Inter-Area Oscillation Damping with Power System Stabilizers and Synchronized Phasor Measurements

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(ABSTRACT)

Low frequency oscillations are detrimental to the goals of maximum power transfer and optimal power system security. A contemporary solution to this problem is the addition of power system stabilizers to the automatic voltage regulators on the generators in the power system. The damping provided by this additional stabilizer provides the means to reduce the inhibiting effects of the oscillations.

This thesis is an investigation of the use of synchronized phasor measurements as input signals for power system stabilizers installed on the generators of a two-area, 4-machine test power system. A remote measurement feedback controller has been designed and placed in the test power system. Synchronized phasor measurements from optimally sited measurement units were shown to improve the damping of low-frequency inter-area oscillations present in the test system when the proposed controller was included in the generator feedback control loop. The benefit of the damping of these oscillations was evident through the ability to increase the tie-line power flowing in the test system once the proposed control scheme was implemented. Time-domain simulations were used to verify the robustness of the proposed control during severe events, such as a short-circuit or sudden large variations of load.

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This thesis is dedicated to the memory of Blaine F. Snyder (1947-1984)

GLOSSARY

AVR Automatic Voltage Regulator - the excitation control of a generator used to control the voltage.

FACTS Flexible Alternating-Current Transmission System - an alternating current transmission system made more “flexible” by the installation of a device such as a shunt or series capacitor bank. This term often indicates the use of a FACTS *controller*.

LFO Low Frequency Oscillation - a control, inter-area, local or torsional oscillation having a frequency between 0.1 and 3.0 Hz. This oscillation is often related to the small-signal stability (linear response) of the power system, but can also be related to the transient stability (nonlinear response).

PMU Phasor Measurement Unit - a device that measures voltage and current phasors (and frequency), and is capable of time-tagging these measurements for use in real-time control applications.

PSS Power System Stabilizer - a control device placed on a generator and used in conjunction with an AVR to provide additional control of oscillations.

SPM Synchronized Phasor Measurements - the synchronized measurements of voltage and/or current phasors provided by a device such as a PMU.

1

INTRODUCTION

1.1 Problem Statement

Some of the earliest power system stability problems included spontaneous power system oscillations at low frequencies. These low frequency oscillations (LFOs) are related to the small-signal stability of a power system and are detrimental to the goals of maximum power transfer and power system security. Once the solution of using damper windings on the generator rotors and turbines to control these oscillations was found to be satisfactory, the stability problem was thereby disregarded for some time. However, as power systems began to be operated closer to their stability limits, the weakness of a synchronizing torque among the generators was recognized as a major cause of system instability. Automatic voltage regulators (AVRs) helped to improve the steady-state stability of the power systems, but transient stability became a concern for the power system operators. With the creation of large, interconnected power systems, another concern was the transfer of large amounts of power across extremely long transmission lines. The addition of a supplementary controller into the control loop, such as the introduction of power system stabilizers (PSSs) to the AVRs on the generators, provides the means to reduce the inhibiting effects of low frequency oscillations [1].

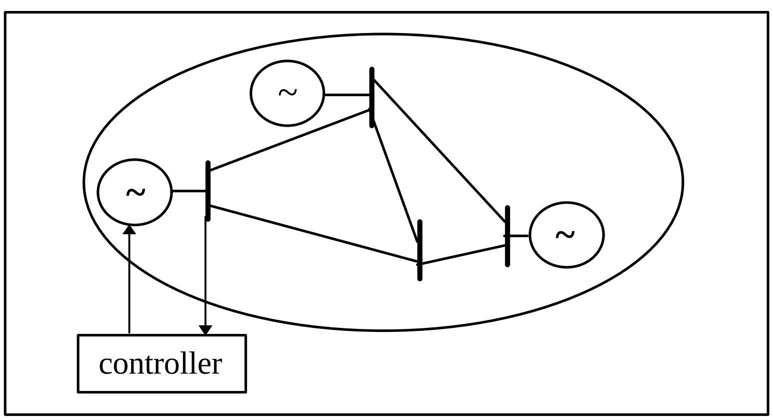

Figure 1.1: Local Feedback Controller [2]

1.1.1 Contemporary Solutions

The PSSs and AVRs are locally controlled; that is, when an instability is sensed, the controller (represented in Figure 1.1) is designed to act on measurements such as bus voltage, generator shaft speed, or rotor angle of the associated machine's controls. This type of control is useful for what will be later defined as *local* and *control* mode oscillations, but may be unsatisfactory for *inter-area* oscillations.

