREA MEASUREMENT AND CONTROL SYSTEM

Over the past decades, the concept of wide area measurement and control systems has been widely discussed. The concept is particularly based on data collection and control of a large interconnected power systems by means of time synchronized phasor measurements [10]. Due to economical constraints, electric utilities are being forced to optimally operate power system networks under very stringent conditions. In addition, deregulation has forced more power transfers over a limited transmission infrastructure. As a consequence, power systems are being driven closer to their capacity limits which may lead to system breakdowns. For this reason, it is necessary for power systems to have high power transfer capacity while maintaining high reliability. One of the main problems of current energy management system (EMS) is inappropriate view of system dynamics from supervisory control and data acquisition (SCADA), and uncoordinated local actions [11]. Wide-area measurement systems (WAMS) and wide-area control systems (WACS) based on synchronized phasor measurement propose a solution to these issues. Consequently, the importance of WAMS and WACS has significantly increased and more attention has been paid toward their increased development [10].

Some of the major applications of WAMS and WACS are the following: event recording [12], real-time monitoring and control [13], phasor-assisted state estimation [14], PMU-only state estimation [15], real-time congestion management [13], post-disturbance analysis [4,13], system model validation [7], and early recognition of instabilities [11].

3.1. Wide-area measurement system

The WAMS project was founded in 1995 by the U.S. Department of Energy (DOE) to encourage the development of advanced tools for wide-area measurement, control, and operation in the Western North American power system (WECC) [16]. The measurement devices used in WAMS are GPS-time synchronized PMUs which provide high sample rate voltage and current phasor measurements.

Other WAMS projects have been established in the past decade, including those in the U.S. Eastern Interconnection (EI) [17], Hydro Québec (Canada) [18], the SIMEFAS system in Mexico [19], China [20,21], Brazil [22], Italy [23], the Nordic power systems [2,24], and others. In the U.S. EI, WAMS has been successful in using PMUs for power system operations [12]. Another application is to improve the knowledge of system dynamics [25].

A review of present PMU-based wide-area monitoring systems around the world, general applications of WAMS, and the future role of WACS is presented in Ref. [10]. It is noted that the most commonly used applications of WAMS are phase angle and oscillation monitoring [17,26,2] with limited use for voltage stability monitoring [27]. Expected future WAMS applications are estimation of electromechanical mode properties (including mode shapes) [28,29], voltage stability assessment [27] and wide area protection for transient stability [30]. For practical implementation of WACS, several additional technical considerations should be made, one of this being GPS-signal loss and also end-to-end delay [31].

Present and past applications of WAMS and WACS at Hydro-Québec are discussed in Ref. [18] where recent studies have been focused on damping stability control. The WAMS implementation at Hydro-Québec shows that wide-area stabilizing PSS controllers using PMU information can improve the dynamic performance of the system [32].

3.2. Wide-area control system

WACS serves as a base for emergency control systems using measurements obtained from WAMS [33]. A recent study on WACS developed by and implemented at Bonneville power administration (BPA) is reported in Ref. [34]. This study describes a discontinuous feedback control application, an on-line demonstration, and the advantages of this approach over the conventional feedforward control used for special protection systems (SPS). The objectives of this control system are blackout prevention, power system stability improvement, and transmission capacity enhancement. WACS uses PMUs as an advanced measurement technology, fiber optic communication, and real-time control computers. Some salient features of WACS described are improvement of observability and controllability, outage control, and high reliability and flexibility.

The remaining challenges are to shift from monitoring to control (WAMS to WACS) and to fully exploit the benefits of synchrophasor measurement technology. Concepts of wide-area control for damping inter-area oscillations are discussed next.

3.3. Wide-area damping control

The objectives for control in today's large interconnected power systems are to improve dynamic performance and to enhance transfer capacity in weak tie-lines. Several studies suggest that due to the lack of observability in local measurements of certain inter-area modes, damping control using global signals may be more effective than local control [18,35,36]. One promising application of WACS using global measurements is wide-area damping control (WADC). The concept is design controllers that use wide-area measurements to improve power system oscillation damping. WADC implementations, such as control of PSSs using synchronized phasor measurements are discussed in Ref. [32,37].

A systematic procedure to design coordinated wide-area damping controllers is presented in Ref. [38,39]. Simulation results on China's Northern grid have demonstrated that the proposed design was successful at achieving its design specifications. Recently, a successful implementation of WADC on China's Southern Power Grid (CSG) was reported in Ref. [40]. Closed-loop field tests show a promising future for WADC. Design of wide-area damping controllers using a multi-objective mixed H_2/H_∞ approach based on centralized control is demonstrated in Ref. [41]. The wide-area damping controllers are employed together with PSS controllers.

Two important factors regarding WAMS, WACS, and WADC are communication, transmission, and end-to-end delays, and loss of remote control signals [32]. Because time delays bring about a phase lag which can affect the control performance and interactions among system dynamics, it must be considered in the model design process. Several studies have considered time delay in control design using different algorithms [35,39,42,43]. In WAMS, the important delay period is between the measurement and the controller input signal arrival, which is around 0.5–1.0 seconds [42]. The total time delay in the control loop in CSG's WADC is about 110 ms, of which 40 ms is from the PMU's data processing [40]. Adaptive WACS designed to include transmission delays from 0 to 1.4 seconds is studied in Ref. [44,45]. Loss of remote signals may be solved by a decentralized control structure [32].

