Concepts for Power System Small Signal Stability Analysis and Feedback Control Design Considering Synchrophasor Measurements

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Abstract

In the Nordic power network, the existence of poorly damped low-frequency inter-area oscillations (LFIOs) has long affected stability constraints, and thereby, limited power transfer capacity. Adequate damping of inter-area modes is, thus, necessary to secure system operation and ensure system reliability while increasing power transfers. Power system stabilizers (PSS) is a prevalent means to enhance the damping of such modes. With the advent of phasor measurement units (PMUs), it is expected that wide-area damping control (WADC), that is, PSS control using wide-area measurements obtained from PMUs, would effectively improve damping performance in the Nordic grid, as well as other synchronous interconnected systems.

Numerous research has investigated one “branch” of the problem, that is, PSS design using various control schemes. Before addressing the issue of controller design, it is important to focus on developing proper understanding of the “root” of the problem: system-wide oscillations, their nature, behavior and consequences. This understanding must provide new insight on the use of PMUs for feedback control of LFIOs.

The aim of this thesis is, therefore, to lay important concepts necessary for the study of power system small signal stability analysis that considers the availability of synchrophasors as a solid foundation for further development and implementation of ideas and related applications. Particularly in this study, the focus is on the application addressed damping controller design and implementation.

After a literature review on the important elements for wide-area damping control (WADC), the thesis continues with classical small signal stability analysis of an equivalent Nordic model; namely, the KTH-NORDIC32 which is used as a test system throughout the thesis. The system’s inter-area oscillations are identified and a sensitivity analysis of the network variables directly measured by synchrophasors is evaluated. The concept of network modeshapes, which is used to relate the dynamical behavior of power systems to the features of inter-area modes, is elaborated.

Furthermore, this network modeshape concept is used to determine dominant inter-area oscillation paths, the passageways containing the highest content of the inter-area oscillations. The dominant inter-area paths are illustrated with the test system. The degree of persistence of dominant paths in the study system is determined through contingency studies. The properties of the dominant paths are used to construct feedback signals as input to the PSS. Finally, to exemplify the use of the dominant inter-area path concept for damping control, the constructed
feedback signals are implemented in a PSS modulating the AVR error signal of a generator on an equivalent two-area model, and compared with that of conventional speed signals.
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Winter is coming.
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Chapter 1

Introduction

1.1 Overview

Power system oscillation damping remains as one of the major concerns for secure and reliable operation of power systems. In response to a continual increase in demand, power systems are driven closer to their limits, especially those of transmission capacity. As such, enhancing the transfer capability, while keeping the system stable, is one of the main goals for system operators.

As power systems cannot operate while being unstable, countermeasures or “controls” are necessary. Designing a control system involves a number of factors such as the consideration of control objectives, control methods, types and locations of controllers, types and locations of control input signals as well as their availability. The question is how to design an “appropriate” control to serve the purpose of damping oscillations.

In the Nordic power system, there exists low-frequency inter-area oscillations having inadequate damping which have a negative impact on stability constraints and thereby limit power transmission capacity [75], [77]. Damping enhancement to meet increasing demand is, therefore, indispensable in the Nordic grid.

There have been several attempts taken to increase damping of these inter-area modes in the Nordic grid. Among them are (re)tuning and implementation of power oscillation dampers such as power system stabilizers [22] and FACTS devices [61]. Up to present, only local measurements are used with such controllers, with the exception of pilot projects in Norway and Finland where wide-area control of SVCs is being investigated [11], [76]. These
pilot project results show that control using wide-area measurements as an alternative to local measurements has a promising future [76]. It is expected that control having both types of measurements may enable the currently implemented controllers to help in improving damping. As a result, system reliability and security may increase.

1.2 Aim

With the continuous increase in electricity demand and the trend for more interconnections [66], one issue of concern is the mitigation of low-frequency inter-area oscillations (LFIO). Typically, inter-area oscillations occur in large power systems interconnected by weak transmission lines [19] that transfer heavy power flows. Usually, these oscillations are caused by incremental changes, (thus, “small-signal”) and have the critical characteristic of poor damping. When a certain type of swing occurs in such system, insufficient damping of LFIOs may lead to a limitation of power transfer capability or, worse than that, a growth in amplitude of the LFIOs which could possibly cause a system to collapse [62].

To enhance transfer capacity while preventing the system from breaking up, a common countermeasure is to install power system stabilizers (PSS), which provide additional damping to the system through generators. Successful damping, however, relies heavily on the locations and types of input signals used by the PSS, as well as the PSS locations. The challenges are to adequately utilize, both existing and potential signals, and to select “appropriate” input signal types for power oscillation damping control; i.e., signals with high robustness and observability.

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 [77], [29]. 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 [29] and is expected to play a more important role in the enhancement of power system controllability [58].

Power system stabilizers (PSSs) are the most common damping control devices in power systems. The PSSs of today usually rely on local mea-
measurements 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.

Numerous research has investigated one “branch” of the problem, that is, PSS design using various control schemes. Before addressing the issue of controller design, it is important to focus on developing a proper understanding of the “root” of the problem: system-wide oscillations, their nature, behavior and consequences. This understanding must provide new insight on the use of PMUs which allows for feedback control of LFIOs.