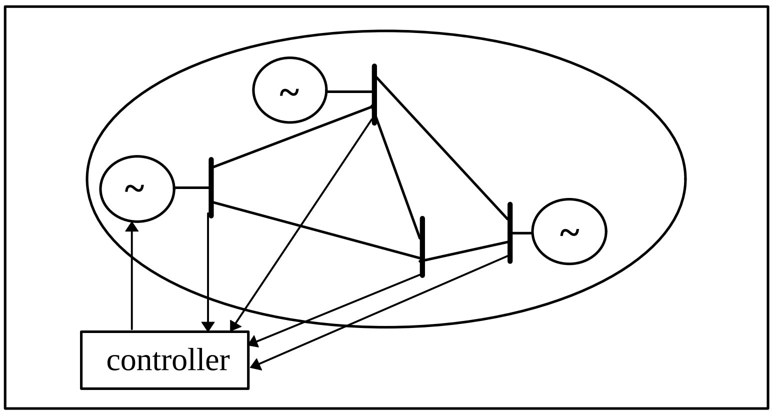

Figure 1.2: Remote Feedback Controller [2]

1.1.2 Proposed Solution

A new method illustrated in Figure 1.2, remote control variable feedback, uses synchronized measurements of voltage and current phasors (referred to as synchronized phasor measurements, or SPMs), frequency and generator rotor angle and speed. The remote-metered synchronized measurements, or SPMs as provided by phasor measurement units (PMUs) [3], are used either in conjunction with or as a replacement for the locally metered input variables for the controls of the generator-turbine sets in the power system [2].

Synchronized measurements have many foreseeable applications, including transient stability control [4,5], state estimation [6] and the control of Flexible Alternating Current Transmission System (FACTS) devices, such as a Thyristor-Controlled Series Capacitor [7]. Many electric utilities have investigated the use of synchronized measurements and SPMs since the introduction of this type of control was summarily discussed in 1981 [8]. The state-of-the-art of the remote feedback control topic has been well documented [9,10]; therefore, the details of this technology will not be discussed in this thesis.

1.2 Research Goals

The focus of this thesis is the design of a SPM-based remote feedback controller used for the damping of low frequency, inter-area oscillations in a two-area, 4-machine power system. A methodology based on eigenanalysis will be derived to place SPM-based controllers in the test system. These controllers will be shown to enhance the observability and the controllability of the inter-area oscillatory modes of interest versus the case of a PSS-based local feedback controller. It will also be demonstrated that the inter-area modes are decoupled from the local modes when the SPM-based controller is installed in the test system. Also demonstrated is the resulting tie-line power transfer gain due to the damped oscillations. Finally, time-domain simulations performed on the test system will be employed to study the nonlinear response following large disturbances.

2

LOW FREQUENCY OSCILLATIONS

2.1 Definition

Low frequency oscillations (LFOs) are generator rotor angle oscillations having a frequency between 0.1-3.0 Hz, and are defined by how they are created or where they are located in the power system. The use of high-gain generator exciters, poorly tuned generation excitation, HVDC converters or static var compensators may create LFOs with negative damping; this is a small-signal stability problem [11]. The mitigation of these oscillations is commonly performed with power system stabilizers (PSSs) [1]. LFOs include *local plant* modes, *control* modes, *torsional* modes induced by the interaction between the mechanical and electrical modes of a turbine-generator system, and *inter-area* modes, which may be caused by either high-gain exciters or heavy power transfers across weak tie-lines [1].

Of special interest here, *inter-area* oscillations are on the order of 0.1-0.7 Hz, and are characterized by groups of coherent generators swinging against each other. When present in a power system, this type of oscillation limits the amount of power transfer on the tie-lines between the regions containing the groups of coherent generators [11].

2.2 Analysis

LFOs can be created by small disturbances in the system, such as changes in the load, and are normally analyzed through the small-signal stability (linear response) of the power system. These small disturbances lead to a steady increase or decrease in generator rotor angle caused by the lack of synchronizing torque, or to rotor oscillations of an increasing amplitude due to a lack of sufficient damping torque. The most typical instability is the lack of a sufficient damping torque on the rotor's low frequency oscillations. Small-signal stability analytical tools aid in the identification and analysis of LFOs. As defined in the following chapter, the eigenvectors of the system state matrix yield indices that provide identification and classification information. Specifically, the concepts of participation factors, mode shape, observability and controllability will be defined when discussing the control of LFOs in a power system.