An outlook for WADC is to implement it to improve damping of LFIO by means of adaptive control. This will allow to achieve robustness and stability over a wide range of operating conditions. Although the concept has not yet been widely implemented in real power systems, it offers a promising solution for the future of damping control.

4. IDENTIFICATION AND MONITORING OF INTER-AREA OSCILLATIONS

One of the most important applications of PMU in WAMS is monitoring of low-frequency oscillations. PMUs provide direct GPS-synchronized measurement of voltage and current phasors. However, on-line monitored data alone cannot detect oscillations. Thus, there is a need to identify them so that system operators can properly monitor (and even make appropriate control decisions) if the damping is insufficient. Consequently, accurate estimation of electromechanical modes is essential for control and operation. Recently, there has been much interests on numerical algorithms that can be employed as tools for mode estimation. Several identification methods are reviewed below.

4.1. Single-input and single-output (SISO) and multiple-input and multiple-output (MIMO) methods

Many methods for detection and characterization of inter-area oscillations have mostly made use of individual measurement signals. In Ref. [46] and its cited literature, three different analysis tools to obtain dynamic information were discussed: spectral and correlation analysis using Fourier transforms, parametric ringdown analysis using Prony, and parametric mode estimation; this method has recently become attractive with the employment of ambient data.

The disadvantage of methods using individual measurements is that, in some measurements, certain inter-area modes cannot be detected. Different measurements have different modal observability [9]. In addition, under/over estimation may occur in some cases when using Autoregressive (AR) models [47]. In Ref. [48], Prony analysis, the Steiglitz-McBride and the Eigensystem realization algorithm (ERA), using a SISO-approach were shown to identify system zeros less accurately than the system

DOI: 10.1002/etep

poles. If a PSS is designed using single input signals, it may not stabilize large power systems as shown in Ref. [35]. As a result, more attention has been paid to multiple input signals.

In Ref. [49], two identification methods using MIMO transfer functions for design of PSS and TCSC were evaluated: the output error (OE) method obtained from nonlinear optimization techniques and the auto regressive exogenous (ARX) method which uses linear regression techniques. Multi-loop PSSs using wide-area measurements from PMUs in MIMO system are investigated in Ref. [37,50]. Implementation with larger scale systems is suggested in the literature.

4.2. *Prony analysis*

Prony analysis was first introduced to power system applications in 1990 (see Ref. [46] and its cited literature). It directly estimates the frequency, damping, and approximates mode shapes from transient responses. In Ref. [51], a single signal with Prony analysis was used to identify damping and frequency of inter-area oscillations in Queensland's power system. Prony analysis with multiple signals was investigated (see Ref. [46] and its cited literature). The result is one set of estimated modes which has higher accuracy than the single signal approach. Although there have been claims of bad performance of Prony analysis under measurement noise [52], there are no supporting extensive numerical experiments to prove this claim. On the other hand, while signal noise might be a limiting factor for Prony analysis, there are extensions that allow for enhanced performance of this method (see Ref. [46] and its cited literature). It has been reported in ([48], see Discussion) that these extensions perform well under measurement noise.

4.3. *Ambient data analysis*

Under normal operating conditions, power systems are subject to random load variations. These random load variations are conceptualized as unknown input noise, which are the main source of excitation of the electromechanical dynamics. This excitation is translated to ambient noise in the measured data. Consequently, analysis of ambient data allows continuous monitoring of mode damping and frequency. The use of ambient data for near-real-time estimation of electromechanical mode as well as the employment of ambient data for automated dynamic stability assessment using three mode-meter algorithms were demonstrated (see Ref. [46] and its cited literature). Several other methods have been applied for ambient data analysis [53]. The Yule Walker (YW), Yule Walker with spectral analysis (YWS), and subspace system identification (N4SID) were compared. Currently, these algorithms have been implemented in the real time dynamic monitoring system (RTDMS).

One benefit of using ambient data is that measurements are available continuously [54]. Injection of probing signals into power systems is a recent approach for enhancing electromechanical mode identification. Output measurements are obtained when input probing signals are injected into the system. A well designed input probing signal can lead to an output containing rich information about the electromechanical modes [4]. The design of probing signals for accuracy in estimation was also investigated (see Ref. [46] and its cited literature).

Perhaps one of the most important advances in ambient data analysis is the additional possibility of estimating mode shapes [28]. It is envisioned that mode shape estimation will allow more advanced control actions in the control room (see Ref. [55] and its cited literature).

4.4. *Kalman filtering (KF)*

Kalman filtering, an optimal recursive data processing algorithm, estimates power system's state variables of interest by minimizing errors from available measurements despite presence of noise and uncertainties. The algorithm has been implemented in several power system identification such as dynamic state estimation [56], frequency estimation [57], and fault detection [58]. Adaptive KF techniques that use modal analysis and parametric AR models have been applied to on-line estimation of electromechanical modes using PMUs. Some of the benefits of KF are: to provide small prediction errors, short estimation time, and insensitive parameter tuning [59]. On the other hand, some concerns of the method are parameters settings of noise and disturbances must be carefully chosen and responses contain delay [60]. Estimation performance of KF and least squares (LS) techniques were investigated in Ref. [61,60]. KF appears to be suitable for on-line monitoring due to its fast computing time and low storage requirements.