The purpose of this thesis is, therefore, to lay important concepts necessary for the study of power system small signal stability analysis that considers the availability of synchrophasors as a solid foundation for further development and implementation of ideas and related applications. Particularly in this study, the focus is on the application addressed damping controller design and implementation. As such, this thesis deals with the following:

- Classical small signal stability analysis whereby the modes of inter-area oscillations can be extracted, evaluated, and made use of.

- A sensitivity analysis that considers the signals directly measured by synchrophasors. Here, the relationship between the network variables and the state variables are analyzed.

- Network modeshapes from variables measured directly by PMUs, which links the two analyses to be used as a means to relate the dynamical behavior of power systems to the features of inter-area modes.

- The use of these PMU-based small-signal analysis concepts to determine dynamic features of large-scale power systems; namely, the existence and persistence of dominant interaction paths.

- The use of these properties of dominant paths to construct feedback signals as input to PSSs.

- The design of PSS that uses these types of signals for damping control.
1.3 Contributions

In summary, the contributions of this thesis are:

- the development of a new Nordic grid model, namely the KTH-NORDIC32 system, in Power System Analysis Toolbox (PSAT),
- a detailed small-signal analysis of the KTH-NORDIC32 system and the identification of inter-area modes,
- a literature review focusing on providing fundamental building blocks for wide-area damping control,
- analyses of network modeshapes from variables measured directly by PMUs,
- the definition of the “dominant inter-area oscillation paths” concept, its features and applications,
- the implementation of PSS control using the network modeshape and dominant paths concepts, and comparing the results with those using the conventional methods and signals,
- the assessment of system performance features using different types of feedback input signals both conventional and those from PMUs, and,
- an analysis revealing that closed loop observability, and therefore damping capabilities, of a given measurement or combination of measurements will depend on the distance of the zeros close to the inter-area modes of the open-loop transfer function which includes the individual or combined signals used for damping control.

Publications

The publications covered in this thesis are as follows.

1.4. OUTLINE


1.4 Outline

The remainder of this thesis is organized as follows.

• Chapter 2 provides a literature review on wide-area damping control which has been presented in six necessary “building blocks”.

• Chapter 3 analyzes the small-signal stability of the test system used in this thesis, the KTH-NORDIC32 system. The system’s critical modes (inter-area modes) are identified while its dynamic behavior is evaluated by eigenanalysis.

• Chapter 4 defines an important concept in this study: dominant inter-area oscillation paths. The main features of the paths are described and the dominant paths of the test system are illustrated.

• Chapter 5 verifies the concept in Chapter 4 by implementing contingency studies on the study system. A set of feasible input signals are proposed.

• Chapter 6 uses the proposed signals with damping controllers: power system stabilizers (PSS) on a conceptualized two-area network. System performance using different types of feedback input signals is analyzed.
• Chapter 7 ends the thesis with conclusions of the study and prospective work to be carried out in the future.
Chapter 2

WADC Building Blocks: A Literature Review

A comprehensive overview for each of the distinct elements, or “building blocks”, necessary for wide-area power system damping using synchrophasors and PSSs is presented in this chapter.

2.1 Fundamental Understanding of Inter-Area Oscillations

Understanding the nature and characteristics of inter-area oscillations is the key to unravel the problems associated with small-signal stability. Defined in many credited sources, inter-area oscillations refer to the dynamics 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 from 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 [62].

Incidents of inter-area oscillations have been reported for many decades. One of the most prominent cases is the WECC breakup in 1996 [38].
properties of LFIO in large interconnected systems depend on the power network configuration, types of generator excitation systems and their locations, and load characteristics [40]. 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 [79], [80] using modal analysis of network variables such as voltage and current magnitude and angles; 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 Wide-Area Measurement and Control Systems

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 [7]. Due to economical constraints, electric power 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 [91]. Wide-Area Measurement Systems (WAMS) and Wide-Area Control Systems (WACS) using 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 towards their further development [7].

Some of the major applications of WAMS and WACS are the following: event recording [26], real-time monitoring and control [56], phasor-assisted state estimation [59], PMU-only state estimation [81], real-time congestion management [56], post-disturbance analysis [29], [56], system model validation [38] and early recognition of instabilities [91].
Wide-Area Damping Control

The objectives for damping control in today’s large interconnected power systems are to improve dynamic performance and to enhance transfer capacity in capacity constrained power transfer corridors. Several studies suggest that due to the lack of observability in local measurements of certain inter-area modes, damping control using wide-area measurements may be more effective than classical control that uses local measurements only [18], [31], [34]. One promising application of WACS that uses wide-area measurements is wide-area damping control (WADC). The concept is to design and implement 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 [33], [32].