A related issue is the ability of the power system to recover following a large disturbance, such as a short-circuit or the loss of a generator. This type of disturbance normally induces nonlinear oscillations of the power system in addition to the small-signal LFO modes. The analysis of these oscillations is beyond the scope of this thesis, hence, time-domain simulations will be used to verify the return to stability of the test system after several transient events. It should be obvious that any control used to damp LFOs must perform satisfactorily under both small-signal and transient conditions [1,11,12,13].

2.3 Control

The control method investigated in this thesis will focus on the use of a power system stabilizer (PSS) in conjunction with the automatic voltage regulators (AVRs) of the generators in the test system to mitigate any LFOs. Damping of the LFOs contributes to the enhancement of the stability limits of the system, signifying greater power transfer through the system. The application of PSSs with local input signals for this particular control problem has been previously investigated. However, the use of the same controller to satisfy different end goals, namely the damping of local *and* inter-area modes over a broad range of operating points, has revealed itself to be difficult to achieve. Often a PSS that is expected to damp oscillations over a broad range of frequencies is not able to sufficiently damp every oscillatory mode that might be excited in the system. A full discussion of the PSS and the related design and control problems is presented in Chapter 4.

Other methods of controlling LFOs are the introduction of passive or active control elements other than PSSs into the power system. These devices include special modulation controls for HVDC-links and static var compensator (SVC) installations in the system, as well as FACTS devices such as thyristor-controlled series capacitors (TCSCs), unified power controllers (UPCs) and thyristor-controlled dynamic brakes [1,11,14]. However, the analysis of these options will not be performed in this thesis.

3

POWER SYSTEM STABILITY

3.1 Stability Definition

In order to clearly determine the goals of this research, the concept of "stability" must be defined since this term represents different concepts to different persons involved with power system stability. A definition given in [11] is as follows:

> "Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance." [11]

From this general definition, two categories of stability are derived: small-signal and transient stability. *Small-signal stability* is the ability of the system to return to a normal operating state following a small disturbance. Investigations involving this stability concept usually involve the analysis of the linearized state space equations that define the power system dynamics. *Transient stability* is the ability of the system to return to a normal operating state following a severe disturbance, such as a single or multi-phase short-circuit or a generator loss. Under these conditions, the linearized power system model does not usually apply and the nonlinear equations must be used directly for the analysis. A third term, dynamic stability, has been used to describe a separate class of stability. However, this term has represented different concepts for different authors, and there has also been a difference between groups of analysts in North America and Europe. For these reasons, several international engineering organizations have recommended that this term not be considered when discussing the stability problem [15,16].

In this thesis, the small-signal and transient stability of a two-area, 4-machine test system will be investigated with regard to the LFO problem. The test system topology, data and state equations are given in Chapter Five.

3.2 State Space Representation

Since the problem of LFOs can be analyzed from a small-signal stability standpoint, the power system is described by a set of state equations that are linearized. For this particular study, a search is performed for unstable or poorly-damped *inter-area* modes of oscillation. A PSS controller is constructed to stabilize and damp these modes together with any local rotor-angle oscillatory modes. However, torsional modes will not be accounted for in the analysis. To this end, a model that is representative of the entire power system, yet which allows the identification of the modes of interest, must be employed. Specifically, the generator and excitation system state equations are linearized and their time derivatives are put into matrix form.

3.2.1 State Space Model

The state space model presented here follows the definitions established in [11], [12] and [13]. The notation is borrowed from [11]. To model the behavior of dynamic systems, quite often a set of *n* first order nonlinear ordinary differential equations are used. This set commonly has the form

$$\dot{x}_i = f_i\left(x_1, x_2, \ldots, x_n;\quad u_1, u_2, \ldots u_r;\quad t\right) \qquad i = 1,2,\ldots,n \qquad (3.1)$$

where *n* is the order of the system and *r* is the number of inputs. If the derivatives of the state variables are not explicit functions of time, (3.1) may then be reduced to:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \qquad (3.2)$$

where *n* is the order of the system, *r* is the number of inputs and **x**, **u** and **f** denote column vectors of the form

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \qquad \mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_r \end{bmatrix} \qquad \mathbf{f} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