4.5. Other subspace identification methods

The use of other subspace methods has gained much attention in recent years due to its algorithmic simplicity [62]. These methods are very powerful and are popular algorithms for MIMO systems. An overview of a popular method can be found in Ref. [63]. In addition to the ERA and N4SID, basic algorithms using subspace method are the MIMO output-error state-space model identification (MOESP), and the canonical variate algorithm (CVA). An application of the subspace algorithm to single-input multiple-output (SIMO) systems is proposed in Ref. [54] whereas [26] considers MIMO systems. In Ref. [47], real-time monitoring of inter-area oscillations in the Nordic power system using PMUs is discussed. The use of stochastic subspace identification (SSI) for determining stability limits is demonstrated in Ref. [64]. Some of the benefits of SSI are small computational time, no disturbance is required to extract information from the measured data, and capability of dealing with signals containing noise.

It has also been suggested in Ref. [54] that it is preferable for the subspace method to have a continuously excited input. Therefore, the use of the subspace method with ambient data and low-signal probing signal may offer a promising alternative for on-line identification of MIMO systems.

5. METHODS OF SMALL-SIGNAL STABILITY ANALYSIS

5.1. Linear analysis methods

5.1.1. Eigenanalysis. This method helps in identifying poorly damped or unstable modes in power systems.

Power systems are highly nonlinear; however, under normal operating conditions, it can be assumed that these systems behave linearly, thus linearization around an operating point can be applied. Eigenanalysis is a well-established approach for studying the characteristics of inter-area modes [65], (see Ref. [2] and its cited literature).

The dynamic model of an n-generator power system is given by a system of differential an algebraic equations

$$\dot{x} = f(x, u), \quad y = g(x, u)$$

where x is the state vector of dimension n, y the output vector of dimension m, and u is the input vector of dimension r. Linearizing these equations about an equilibrium yields

$$\Delta\dot{x} = A\Delta x + B\Delta u, \quad \Delta y = C\Delta x + D\Delta u$$

where A is the state matrix of size $n \times n$, B the control or input matrix of size $n \times r$, C the output matrix of size $m \times n$, and D is the feedforward matrix of size $m \times r$.

Eigenanalysis has several attractive features: each individual mode is clearly identified by the eigenvalues, and mode shapes are readily available (see Ref. [1] and its cited literature). Eigenanalysis is commonly used in multi-machine systems to investigate inter-area oscillations. In addition, the analysis also provides valuable information about sensitivities to parameter changes.

5.1.2. Time-domain signal using Prony analysis. In Ref. [46] and its cited literature, Prony, together with time-domain simulations, is used to estimate the frequency and damping of oscillatory modes. Time domain responses can be used to formulate a linear model to verify the results of linear modal analysis. This approach is effective in getting modal information from time-domain measurements or nonlinear simulations.

5.2. Nonlinear analysis methods

Large interconnected power systems exhibit highly nonlinear behavior. To get a more comprehensive understanding of power system dynamics, nonlinear analysis can be exploited.

DOI: 10.1002/etep

5.2.1. Time-domain analysis. Time-domain nonlinear simulations have been widely employed to verify control performance. Limitations of nonlinear time domain analysis are: (1) poorly damped modes may not be observable in the response, (2) critical modes may not be sufficiently excited by the injected disturbance, (3) time-consuming computations, and when more than one inter-area mode is excited (4) it is difficult to identify the sources of the oscillations.

5.2.2. Normal forms of vector fields. A well-established and conceptually simple technique that, under certain conditions, can transform a high order differential equation into a simpler form. Generally speaking, high order terms contain valuable information of the system dynamics. The normal forms approach is able to identify and capture some important characteristics of dynamic performance, which are not available in linear analysis or time domain simulations. The main advantage of this method is that it is suitable for implementation along with eigenanalysis [66].

Second order nonlinear modal interactions between low frequency modes obtained via normal forms are important to understand complex dynamic behavior. The technique in Ref. [67] is able to identify nonlinear interactions between control and inter-area modes. The concept of nonlinear participation factors and sensitivity of normal forms coefficients are described. Results on a test system indicate the importance of including nonlinearity as well as some of the drawbacks of linear analysis.

6. CONTROL INPUT SIGNALS

6.1. Input signals selection

Generator speed, terminal-bus frequency, and active power are the most commonly used control input signals. The most common input signal for local control is generator speed deviations ($\Delta\omega$) [1] although, when selecting this signal, torsional oscillations need to be considered [68]. Angle differences between buses are used as input signal in Ref. [36,69]. The most common method for input signal selection is based on modal observability which indicates that modes of concern must be observable in the signals. Depending on different control design objectives, some signals are preferable to others.

Recently, wide-area or global signals obtained from PMUs have gradually gained popularity as promising alternatives to local signals. In Ref. [41] it is shown that if $\Delta\omega$ signals are used, they must be synchronized. In Ref. [38], inter-area active power is chosen as input signal due to the following reasons: active power has high observability of the inter-area modes under most operating scenarios, and it might be feasible to measure these quantities with WAMS if the main inter-area mode transfer paths are known. Using these signals, it may also be possible to maximize the inter-area power transfer.

In longitudinal power systems such as the Queensland power system [51], it is straightforward to determine where the inter-area mode power transfers will be transported. In addition, in more complex power networks such as the WECC system, there is operational knowledge of major inter-area mode power transfer corridors gained from off-line analysis of PMU data[4]. However, for most meshed power networks, it is not obvious how to determine where these power oscillations will travel.

In Ref. [8,9] a theoretical method exploiting eigenanalysis is used to determine the transmission lines involved in each swing mode. This is done by analyzing the modal observability contained in network variables such as voltage and current phasors, which are measured directly by PMUs. Thus, this method can be used to determine both the transmission corridors involved in the swing modes, and at the same time to indicate which PMU signal will have the highest inter-area content.