Two important factors to take into account for WACS and WADC are data delivery (communication, transmission, and end-to-end delays), and loss of wide-area feedback signals [33]. Several studies have considered time delay in control design using different algorithms [18], [87], [10], [53]. In Statnett’s WADC for wide-area power oscillation damper (WAPOD), the end-to-end latency could be from zero and occasionally up to 200-300 ms [76]. 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 [57]. Adaptive WACS designed to include transmission delays from 0 to 1.4 s is studied in [12], [69]. Loss of remote signals may be solved by a decentralized control structure [33]. As the experience from Statnett indicates, a WACS system for damping LFIOs may be designed to have switch-over mechanisms which allow continuous control by changing between local and wide-area signals in the case of too long delays or signal losses. It seems that a more relevant issue beyond delay considerations on control design is the adaptive selection of control input signals, and controller parameters in situations where a controller is changed between local or wide-area signals [76].

An outlook for WADC is to implement it to improve damping of LFIO by means of adaptively selecting proper feedback signals and controller designs. 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 future designs of damping control.
CHAPTER 2. WADC BUILDING BLOCKS: 
A LITERATURE REVIEW

2.3 Signal Processing and Mode Identification

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.

Mode property estimation allows to have better understanding of the small-signal dynamics of real power systems. Before WADC is implemented, studies on the small-signal dynamics of the network and signals in which the controllers are going to be installed need to be carried out.

Single-Input and Single-Output (SISO) and Multiple-Input and Multiple-Output (MIMO) Mode Estimation Methods

Many methods for detection and characterization of inter-area oscillations have mostly made use of individual measurement signals. In [71], 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 measured quantities, certain inter-area modes cannot be detected. Different measurements have different modal observability [80]. In addition, under/over estimation may occur in some cases when using Autoregressive (AR) models [43]. In [65], Prony analysis, the Steiglitz-McBride and the Eigen-system realization algorithm (ERA), using a SISO-approach were shown to identify system zeros less accurately than the system poles. If a PSS is designed using single input signals, it may not stabilize large power systems as shown in [18]. As a result, more attention has been paid to multiple input signals. Several identification methods are reviewed next.
2.3. SIGNAL PROCESSING AND MODE IDENTIFICATION

2.3.1 Prony Analysis

Prony analysis was first introduced to power system applications in 1990 [71]. It directly estimates the frequency, damping and approximates mode shapes from transient responses. In [45], 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 in [71]. 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 [8], 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 [71]. It has been reported in ([65], see Discussion) that these extensions perform well under measurement noise.

2.3.2 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 [71]. Several other methods have been applied for ambient data analysis [82]. 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 [90]. 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 [29]. The design of probing signals for accuracy in estimation was also investigated [71].
Perhaps one of the most important advances in ambient data analysis is the additional possibility of estimating mode shapes [72]. It is envisioned that mode shape estimation will allow more advanced control actions to become possible [73].

2.3.3 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 [5], frequency estimation [64], and fault detection [20]. 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 [37]. On the other hand, some concerns of the method are parameters settings of noise and disturbances must be carefully chosen and responses contain delay [88]. Estimation performance of KF and Least Squares (LS) techniques were investigated in [24], [88]. KF appears to be suitable for on-line monitoring due to its fast computing time and low storage requirements.

2.3.4 Other Subspace Identification methods

The use of other subspace methods has gained much attention in recent years due to its algorithmic simplicity [54]. These methods are very powerful and are popular algorithms for MIMO systems. An overview of a popular method can be found in [23]. 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 [90] whereas [74] considers MIMO systems. In [43], 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 [27]. 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 [90] 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.

2.4 Methods for Small-Signal Analysis

2.4.1 Linear Analysis Methods: Eigenanalysis

Eigenanalysis helps in identifying poorly damped or unstable modes in power system dynamic models. 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 [63],[77]. The approach has several attractive features: each individual mode is clearly identified by the eigenvalues, and mode shapes are readily available [40]. Eigenanalysis is commonly used to investigate the properties of inter-area oscillations in multi-machine power system models. In addition, the analysis also provides valuable information about sensitivities to parameter changes. More details of the analysis and its implementation will be discussed in the following chapter.

2.5 Feedback Control Input Signal

In the case of generator stabilizing controls, i.e., PSSs, the most common signals used for damping control are local measurements, such as generator speed, terminal-bus frequency, and active power. The most common method for input signal selection uses 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 signals obtained from PMUs have gradually gained popularity as promising alternatives to local signals. In [89] it is shown that if $\Delta \omega$ signals are used, they must be synchronized. Note that, the current state-of-art in the IEEE C37.118-2011 standard [68] shows that speed measurements are not available at most PMUs, and assuming they are omnipresent in WAMS is a design failure. In [86], 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. Angle differences between buses are used as input signal in [30, 34, 76]. However, as shown in [76], power flow measurements are more sensitive to local switching which is undesirable. As such, angle differences are the preferable candidate input signals.

In longitudinal power systems such as the Queensland power system [45], 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 [29]. However, for most meshed power networks, it is not obvious how to determine where these power oscillations will travel.

In [79], [80] 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. This is discussed in detail in Chapter 4.

2.5.1 Local vs. Wide-Area Signals

Several studies agree that wide-area signals are preferable to local signals. The disadvantages of local signals are lack of wide-area observability, lack of mutual coordination, and placement flexibility [18], [30], [1].