The state vector **x** contains the state variables of the power system, the vector **u** contains the system inputs and $\dot{\mathbf{x}}$ encompasses the derivatives of the state variables with respect to time. The equation relating the outputs to the inputs and state variables can be written as

$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u}) \qquad (3.3)$$

The state concept may be illustrated by expressing the swing equation of a generator in per-unit torque as follows:

$$\frac{2\mathrm{H}}{\omega_o}\frac{d^2\delta}{dt^2} = \mathrm{Tm} - \mathrm{Te} - \mathrm{K_D}\Delta\omega_r \qquad (3.4)$$

where H is the inertia constant at the synchronous speed ω_o (ω_o in electrical radians/second), *t* is time in seconds, δ is the rotor angle in electrical radians, Tm and Te are the per-unit mechanical and electrical torque, respectively, K_D is the damping coefficient on the rotor and $\Delta\omega_r$ is the per-unit speed deviation. Now, expressing (3.4) as two first-order differential equations yields

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}\left(Tm - Te - K_D\Delta\omega_r\right) \qquad (3.5)$$

$$\frac{d\delta}{dt} = \omega_o\Delta\omega_r \qquad (3.6)$$

If the classical generator model is used and assumed to be connected to an infinite bus through a reactance X_T, the dependence of Te on δ can then be written as

$$Te = KT \cdot \sin\delta \qquad (3.7)$$

with $KT = E_{GT}E_B/X_T$, where E_{GT} is the generator terminal voltage and E_B the infinite bus voltage. It is seen that the derivatives of the state variables $\Delta\omega_r$ and δ depend on the latter along with the mechanical torque output Tm. In matrix form, (3.5) and (3.6) reduce to (3.2).

3.2.2 Linearization

For the general state space system, the linearization of (3.2) and (3.3) about the operating point $\mathbf{x}_o$ and $\mathbf{u}_o$ yields the linearized state space system given by

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \qquad (3.8)$$

$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u} \qquad (3.9)$$

Here, $\Delta\mathbf{x}$ is the *n* state vector increment, $\Delta\mathbf{y}$ is the *m* output vector increment, $\Delta\mathbf{u}$ is the *r* input vector increment, **A** is the *nxn* state matrix, **B** is the *nxr* input matrix, **C** is the *mxn* output matrix and **D** is the *mxr* feed-forward matrix. Specifically, $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x_o}$, $\Delta\mathbf{y} = \mathbf{y} - \mathbf{y_o}$, and $\Delta\mathbf{u} = \mathbf{u} - \mathbf{u_o}$.

As an example, (3.5) and (3.6) are linearized about the operating point (δ_o, ω_o), yielding

$$\frac{d}{dt}\Delta\omega_r = \frac{1}{2H}\left[\Delta Tm - K_S\Delta\delta - K_D\Delta\omega_r\right] \qquad (3.10)$$

$$\frac{d}{dt}\Delta\delta = \omega_o\Delta\omega_r \qquad (3.11)$$

where K_S is the synchronizing torque coefficient.

3.3 Eigenvalues and Stability Analysis

Once the state space system for the power system is written in the general form given by (3.8) and (3.9), the stability of the system can be calculated and analyzed. The analysis performed follows traditional root-locus (or root-loci) methods such as those discussed in [11], [12] and [13]. First, the eigenvalues λ_i are calculated for the **A**-matrix, which are the non-trivial solutions of the equation

$$\mathbf{A\Phi} = \lambda\mathbf{\Phi} \qquad (3.12)$$

where $\mathbf{\Phi}$ is an *nx1* vector. Rearranging (3.12) to solve for λ yields

$$\det(\mathbf{A} - \lambda \mathbf{I}) = 0 \tag{3.13}$$

The *n* solutions of (3.13) are the *eigenvalues* ($\lambda_1, \lambda_2, \ldots, \lambda_n$) of the *nxn* matrix **A**. These eigenvalues may be real or complex, and are of the form $\sigma \pm j\omega$. If **A** is real, the complex eigenvalues always occur in conjugate pairs.

The stability of the operating point (δ_o, ω_o) may be analyzed by studying the eigenvalues. The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues appear on or to the right of this axis, the corresponding modes are said to be unstable, as is the system. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalue λ_i, given by $e^{t\lambda i}$. The latter shows that a real eigenvalue corresponds to a non-oscillatory mode. If the real eigenvalue is negative, the mode decays over time. The magnitude is related to the time of decay: the larger the magnitude, the quicker the decay. If the real eigenvalue is positive, the mode is said to have aperiodic instability.