However, the full dynamic model of the power system must be known and in practice these models are not always readily available. An alternative approach using signal processing techniques has been proposed in Ref. [70]. This method aids in identifying proper PMU signals with high swing mode observability by performing spectral analysis of different available PMU measurements.

Although these methods provide a good insight on PMU signal modal-observability, they do not indicate which of these signals is the most adequate for closed-loop feedback control using PSSs. For control design, it is necessary to have knowledge of a measurement's observability transfer function [71]. For PSSs using PMU control input signals, this important aspect has not been addressed in the literature. However, this is a topic currently being investigated at KTH and interesting results will be available soon.

6.2. Studies comparing local and global signals

Several studies agree that global or wide-area signals are preferable to local signals. The disadvantages of local signals are lack of global observability, lack of mutual coordination, and placement flexibility [35,69,72].

Several approaches for the selection of PSS control input signals for damping of inter-area oscillations are described in Ref. [69,71]. In Ref. [69], the geometric and residue approaches using a joint controllability/observability measure [73] were applied to select wide-area signals for damping control in the Hydro-Québec system. Input signals were chosen with this methodology, and more efficient damping control was obtained when the selected input signals had the largest value of the proposed joint measure. The results show that the wide-area signal based geometric approach can yield better performance than that of the residue approach.

In controller design for WADC systems, the most effective stabilizing signals derived from the geometric approach are line power flows and currents [41]. One explanation is that when the output matrix C involves many signals of different types [8,9], the residue approach might be affected by scaling issues, whereas the geometric approach is dimensionless [32]. The use of geometric measures of controllability and observability to select signals for WADC applications is illustrated in Ref. [74].

6.3. Studies comparing single and multiple input signals

As mentioned before, it has been demonstrated in Ref. [35] that PSS control using single input signals is incapable of stabilizing unstable modes. Attention on multiple input signals is necessary for power system damping controller design.

6.4. PMU placement for dynamic observability

Conventional state estimators (SEs) use data from SCADA with a sampling rate of 1 sample per 4–10 seconds [15] which is too slow to monitor the dynamics of a network. If PMU-only SE is implemented [14,15], PMUs having a sampling rate between 30–60 samples/seconds may enhance the observability of system dynamics. Studies for obtaining dynamic observability from PMU-only state estimation are presented in Ref. [75]. A PMU-only state estimator requiring a minimum number of PMUs is illustrated in Ref. [15].

Site selection is another challenge. Due to economic and available communication infrastructure constraints, it is impractical to place PMUs at every desired location. Therefore, the number of PMU installations must be optimized for cost effectiveness. Placement algorithms should meet the following requirements: complete observability with minimum number of PMUs, and inherent bad-data detection [76]. Various algorithms for optimal PMU placement have been proposed in the past decades. For example, a dual search technique, a bisecting search approach, and a simulated annealing method are employed in Ref. [75]. In this study, the number of PMUs to be installed at system buses for the system to be observable is optimized. For a detailed report on PMU placement for different applications, the reader is referred to Ref. [77].

PMU's signal selection for optimally monitoring dynamic observability has to be further investigated.

7. PSS CONTROLLER DESIGN

Power System Stabilizers are supplementary control devices which are installed in generator excitation systems. Their main function is to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations [78]. In addition, it has become more common to use the supplementary damping control available in flexible alternating current transmission systems

DOI: 10.1002/etep

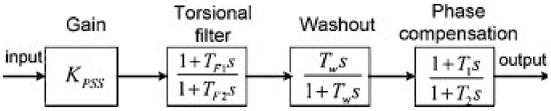

Figure 1. An example of PSS block diagram.

(FACTS). Conceptually, this supplementary damping control is similar to PSSs. Recently, Thyristor controlled series capacitors (TCSC) along with PSSs have been used to enhance the power system dynamic performance [49].

A generic PSS block diagram is shown in Figure 1. It consists of three blocks: a gain block, a washout block and a phase compensation block. An additional filter may be needed in the presence of torsional modes [79]. Depending on the availability of input signals, PSS can use single or multiple inputs. General procedures for the selection of PSS parameters are also described in Ref. [80].

Recent studies on controller design have focused on using multi-objective control [41], adaptive coordinated multi-controllers [81], and a hierarchical/decentralized approach [32,37]. A significant advantage of the decentralized hierarchical approach is that several measurements are used for feedback in the controllers. In addition, this approach is reliable and more flexible than the centralized approach because it is able to operate under certain stringent conditions such as loss of remote signal [32]. It is also important to mention that, as shown in Ref. [82], centralized controllers require much smaller gain than in the decentralized approach to achieve a similar damping effect. On the other hand, the ability to reject disturbances is lower for centralized control. Because of these tradeoff between the two design methods, an alternative is to use mixed centralized/decentralized control scheme to effectively yield both global and local damping [41].

7.1. Design methods

7.1.1. Pole placement. The goal of this method is to shift the poles of the closed loop system to desired locations. Pole placement employs multi-variable state space techniques. One disadvantage of this method is that, although it allows to consider large system models, it is not suitable for complex and multiple inter-area oscillations problems due to its complexity (see Ref. [1] and its cited literature).

7.1.2. H_∞. Employing a reduced-order system model, this method aims to minimize the H_∞ norm of the electromechanical transfer function. This is done by perturbing the transfer function input with a small disturbance and measuring the output of the closed-loop system while considering all possible stabilizing controller. The technique uses information from the frequency domain and is considerably robust. The H_∞ approach is used in several control designs for damping of large power system [65,83,84].