In controller design for WADC systems, the stabilizing signals derived from the geometric approach are line power flows and currents [89]. One explanation is that when the output matrix $C^1$ involves many signals of different types [79], [80], the residue approach might be affected by scaling issues, whereas the geometric approach is dimensionless [33]. The use of geometric measures of controllability and observability to select signals for WADC applications is illustrated in [3].

\[ \dot{x} = Ax + Bu, \quad y = Cx + Du. \]

\(^1\) from the linearized power system model: $\dot{x} = Ax + Bu, y = Cx + Du$. 
This thesis discusses more about the practical approaches for selecting signals and constructing feedback control inputs.

2.5.2 PMU Placement for Dynamic Observability

Conventional state estimators (SEs) use data from SCADA with a sampling rate of 1 sample per 4-10 seconds [81] which is too slow to monitor the dynamics of a network. If PMU-only SE is implemented [59], [81], PMUs having a sampling rate between 30-60 samples/s may enhance the observability of system dynamics. Studies for obtaining dynamic observability from PMU-only state estimation are presented in [4]. A PMU-only state estimator requiring a minimum number of PMUs is illustrated in [81].

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 [60]. 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 [4]. Guidelines for the placement of PMUs in practical power systems have been developed by the North American Synchrophasor Initiative [16].

2.6 PSS Controller Design

Power System Stabilizers are supplementary control devices which are installed at generator excitation systems. Their main function is to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations [41].

A generic PSS block diagram is shown in Figure 2.1. 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 [44]. 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 [2].

Recent studies on controller design have focused on using multi-objective control [89], adaptive coordinated multi-controllers [9], and a hierarchical/
decentralized approach [33], [32]. 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 wide-area signal [33]. It is also important to mention that, as shown in [6], 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 wide-area and local damping [89]. PSS designers may choose different algorithms or different approaches depending on the objectives of the designs. Four commonly used concepts of PSS designs are described below.

2.6.1 Design Methods

Pole Placement

The goal of this method is to shift the poles of the closed loop system to desired locations. Pole placement employs a multi-variable state-space technique. 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 [40]. Furthermore, the pole placement method may lead to too high value of gain $K$ which results in unsatisfactory performance [25].

$H_\infty$

Reduced-order system model aims at minimizing the $H_\infty$ 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.
2.6. PSS CONTROLLER DESIGN

The technique uses information from the frequency domain and is considerably robust. The $H_\infty$ approach is used in several control designs for damping of large power systems [63], [35], [55]. The advantage of this method over classical control designs is it being applicable to multi variable feedback systems [48].

**Linear Matrix Inequalities (LMI)**

LMI is a robust control technique which solves constrained problems by means of convex optimization and is applicable to low-order centralized and decentralized PSS design as shown in [18], [6].

**$\mu$-Synthesis (or singular value decomposition)**

$\mu$-synthesis, a robust control technique, 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 [67] to coordinate PSS and SVC and in [6] to design centralized control.

Although many other methods are available for PSS design [2], we have only highlighted those that in our view could be most successful for WADC applications. Perhaps, a promising method for control design is the one described in [42], however, this method has not been yet used for PSS control design considering PMUs.

2.6.2 PSS Placement

PSSs are the most cost-effective control devices for improving damping of power system oscillations [62]. In [21], 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 [49], the most suitable locations for installing PSSs were determined by an algorithm exploiting transfer function residues. In [63], the use of participation factors to determine PSS locations is proposed; however, this method needs to be supplemented by residues and frequency responses. In [86], 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.
Chapter 3

Linear Analysis of a Nordic Grid Test System

This chapter describes the dynamic modelling of the study system used in this thesis, the KTH-NORDIC32 in PSAT and results from small-signal stability analysis. The linear model of KTH-NORDIC32 is validated by nonlinear time-domain simulations.

A set of important dynamic properties of power systems are those related to small-signal (or linear) stability. Understanding dynamic responses of a power system is a vital key in assessing the system’s characteristics. Once these characteristics of the system have been well-understood, the response of the system to some disturbances may be anticipated. This allows for the design of countermeasures that would limit the negative impact of these disturbances. The small-signal dynamic behavior of power systems can be determined by eigenanalysis, which is a well-established linear-algebra analysis method [85], if a dynamic power system model is available.

The system analyzed in this study is a conceptualization of the Swedish power system and its neighbors circa 1995. It is based on a system data proposed by T. Van Cutsem [78] which is a variant of the Nordic 32 test system developed by K.Walve [70]. Because several modifications have been made to the system model, the system in this study has been renamed KTH-NORDIC32.

The KTH-NORDIC32 test system has the characteristic of having heavy power flow transfer from the northern region to the southern region, through
weak transmission ties [19]. Such kind of loosely interconnected system tends to exhibit lightly damped low frequency inter-area oscillations (LFIOs). These oscillations result from the swing of groups of machines in one area against groups of machines in the other area; hence the name 'inter-area' oscillation. Poorly damped LFIOs commonly arise from small perturbations (e.g. device switchings, non-critical line switching, etc.), although they may also emerge in the aftermath of a large disturbance. This is of relevance because the narrow damping of these modes may result in limitation of power transfer capacity and even lead to system breakups.

Power System Analysis Toolbox (PSAT©) [51], an educational open source software for power system analysis studies [50], is employed as a simulation tool in this study.