On the other hand, the conjugate-pair complex eigenvalues ($\sigma \pm j\omega$) each correspond to an oscillatory mode. A pair with a positive σ represent an unstable oscillatory mode since these eigenvalues yield an unstable time response of the system. In contrast, a pair with a negative σ represent a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that the desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

Other information that can be determined from the eigenvalues are the oscillatory frequency and the damping factor. The damped frequency of the oscillation in Hertz is given by

$$f = \frac{\omega}{2\pi} \tag{3.14}$$

and the damping factor (or damping ratio) is given by

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{3.15}$$

3.3.1 Eigenvectors and Modal Matrices

Given any eigenvalue λ_i, the *n*-column vector $\mathbf{\Phi}_i$ which satisfies

$$\mathbf{A}\mathbf{\Phi}_i = \lambda_i \mathbf{\Phi}_i \tag{3.16}$$

is called the *right eigenvector* of **A** associated with the eigenvalue λ_i. Quite similarly, the *n*-row vector $\mathbf{\Psi}_i$ which satisfies

$$\mathbf{\Psi}_i \mathbf{A} = \lambda_i \mathbf{\Psi}_i \tag{3.17}$$

is called the *left eigenvector* associated with the eigenvalue λ_i. For convenience, it is assumed here that the eigenvectors are normalized so that

$$\mathbf{\Psi}_i \mathbf{\Phi}_i = 1 \tag{3.18}$$

To continue the eigenanalysis of the matrix **A**, the following modal matrices are introduced:

$$\mathbf{\Phi} = \begin{bmatrix} \mathbf{\Phi}_1 & \mathbf{\Phi}_2 & \cdots & \mathbf{\Phi}_n \end{bmatrix} \tag{3.19}$$

$$\mathbf{\Psi} = \begin{bmatrix} \mathbf{\Psi}_1^T & \mathbf{\Psi}_2^T & \cdots & \mathbf{\Psi}_n^T \end{bmatrix}^T \tag{3.20}$$

$\mathbf{\Lambda}$ = diagonal matrix with eigenvalues as diagonal elements (3.21)

The relationships (3.16) and (3.18) can be written in a compact form as

$$\mathbf{A\Phi} = \mathbf{\Phi\Lambda} \tag{3.22}$$

$$\mathbf{\Psi\Phi} = 1 \text{, yielding} \qquad \mathbf{\Psi} = \mathbf{\Phi}^{-1} \tag{3.23}$$

Once the oscillatory modes have been identified and the modal matrices constructed, an analysis is performed to find the specific *rotor-angle* modes. These modes provide the largest contribution to the low frequency oscillations. It will be shown in Section 3.3.2 that the rotor-angle modes can be identified by analyzing the right and left eigenvectors in conjunction with the *participation factors*. Next, the *mode shape* of the rotor-angle modes is examined to confirm whether the particular mode is of local or inter-area type. Finally, once these modes have been identified, the *observability* and *controllability* indices may be calculated to complete the analysis.

3.3.2 Participation Factors

Originally proposed in [17], a matrix called the participation matrix, denoted by **P**, provides a measure of association between the state variables and the oscillatory modes. It is defined as

$$\mathbf{P} = \begin{bmatrix} \mathbf{p}_1 & \mathbf{p}_2 & \cdots & \mathbf{p}_n \end{bmatrix} \tag{3.24A}$$

with

$$\mathbf{p_i} = \begin{bmatrix} p_{1i} \\ p_{2i} \\ \vdots \\ p_{ni} \end{bmatrix} = \begin{bmatrix} \Phi_{1i}\Psi_{i1} \\ \Phi_{2i}\Psi_{i2} \\ \vdots \\ \Phi_{ni}\Psi_{in} \end{bmatrix} \tag{3.24B}$$

The element $p_{ki} = \Phi_{ki}\Psi_{ik}$ is called the *participation factor*, and gives a measure of the participation of the *k*th state variable in the *i*th mode, and vice versa. The use of the participation factor in this thesis will be presented in the analysis of the “oscillation profile” of the power system, discussed in Section 6.1.