7.1.3. Linear matrix inequalities (LMI). Is a robust control technique. This technique can solve constrained problems by means of convex optimization and is applicable to low-order centralized and decentralized PSS design as shown in Ref. [35,82].

7.1.4. μ-Synthesis (or singular value decomposition). Is also a robust control technique. This method considers perturbations in an uncertainty matrix defined as the difference in system parameters between the nominal and the actual system models. It is employed in Ref. [85] to coordinate PSS and SVC and in Ref. [82] to design centralized control.

Although many other methods are available for PSS design [80], we have only highlighted those that in our view could be most successful for WADC applications.

In the context of input signals selection in Section 4, we have discussed about the potentials of partial multi-modal decomposition. This methodology also shows promise for control design when considering different input signals available from PMUs.

7.2. *PSS placement*

PSSs are the most cost-effective control devices for improving damping of power system oscillations [6]. In Ref. [86], a study using eigenvalue analysis for selecting the most effective locations of PSSs in multi-machine systems was conducted. Another method for determining controller locations is to use modal controllability. For example, in Ref. [87], the most suitable locations for installing PSSs were determined by an algorithm exploiting transfer function residues. In Ref. [65], the use of participation factors to determine PSS locations is proposed; however, this method needs to be supplemented by residues and frequency responses. In Ref. [38], a comprehensive controllability index is used. Here the index defines the sensitivity of a control input to the output so that the controllers can be located at the generators with larger controllability indices. Perhaps, one of the most promising methods for control design considering PMUs is the one described in Ref. [71], however, this method has not been yet used for PSS control design.

A recent method for optimal siting of PSS based on nonlinear normal forms is proposed in Ref. [88]. The technique considers the effect of nonlinear behavior and modal interaction. PSS sensitivity indices are employed to determine the optimum sites to place PSSs.

8. CONCLUSION

A review of the necessary building blocks for PMU-based control of PSSs has been presented in this paper. The importance of PMUs and their implementation in WAMS and WACS for inter-area mode monitoring and damping in large interconnected systems has been highlighted. The main characteristics of inter-area oscillations have been summarized. It has been suggested in several studies that the information obtained from PMUs is valuable for damping control, and with properly tuned controllers, global control may yield better performance than local control. The most important open question is if the current design methods can properly deal with new signals available from PMUs and how to adequately implement those signals in closed-loop feedback. PSSs should be designed to cover damping over a wide range of modes with high robustness and, in addition, the effect of time delays needs to be taken into account.

The number of PMU installations and the signals used for wide-area damping feedback control will be contingent upon the number of inter-area modes present in the system and the degree of observability for closed-loop control available in the selected control input signals. Further research is necessary to determine the specific number of PMU sitings and optimal closed-loop feedback control input signal selection.

9. LIST OF ABBREVIATIONS

AR	Autoregressive
ARX	Auto Regressive Exogenous
CVA	Canonical Variate Algorithm
EI	Eastern Interconnection
EMS	Energy Management System
ERA	Eigensystem Realization Algorithm
FACTS	Flexible Alternating Current Transmission Systems
HVDC	High-Voltage Direct Current
KF	Kalman Filtering
LFIO	Low-frequency inter-area oscillation
LS	Least Square
MIMO	Multiple-Input Multiple-Output
MOESP	MIMO Output-error State-space Model Identification
N4SID	Subspace System Identification
OE	Output Error

PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
SCADA	Supervisory Control and Data Acquisition
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SVC	Static VAR Compensator
RTDMS	Real Time Dynamic Monitoring System
SSI	Stochastic Subspace Identification
WACS	Wide-Area Control System
WADC	Wide-Area Damping Control
WAMS	Wide-Area Measurement System
WECC	Western Electricity Coordinating Council
YW	Yule Walker
YWS	Yule Walker Spectral