3.1 KTH-NORDIC32 System

3.1.1 System Characteristics

The KTH-NORDIC32 system is depicted in Fig. 3.1. The overall topology is longitudinal; two large regions are connected through weak transmission lines. The first region is formed by the North and the Equivalent areas located in the upper part, while the second region is formed by the Central and the South areas located in the bottom part. The system has 52 buses, 52 transmission lines, 28 transformers and 20 generators, 12 of which are hydro generators located in the North and the Equivalent areas, whereas the rest are thermal generators located in the Central and the South areas. There is more generation in the upper areas while more loads congregate in the bottom areas, resulting in a heavy power transfer from the northern area to the southern area through weak tie-lines.

3.1.2 Dynamic Modelling

Dynamic models of synchronous generators, exciters, turbines, and governors for the improved Nordic power system are implemented in PSAT. All models used are documented in the PSAT Manual. Parameter data for the machines, exciters, and turbine and governors are referred to [78, 70] and provided in Appendix A.
3.1. KTH-NORDIC32 SYSTEM

Figure 3.1: KTH-NORDIC32 Test System
CHAPTER 3. LINEAR ANALYSIS OF A NORDIC GRID TEST SYSTEM

Generator Models

Two synchronous machine models are used in the system: three-rotor windings for the salient-pole machines of hydro power plants and four-rotor windings for the round-rotor machines of thermal plants. According to Fig. 3.1, thermal generators are denoted by $G_6, G_7$ and $G_{13}$ to $G_{18}$ whereas hydro generators are denoted by $G_1$ to $G_5$, $G_8$ to $G_{12}$, $G_{19}$ and $G_{20}$. These two types of generators are described by five and six state variables, respectively: $\delta, \omega, e'_q, e''_q, e'_d$, and with an additional state $e''_d$ for the six-state-variables machines. Note that all generators have no mechanical damping and saturation effects are neglected.

Automatic Voltage Regulator and Over Excitation Limiter Models

The same model of AVR, as shown in Fig. 3.2, is used for all generators but with different parameters. The field voltage $v_f$ is subject to an anti-windup limiter. Not all the parameters are provided therefore recommended values in [21] are used.

![Figure 3.2: Exciter Model](image)

The model of over excitation limiters (OXL) used in the system is shown in Fig. 3.3. A default value of 10 s is used for the integrator time constant $T_0$, while the maximum field current was adjusted according to each field voltage value so that the machine capacity is accurately represented.

Turbine and Governor Models

Two models of turbine and governors; namely Model 1 and Model 3 are used to represent thermal generators and hydro generators, respectively. Note
3.2. SMALL-SIGNAL STABILITY ANALYSIS

Small-signal stability is defined as the ability of a power system to maintain its synchronism after being subjected to a small disturbance [39]. Small-signal stability analysis reveals important relationships among state variables of a system and gives an insight into the electromechanical dynamics of the network.

Figure 3.3: Over Excitation Limiter Model

that Model 3 is not provided in PSAT; the model was developed in [46]. Their corresponding block diagrams are depicted in Fig. 3.4 and 3.5.

Figure 3.4: Turbine Governor Model used for thermal generators: Model 1

Differential equations for the state variables of the generators, exciter models, and turbine and governor model used for thermal generators are described in [14, 52] while those of hydro turbine and governor are described in [46].

Loading Scenarios

Two loading scenarios are considered: heavy flow and moderate flow. Power generation and consumptions for each scenario are summarized in Table 3.1.

3.2 Small-Signal Stability Analysis

Small-signal stability is defined as the ability of a power system to maintain its synchronism after being subjected to a small disturbance [39]. Small-signal stability analysis reveals important relationships among state variables of a system and gives an insight into the electromechanical dynamics of the network.
Eigenanalysis, a well-established linear-algebra analysis method [85], is employed to determine the small-signal dynamic behavior of the study system. Applying the technique to the linearized model of the KTH-NORDIC32 system, small-signal stability is studied by analyzing four properties: eigenvalues, frequency of oscillation, damping ratios and eigenvectors (or mode shapes).

In eigenanalysis, the linearized model of a power system is represented in a state-space form as

$$\Delta x_P = A_P \Delta x_P + B_P \Delta u_P$$

$$\Delta y_P = C_P \Delta x_P + D_P \Delta u_P$$

(3.1)

where vectors $\Delta x_P$, $\Delta y_P$, and $\Delta u_P$ represent the state variables, the output variables, and the inputs, respectively. The eigenvalues, $\lambda_i$, are computed from the $A_P$-matrix from
3.2. SMALL-SIGNAL STABILITY ANALYSIS

\[ \text{det}(\lambda I - A_P) = 0. \]  

(3.2)

The damping ratio, \( \zeta_i \), and oscillation frequency, \( f_i \), for each mode, \( i \), are calculated from

\[
\lambda_i = \sigma_i \pm j\omega_i \\
\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \\
f_i = \frac{\omega_i}{2\pi} = \frac{\text{Imag}(\lambda_i)}{2\pi}
\]

(3.3)

Stability of a system depends on the sign of the real part of eigenvalues; if there exists any positive real part, that system is unstable. The frequency of oscillation is derived from the imaginary part of eigenvalues while the damping ratio is derived from the real part. Damping ratios indicate “how” stable a system is; the higher the (positive) value of a damping ratio, the more stable the system is for a given oscillation. For instance, a low (but positive) damping ratio implies that, although the system is stable, the system is more prone to instability than other systems having higher damping ratios. Consequently, the eigenvalues having the lowest damping ratios are of main concern in the system’s stability analysis.