3.3.3 Mode Shape

It is possible to choose a new set of decoupled state variables contained in the vector **z**, which is related to the state vector Δ**x** through the transformation

$$\Delta \mathbf{x} = \mathbf{\Phi z} \qquad (3.25)$$

Once the state equations are decoupled through this transformation, the response of a particular state variable, say Δx_k, may be examined in each *i*th mode in the right eigenvector **Φ**. This response is called the *mode shape* of the particular oscillatory mode.

3.3.4 Controllability and Observability

Expressing the state equations in terms of the **z** variable defined in (3.25) and rearranging them into a convenient, decoupled form yields

$$\dot{\mathbf{z}} = \mathbf{\Lambda z} + \mathbf{B}'\Delta\mathbf{u} \qquad (3.26)$$

$$\Delta\mathbf{y} = \mathbf{C}'\mathbf{z} + \mathbf{D}\Delta\mathbf{u} \qquad (3.27)$$

with

$$\mathbf{B}' = \mathbf{\Phi}^{-1}\mathbf{B} \qquad (3.28)$$

$$\mathbf{C}' = \mathbf{C\Phi} \qquad (3.29)$$

The entries of the matrix $\mathbf{B}'$ relate the inputs to the oscillatory modes in the system. As a result, if the *i*th row is zero, the inputs have no effect on that mode and the mode is considered to be *uncontrollable*. Therefore, $\mathbf{B}'$ is called the *mode controllability matrix*.

On the other hand, the entries of the matrix $\mathbf{C}'$ relate the state variables z_i to the outputs of the system. Because of this, if the *i*th column is zero, the outputs do not contribute to that mode and the mode is considered to be *unobservable*. Hence, $\mathbf{C}'$ is called the *mode observability matrix* [11].

3.4 Limitations of Eigenanalysis

Eigenanalysis has been used in relation to the PSS control problem for some time, and the approach and techniques presented in Chapter 3 represent the state-of-the-art of this field. Only with the development of high-speed computational tools has eigenanalysis been able to be carried out in a simple manner for large systems. With the advent of computer-based measurement devices such as PMUs, real-time control may also be considered.

Related to the approach and definitions in this thesis, participation factors have been used by Ostojic [18] to develop a coupling factor for the problem of optimal placement of PSSs, while in [19], Ostojic used the right and left eigenvectors to develop a tuning method for PSSs. Yang and Feliachi [20,21] developed controllability and observability indices for PSS placement and tuning and also formed a residue matrix, combining the eigenvectors and the observability and controllability indices, for their particular method of inter-area oscillation mode stabilization. Finally, Aboul-Ela et al. [22] used a combination of participation factors and controllability/observability indices to achieve similar goals.

To extend tuning approaches to a broad operation range, most design methodologies are based on a one-machine, infinite-bus system. Approaches based on residues, such as the ones proposed in [21-23], provide stabilizer designs that work well in the neighborhood of the operating point where the multi-machine power system model has been linearized. The controller, proposed in [21], and tested on a similar 4-machine system, provided good response to the inter-area oscillation for a tie-line power flow of 400MW. The authors concluded through frequency domain analysis at two operating points that the controller should be robust over the operating range of 0-400MW. The authors also mention that observability and controllability of the inter-area mode may be increased if a centralized remote measurement control scheme, such as the one proposed in this thesis, is in service. In [22], the same approach is applied to a much larger power system. The controllability and observability indices and the residues again give the basis for the analysis of the inter-area modes and the tuning of the PSS. Here, however, the authors mention the limitations of this analysis to a region close to the design operating point. A similar approach was examined on yet another power system over a broad range of operating conditions in [23]. It was shown once again that designs based on the residue concept provide good control over the conditions analyzed, but that the use of remote signals such as rotor speed or tie-line power may improve the operation of the controllers. Finally, an advanced desensitized design approach using linear quadratic control and state variable feedback has been proposed by Bourlès et al. [26]. This method has been demonstrated to be robust for the one-machine infinite bus case and a small test power system.

Another problem which has not yet received a satisfactory solution is the interaction between local modes and inter-area modes coexisting in the power system. Often, the damping of the local modes involving the machines with the PSS installed supersedes the damping of any inter-area oscillations in the system. The reverse may also occur. Specifically, once the PSS is tuned to eliminate the inter-area modes of interest, local modes of the machines involved in the inter-area oscillation may become unstable. It is this type of interaction that has caused much of the recent problems when damping of the inter-area mode has been attempted [1,11,12,21,22].