REFERENCES

1. Kundur. *Power System Stability and Control*, McGraw-Hill: New York, NY, USA, 1993.
2. Uhlen K, Warland L, Gjerde J, *et al*. "Monitoring amplitude, frequency and damping of power system oscillations with PMU measurements," *Proceedings of the IEEE PES General Meeting*, 2008.
3. Yuan Z, Xia T, Zhang Y, *et al*. "Inter-area oscillation analysis using wide area voltage angle measurements from FNET," *Proceedings of the IEEE PES General Meeting*, 2010.
4. Hauer J, Mittelstadt W, Martin K, Burns JW, Lee H. Integrated Dynamic Information for the Western Power System: WAMS Analysis in 2005. *Chapter 14 in Power System Stability and Control: Electric Power Engineering Handbook, ed. Leonard L. Grigsby*, pp. 14-1–14-51. CRC Press: Boca Raton, FL, 2007.
5. Phadke A, Thorp J. *Synchronized Phasor Measurements and Their Applications*, Lightning Source UK Ltd.: Milton Keynes, UK, 2008.
6. Rogers G. Demystifying power system oscillations. *IEEE on Computer Applications Power* 1996; **9**(3): 30–35.
7. Kosterev D, Taylor C, Mittelstadt W. Model validation for August 10, 1996 WSCC system outage. *IEEE Transactions on Power System* 1999; **14**(3): 967–979.
8. Vanfretti L, Chow J. "Computation and analysis of power system voltage oscillations from interarea modes," *Proceedings of the IEEE PES General Meeting*, 2009.
9. Vanfretti L, Chow J. "Analysis of power system oscillations for developing synchrophasor data applications," *accepted for 2010 IREP Symposium – Bulk Power System Dynamics and Control*, 2010.
10. C. C4.601, "Wide Area Monitoring and Control for transmission capability enhancement," Report, August 2007.
11. Zima M, Larsson M, Korba P, Rehtanz C, Andersson G. Design aspects for wide-area monitoring and control systems. *Proceedings of the IEEE* 2005; **93**(5): 980–996.
12. Galvan F, Mandal S, Thomas M. Phasor measurement units (PMU) instrumental in detecting and managing the electrical island created in the aftermath of hurricane Gustav. *IEEE/PES Power Systems Conference and Exposition* 2009; 1–4.
13. Parashar M, Mo J. "Real time dynamics monitoring system (RTDMS): Phasor applications for the control room," *Proceedings of the 42nd Hawaii International Conf. System Sciences*, 2009.
14. Phadke A, Thorp J, Karimi K. State estimation with phasor measurements. *IEEE Transactions on Power System* 1986; **1**(1): 233–238.
15. Vanfretti L, Chow J, Sarawgi S, Fardanesh B. A phasor-data-based state estimator incorporating phase bias correction. *IEEE Transactions on Power System* 2010; **PP**(99): 1–9.
16. Mittelstadt W, Krause P, Overholt P, Hauer J, Wilson R, Rizy D. "The DOE Wide Area Measurement System (WAMS) Project - Demonstration of dynamic information technology for the future power system," *Proceedings of the Fault and Disturbance Analysis/Precise Measurements in Power System Conference*, 1995, available online: http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=E82F7BCE54A65C79E2D4581640101771?purl=/204701-kOaANH/webviewable/
17. Hauer J, Bhatt N, Shah K, Kolluri S. Performance of WAMS East in providing dynamic information for the North East blackout of August 14,2003. *IEEE Power Engineering Society General Meeting* 2004; **2**: 1685–1690.
18. Kamwa I, Beland J, Trudel G, Grondin R, Lafond C, McNabb D. Wide-Area Monitoring and Control at Hydro-Québec: Past, present and future. *IEEE Power Engineering Society General Meeting* 2006.
19. Martinez E. SIMEFAS: A phasor measurement system for the security and integrity of Mexico's electric power system. *IEEE PES General Meeting – Conversion and Delivery of Electrical Energy in the 21st century* 2008.
20. Xie X, Xin Y, Xiao J, Wu J, Han Y. WAMS applications in Chinese power systems. *IEEE Power Energy* 2006; **4**(1): 54–63.