Small-signal stability issues are mainly associated with insufficient generator damping. Of particular interest are those having low frequency of oscillations. These types of oscillations, namely low-frequency inter-area oscillations (LFIO), occur in large power systems interconnected by weak transmission lines [19] that transfer heavy power flows. The system of study, KTH-NORDIC32, has the characteristics of bearing heavy power flow from the northern region supplying the load in the southern region through loosely connected transmission lines. Consequently, the system exhibits lightly damped low frequency inter-area oscillations. Table 3.2 provides the two lowest damping modes, their corresponding frequencies and damping ratios, and the most associated state variables for both scenarios considering the case with and without controls (i.e. AVR and TGs).
Table 3.2: Linear analysis results of the two lowest damping modes in KTH-NORDIC32

<table>
<thead>
<tr>
<th>Loading Scenario</th>
<th>Mode</th>
<th>Eigenvalues</th>
<th>Frequency (Hz)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy, no control</td>
<td>1</td>
<td>-0.0663 ± j3.0511</td>
<td>0.4856</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.1079 ± j4.5085</td>
<td>0.7176</td>
<td>2.38</td>
</tr>
<tr>
<td>Heavy, with control</td>
<td>1</td>
<td>-0.0062 ± j3.1015</td>
<td>0.4936</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.0399 ± j4.8658</td>
<td>0.7744</td>
<td>0.8</td>
</tr>
<tr>
<td>Moderate, no control</td>
<td>1</td>
<td>-0.1036 ± j3.7543</td>
<td>0.5975</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.2288 ± j4.8881</td>
<td>0.778</td>
<td>4.68</td>
</tr>
<tr>
<td>Moderate, with control</td>
<td>1</td>
<td>-0.0827 ± j3.7798</td>
<td>0.6016</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.2024 ± j4.9182</td>
<td>0.7828</td>
<td>4.11</td>
</tr>
</tbody>
</table>

Mode Shapes

Mode shapes give the relative activity of state variables in each mode. They are obtained from the right eigenvectors, \( v_i \), in the following equation

\[
A v_i^r = \lambda_i v_i^r.
\]  

(3.4)

The larger the magnitude of the element in \( v_i^r \), the more observable of that state variable is. In this study, the state variable generator speed, \( \omega_i \), is used for analysis. The generator having the largest magnitude of mode shape has the largest activity in the mode of interest. Moreover, mode shapes also help to determine the optimum location for installing power oscillation dampers (PODs) such as power system stabilizers (PSSs). It is expected that by installing a PSS at the generator having the largest magnitude in the mode shape (at the mode of interest), a more significant damping than installing at the other generators [21] can be established.

Mode shape plots of the corresponding scenarios in Table 3.2 are illustrated in Fig. 3.6-3.7 as follows. In all cases, it can be observed that \( \omega_{18} \) is the most observable in Mode 1 whereas \( \omega_6 \) is the most observable in Mode 2 of both scenarios.
3.2. SMALL-SIGNAL STABILITY ANALYSIS

Figure 3.6: Mode shape plots: heavy scenario, with control

(a) Mode 1, no control
(b) Mode 2, no control
(c) Mode 1, with control
(d) Mode 2, with control
Figure 3.7: Mode shape plots: moderate scenario, with control
3.3 Linear Model Validation Through Nonlinear Time-Domain Simulation

Power systems are nonlinear in nature as such their behavior is difficult to analyze. To simplify analysis of electromechanical oscillations (which are the primary concern), linearization techniques can be applied to the nonlinear systems as previously shown in the small signal analysis section. To verify how well the linearized model represents the behavior of the nonlinear model under the linear-operating region where the model has been linearized, linear models can be validated by: 1) verifying the linear properties from time-domain responses due to small perturbations and/or 2) tracking the response to control input changes. As such, the following three studies are conducted on the linearized model of the KTH-NORDIC32 system. Note that in the studies below, only the heavy flow scenario with controls having Model 1 implemented as thermal turbine and governors and Model 3 as hydro turbine and governors is considered.

3.3.1 Fault Occurrence

To capture the general behavior of the KTH-NORDIC32 system, one approach is to apply a three-phase fault at a bus as a perturbation and study the dynamic response from a time-domain simulation. The fast Fourier transform (FFT) is employed to identify the prominent frequency components contained in the simulated signal. Based on the small-signal studies in the previous section, the state variables $\omega_6$ and $\omega_{18}$ are of our interests and their corresponding FFTs are depicted in Fig. 3.8a and 3.8b, respectively.