21. Yang Q, Bi T, Wu J. WAMS implementation in China and the challenges for bulk power system protection. *IEEE Power Engineering Society General Meeting* 2007; 1–4.
22. Decker I, Dotta D, Agostini M, Zimath S, Silva A. Performance of a synchronized phasor measurements system in the Brazilian power system. *IEEE/PES Power Systems Conference and Exposition June* 2006; 1–8.
23. Bruno S, De Benedictis M, La Scala M. Taking the pulse'' of power systems: Monitoring oscillations by wavelet analysis and Wide Area Measurement System. *IEEE/PES Power Systems Conference and Exposition* 2006; 436–443.
24. Leirbukt A, Gjerde J, Korba P, Uhlen K, Vormedal L, Warland L. Wide Area Monitoring experiences in Norway. *IEEE/PES Power Systems Conference and Exposition* 2006; 353–360.
25. Samuelsson O. ''Wide Area Measurements of power system dynamics: The North American WAMS Project and its applicability to the Nordic countries,'' Report, January 2000, available online: http://www.iea.lth.se/ ielolof/olof/Rpt99_50.pdf.
26. Turunen J, Larsson M, Korba P, Jyrinsalo J, Haarla L. Experiences and future plans in monitoring the inter-area power oscillation damping. *IEEE PES General Meeting – Conversion and Delivery of Electrical Energy in the 21st century* 2008; 1–8.
27. Glavic M, Van Cutsem T. Wide-Area detection of voltage instability from synchronized phasor measurements. Part I: Principle. *IEEE Transactions on Power System* 2009; **24**(3): 1408–1416.
28. Trudnowski DJ. Estimating electromechanical mode shape from synchrophasor measurements. *IEEE Transactions on Power System* 2008; **23**(3): 1188–1195.
29. Chaudhuri NR, Chaudhuri B. Damping and relative mode-shape estimation in near real-time through phasor approach. *IEEE Transactions on Power System* 2010; **PP**(99): 1.
30. Rehtanz C, Bertsch J. A new Wide Area protection system. *Proceedings of the IEEE Porto Power Technology Conference*, 2001.
31. Chenine M. ''Wide Area Monitoring and Control Systems - Application communication requirements and simulation,'' Licentiate Thesis, KTH, Royal Institute of Technology, September 2009.
32. Kamwa I, Grondin R, Hebert Y. Wide-Area Measurement based stabilizing control of large power systems - A decentralized/hierarchical approach. *IEEE Transactions on Power System* 2001; **16**(1): 136–153.
33. Wilson RE, Taylor C. Using dynamic simulations to design the wide-area stability and voltage control. *IEEE/PES Power Systems Conference and Exposition* 2004; **1**, 100–107.
34. Taylor C, Erickson D, Martin K, Wilson R, Venkatasubramanian V. WACS-Wide-Area stability and voltage control system: R&D and online demonstration. *Proceedings of the IEEE* 2005; **93**(5): 892–906.
35. Chow J, Sanchez-Gasca J, Ren H, Wang S. Power system damping controller design using multiple input signals. *IEEE Control Systems Magazine* 2000; **20**(4): 82–90.
36. Kamwa I, Heniche A, Trudel G, Dobrescu M, Grondin R, Lefebvre D. Assessing the technical value of FACTS-based wide-area damping control loops. *IEEE Power Engineering Society General Meeting* 2005.
37. Kamwa I, Gerin-Lajoie L, Trudel G. Multi-loop power system stabilizers using wide-area synchronous phasor measurements. *Proceedings of the American Control Conference* 1998; 2963–2967.
38. Xie X, Lu C. Optimization and coordination of Wide-Area damping controls for enhancing the transfer capability of interconnected power systems. *Electric Power Systems Research* 2008; **78**: 1099–1108.
39. Xie X, Xiao J, Lu C, Han Y. Wide-Area stability control for damping interarea oscillations of interconnected power systems. *Proceedings of the IEEE Generation, Transmission and Distribution* 2006; **153**(5): 507–514.
40. Peng L, Xiaochen W, Chao L, Jinghai S, Jiong H, Jingbo H, Yong Z, Aidong X. Implementation of CSG's wide-area damping control system: Overview and experience. *IEEE/PES Power Systems Conference and Exposition* 2009.
41. Zhang Y, Bose A. Design of Wide-Area damping controllers for interarea oscillations. *IEEE Transactions on Power System* 2008; **23**(3): 1136–1145.
42. Chaudhuri B, Majumder R, Pal B. Wide-Area Measurement-based stabilizing control of power system considering signal transmission delay. *IEEE Transactions on Power System* 2004; **19**(4): 1971–1979.
43. Nguyen-Duc H, Dessaint L, Okou A, Kamwa I. A power oscillation damping control scheme based on bang-bang modulation of FACTS signals. *IEEE Transactions on Power System* 2010; **25**(4): 1918–1927.
44. Chaudhuri N, Ray S, Majumder R, Chaudhuri B. A new approach to continuous latency compensation with adaptive phasor Power Oscillation Damping controller (POD). *IEEE Transactions on Power System* 2010; **25**(2): 939–946.
45. Stahlhut JW, Browne TJ, Heydt GT, Vittal V. Latency viewed as a stochastic process and its impact on wide area power system control signals. *IEEE Transactions on Power System* 2008; **23**(1): 84–91.
46. Trudnowski D, Pierre J. *Inter-area Oscillations in Power Systems: A Nonlinear and Nonstationary Perspective, ser. Power Electronics and Power Systems*, Messina A (ed). Springer: 2009.
47. Larsson M, Laila D. Monitoring of inter-area oscillations under ambient conditions using subspace identification. *IEEE PES General Meeting* 2009.
48. Sanchez-Gasca J, Chow J. Performance comparison of three identification methods for the analysis of electromechanical oscillations. *IEEE Transactions on Power System* 1999; **14**(3): 995–1002.
49. Pourramazan R, Vaez-Zadeh S, Nourzadeh H. Power system MIMO identification for coordinated design of PSS and TCSS controller. *IEEE Power Engineering Society General Meeting* 2007.
50. Kamwa I. Using MIMO system identification for modal analysis and global stabilization of large power systems. *IEEE Power Engineering Society General Meeting* 2000.