As shown in the figures, there are two primary frequency components: 0.49438 and 0.77515 Hz, as well as an inconspicuous frequency at 0.057983 Hz. The two primary frequencies belong to system electromechanical oscillations, which correspond to the two lowest damping inter-area oscillations, while the other smaller frequency is caused by turbine/governor dynamics. These results are in accordance with those of the small-signal studies (see Table 3.2) where 0.49-Hz mode is dominated by the dynamics of $G_{18}$ and 0.77-Hz mode by that of $G_6$. It is thus demonstrated here that the responses of the nonlinear time-domain simulation do capture the same dominant modes as the linear analysis does.
3.3.2 Disturbance at AVR’s Reference Voltage

To assess the effects of controllers, such as power system stabilizers (PSS), on the system behavior, a perturbation is applied at the AVR’s reference voltage ($V_{ref}$) since the PSS output modifies the AVR’s reference voltage. The perturbation here is a 2% step change in $V_{ref}$ of the AVR at $G_2$ at $t = 1$ s and is simulated for 20 s. Two parallel simulations are conducted: a time-domain simulation to investigate the nonlinear model response and a time response of the linearized system. Both responses are analyzed and compared to validate the consistency of the system model. Note that over excitation limiters are removed to avoid changes in the AVR’s reference voltage.

The comparison between nonlinear and linear simulations at generator terminal voltages $V_6$ and $V_{18}$ are depicted in Fig. 3.9a and 3.9b, respectively. As seen from the figures, the results of both methods are consistent with each other. Although not shown here, using the FFT technique, the dominant frequencies in $V_6$ and $V_{18}$ responses are approximately 0.49, 0.79 and 0.06 Hz which correspond to system oscillations and turbine/governor dynamics, respectively. Both results capture the dominant mode of concern and are coherent with each other.

3.3.3 Disturbance at Governor’s Reference Speed

To assess the effects of turbine and governors on the system behavior, a perturbation is applied at the governor’s speed reference ($\omega_{ref}$). The perturbation is a 0.05-Hz step change in $\omega_{ref}$ of $G_2$ at $t = 1$ s and is simulated
3.3. LINEAR MODEL VALIDATION THROUGH NONLINEAR TIME-DOMAIN SIMULATION

Figure 3.9: Responses after applying a perturbation at the voltage reference of $G_2$.

Figure 3.10: Mechanical Power output at $G_{18}$.

for 20 s. Similar to the previous section, a time-domain simulation is compared with a time response of the linearized system. As shown in Fig. 3.10, both linear and nonlinear responses of the mechanical power at $G_{18}$ are in accordance with each other.
Chapter 4

Dominant Inter-Area Oscillation Paths

This chapter introduces and defines the concept of “dominant inter-area oscillation paths”. The paths’ main features are explained and their relevance for identifying inter-area-mode-dominated power transfer corridors is highlighted.

Interaction Paths

The concept of “interaction paths” as the group of transmission lines, buses and controllers which the generators in a system use for exchanging energy during swings has been useful for characterizing the dynamic behaviour of the Western Electric Coordinating Council (WECC). In [28], interaction paths in the WECC have been determined by performing active power oscillation signal correlation from one important line against all other key lines in the network. This analysis showed that the interaction between two distantly located transmission lines was apparent from a coherency function, thus allowing to locate transmission corridors with relevant oscillatory content in the measured signals passing through them. The long experience in the WECC in the determination of this complex network’s most important paths has been carried out through a signal analysis approach using multiple data sets; this is a vigorous chore for such a complex and large interconnected network. For predominantly radial systems, fortunately, it is more straightforward to determine interaction paths. As an example, consider the Queensland power
system [45] where the main oscillation modes interact through radial links, one from the north to the center of the system, and a second from the south to the center of the system; here the interaction paths are obvious and predetermined by the radial nature of the transmission network and allocation of generation sources.

4.1 Assumption and Hypotheses

Building upon the aforementioned observations to bridge the gap in the understanding of the so-called “interaction paths” and their behavior, it is assumed that the propagation of inter-area oscillations in inter-connected system is deterministic [19]; i.e., the oscillation always travels in certain paths, and the main path can be determined a priori. This path is denominated as the dominant inter-area path: the passageway containing the highest content of the inter-area oscillations.

With this assumption, two hypotheses are made in this study.

1. Network signals from the dominant path are the most visible among other signals within a system, and they have the highest content of inter-area modes. These signals may be used for damping control through PSS.

2. There is a degree of persistence to the existence of the dominant path; i.e., it will be consistent under a number of different operating conditions and the signals drawn from it will still be robust and observable.

These hypotheses will be corroborated by contingency studies in the following chapters.