DOI: 10.1002/etep

51. Ledwich G, Palmer E. Modal estimates from normal operation of power systems. *IEEE Power Engineering Society General Meeting* 2000; 1527–1531.
52. Cai G, Yang D, Jiao Y, Shao C. Power system oscillation mode analysis and parameter determination of PSS based on stochastic subspace identification. *IEEE/PES Power and Energy Engineering Conference: Asia-Pacific* 2009.
53. Vanfretti L, Garcia-Valle R, Uhlen K, *et al*. "Estimation of Eastern Denmark's electromechanical modes from ambient phasor measurement data," *accepted for future publication in IEEE PES General Meeting*, 2010, available online: http://idisk.me.com/vanfretti/Public/publications/conference/10_LV_RV_DKModeEst_PESGM2010_v2.pdf.
54. Zhou N, Pierre J, Hauer J. Initial results in power system identification from injected probing signals using a subspace method. *IEEE Transactions on Power System* 2006; **21**(3): 1296–1302.
55. Trudnowski D, Pierre J, Zhou N, Hauer J, Parashar M. Performance of three mode-meter block-processing algorithms for automated dynamic stability assessment. *IEEE Transactions on Power System* 2008; **23**(2): 680–690.
56. Beides H, Heydt G. Dynamic state estimation of power system harmonics using kalman filter methodology. *IEEE Transactions on Power Delivery* 1991; **6**(4): 1663–1670.
57. Routray A, Pradhan A, Rao K. A novel kalman filter for frequency estimation of distorted signals in power systems. *IEEE Transactions on Instrumentation and Measurement* 2002; **51**(3): 469–479.
58. Chowdhury F, Christensen J, Aravena J. Power system fault detection and state estimation using kalman filter with hypothesis testing. *IEEE Transactions on Power Delivery* 1991; **6**(3): 1025–1030.
59. Korba P, Larsson M, Rehtanz C. Detection of oscillations in power systems using kalman filtering techniques. *Proceedings of the IEEE Control Applications Conference* 2003.
60. Zadeh R, Ghosh A, Ledwich G. Combination of kalman filter and least-error square techniques in power system. *IEEE Transactions on Power Delivery* 2010; **25**(4): 2868–2880.
61. Feilat EA. Performance estimation techniques for power system dynamic stability using least squares, kalman filtering and genetic algorithms. *Proceedings of the IEEE Southeastcon* 2000.
62. Overshee P, Moor B. *Subspace Identification for Linear Systems: Theory-Implementation-Applications*. Kluwer Academic Publishers, 1996.
63. Favoreel W, De Moor B, Overschee P. Subspace state space system identification for industrial processes. *Journal of Process Control* 2000; **10**: 149–155.
64. Ghasemi H, Canizares C, Moshref A. Oscillatory stability limit prediction using stochastic subspace identification. *IEEE Transactions on Power System* 2006; **21**(2): 736–745.
65. Rogers G. *Power System Oscillations*. Kluwer Academic Publishers Group: Norwell, Massachusetts, USA, 2000.
66. Gibbard M, Martins N, Sanchez-Gasca J, Uchida N, Vittal V, Wang L. Recent applications of linear analysis techniques. *IEEE Transactions on Power System* 2001; **16**(1): 154–162.
67. Jang G, Vittal V, Kliemann W. Effect of nonlinear modal interaction on control performance: Use of Normal Forms technique in control design Part I: General theory and procedure. *IEEE Transactions on Power System* 1998; **13**(2): 401–407.
68. Chow J, Javid S, Sanchez-Gasca J, Bowler C, Edmonds J. Torsional model identification for turbine-generators. *IEEE Transactions on Energy Conversion* 1986; **EC-1**(4): 83–91.
69. Heniche A, Kamwa I. Assessment of two methods to select wide-area signals for power system damping control. *IEEE Transactions on Power System* 2008; **23**(2): 572–581.
70. Vowles D, Gibbard M. "Illustration of an analytical method for selecting signals and locations for power system modal-estimators," *accepted for publication in IEEE PES General Meeting*, 2010.
71. Larsen E, Sanchez-Gasca J, Chow J. Concepts of design of FACTS controllers to damp power swings. *IEEE Transactions on Power System* 1995; **10**(2): 948–956.
72. Aboul-Ela M, Sallam A, McCalley J, Fouad A. Damping controller design for power system oscillations using global signals. *IEEE Transactions on Power System* 1996; **11**(2): 767–773.
73. Hamdan H, Hamdan A. On the coupling measures between modes and state variables and subsynchronous resonance. *Electric Power Systems Research* 1987; **13**: 165–171.
74. Almutairi A, Milanovic J. Optimal input and output signal selection for wide-area controllers. *IEEE Bucharest PowerTechnolgy* 2009.
75. Baldwin T, Mili L, Boisen M Jr, Adapa R. Power system observability with minimal phasor measurement placement. *IEEE Transactions on Power System* 1993; **8**(2): 707–715.
76. Phadke A, Thorp J, Nuqui R, Zhou M. Recent developments in state estimation with phasor measurements. *IEEE/PES Power Systems Conference and Exposition* 2009.
77. NASPI, "White paper on PMU measurement," NASPI, Tech. Rep., 2010, to be published at http://www.naspi.org/resources/ritt/rittresources.stm.
78. Larsen E, Swann D. Applying power system stabilizers: Parts I, II and III. *IEEE Transactions on Power Apparatus and Systems* 1981; **PAS-100**: 3017–3046.
79. Lawson R, Swann D, Wright G. Minimization of power system stabilizer torsional interaction on large steam turbine-generators. *IEEE Transactions on Power Apparatus and Systems* 1978; **PAS-97**(1): 183–190.
80. Agee J, Patterson S, Beaulieu R, *et al*. IEEE tutorial course power system stabilization via excitation control. Available online at: http://www.pes-store.org
81. Cai L, Erlich I. Simultaneous coordinated tuning of PSS and FACTS damping controllers in large power systems. *IEEE Transactions on Power System* 2005; **20**(1): 294–300.

82. Boukarim G, Wang S, Chow J, Taranto G, Martins N. A comparison of classical, robust, and decentralized control designs for multiple power system stabilizers. *IEEE Transactions on Power System* 2000; **15**(4): 1287–1292.
83. Klein M, Le L, Rogers G, Farrokhpay S, Balu N. H_∞ damping controller design in large power systems. *IEEE Transactions on Power System* 1995; **10**(1): 158–166.
84. Pal B, Chaudhuri B. *Robust Control in Power Systems*. Springer: New York, NY, USA, 2005.
85. Senjyu T, Kuninaka R, Urasaki N, Fujita H, Funabashi T. Power system stabilization based on robust centralized and decentralized controllers. *IEEE Power Engineering Conference* 2005; **2**: 905–910.
86. DeMello F, Nolan P, Laskowski T, Undrill J. Coordinated application of stabilizers in multimachine power systems. *IEEE Transactions on Power Apparatus and Systems* 1980; **PAS-99**(3): 892–901.
87. Martins N, Lima L. Determination of suitable locations for power system stabilizers and static var compensators for damping electromechanical oscillations in large scale power systems. *IEEE Transactions on Power System* 1990; **5**(4): 1455–1469.
88. Liu S, Messina A, Vittal V. A Normal Form analysis approach to siting power system stabilizers (PSSs) and assessing power system nonlinear behavior. *IEEE Transactions on Power System* 2006; **21**(4): 1755–1762.

DOI: 10.1002/etep