4.2 Theoretical Foundations

4.2.1 Mode Shape

Denoted by $W(A)$, mode shape is an element describing the distribution of oscillations among system’s state variables. In mathematical terms, it is the right eigenvector obtained from an eigenanalysis of a linearized system. The mode shapes of interest here are those that belong to electromechanical oscillations, of which the corresponding state variables are generator rotor angles ($\delta$) and speed ($\omega$). Mode shape plots give directions of the oscillations
4.2. THEORETICAL FOUNDATIONS

and, thus, are used to determine groups of generators. The derivations of electromechanical mode shapes will be briefly described here. Consider a linearized \( N \)-machine system in a state-space form

\[
\begin{align*}
\Delta \dot{x}_P &= A_P \Delta x_P + B_P \Delta u_P \\
\Delta y_P &= C_P \Delta x_P + D_P \Delta u_P,
\end{align*}
\]

(4.1)

where vectors \( \Delta x_P, \Delta y_P, \) and \( \Delta u_P \) represent the state variables, the output variables and the inputs, respectively. With no input, the electromechanical model is expressed as

\[
\begin{bmatrix}
\Delta \dot{\delta} \\
\Delta \dot{\omega}
\end{bmatrix}
= A \begin{bmatrix}
\Delta \delta \\
\Delta \omega
\end{bmatrix}
\]

(4.2)

where matrix \( A \) represent the state matrix corresponding to the state variables \( \Delta \delta \) and \( \Delta \omega \). Then, performing eigenanalysis, the electromechanical mode shape is derived from

\[
AW(A) = \lambda W(A)
\]

(4.3)

where \( \lambda \) are eigenvalues of the electromechanical modes of the system. Inter-area oscillations, as well as other modes, are determined from the eigenvalues.

4.2.2 Network Sensitivities

The sensitivities of interest are those from network variables; namely, bus voltages with respect to change in the state variables, e.g. machine’s rotor angle or speed. Since PMUs provide measurement in phasor form, the analyses in this study regard two quantities: voltage magnitude (\( V \)) and voltage angle (\( \theta \)). That is, the network sensitivities are the \( C \) matrix from (4.1) with voltage magnitude and angle as the outputs \( \Delta y \). Sensitivities of the voltage
magnitude ($C_V$) and voltage angle ($C_\theta$) are expressed as

$$\begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} = \begin{bmatrix} \frac{\partial V}{\partial \delta} & \frac{\partial V}{\partial \omega} \\ \frac{\partial \theta}{\partial \delta} & \frac{\partial \theta}{\partial \omega} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \end{bmatrix}$$

$$\Delta y = \begin{bmatrix} CV \delta & CV \omega \\ C_\theta \delta & C_\theta \omega \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \end{bmatrix}$$

$$C_V = \begin{bmatrix} CV \delta & CV \omega \end{bmatrix}$$

$$C_\theta = \begin{bmatrix} C_\theta \delta & C_\theta \omega \end{bmatrix}.$$  

(4.4)

### 4.2.3 Network Modeshape

As introduced in [80, 83], network modeshape ($S$) is the projection of the network sensitivities onto the electromechanical modeshape, which is computed from the product of network sensitivities and mode shapes. It indicates how much the content of each (inter-area) mode is distributed within the network variables. In other words, how “observable” the voltage signals on the dominant path are for each mode of oscillation. The expressions for voltage magnitude and voltage angle modeshapes ($S_V$ and $S_\theta$) are

$$S_V = C_V W(A)$$

$$S_\theta = C_\theta W(A).$$  

(4.5)

It can therefore be realized that the larger in magnitude and the lesser in variation the network modeshape is (under different operating points), the more observable and the more robust the signals measured from the dominant path become.

As previously stated, dominant inter-area oscillation paths are defined as the corridors within a system with the highest content of the inter-area oscillations. Important features of the dominant path are summarized below.

- The largest $S_V$ or the smallest $S_\theta$ element(s) indicates the center of the path. This center can be theorized as the “inter-area mode center of inertia” or the “inter-area pivot” for each of the system’s inter-area modes.

- The difference between $S_\theta$ elements of two edges of the path are the largest among any other pair within the same path. In other words,
the oscillations are the most positive at one end while being the most negative at the other end. Hence, they can be theorized as the “tails” for each inter-area mode.

- $S_V$ elements of the edges are the smallest or one of the smallest within the path.

- Inter-area contents of the voltage magnitude modeshapes are more observable in a more stressed system.

These features are illustrated with the KTH-NORDIC32 test system next.

4.3 Dominant Inter-Area Paths of the KTH-NORDIC32

The system’s dominant inter-area paths are illustrated in Fig. 4.1 where the yellow stars denote the path of Mode 1 and the green cross denote that of Mode 2. Corresponding voltage magnitude and angle modeshapes are depicted and compared between the two loading scenarios in Fig. 4.2a-4.2b. In these figures, blue dots indicate network modeshapes of the heavy flow while red dots indicate network modeshapes of the moderate flow.

Analyzing both figures, although there are significant drops in the voltage magnitude modeshapes in both paths when the loading scenario shifts from heavy to moderate, the characteristics of the dominant paths discussed above become obvious and remained preserved.
Figure 4.1: Dominant Inter-Area Paths: Mode 1 and Mode 2
4.3. DOMINANT INTER-AREA PATHS OF THE KTH-NORDIC32

Figure 4.2: Voltage magnitude and angle modes shapes.
Chapter 5

Persistence of Dominant Inter-Area Paths and Construction of Controller Input Signals

This chapter demonstrates the degree of persistence of dominant inter-area oscillation paths by carrying out a number of contingency studies. The contingency studies are limited to faults being imposed on different transmission lines selected to study the persistence of the dominant path. The path persistence is then examined from the relationship between two key factors: sensitivity analysis of the network variables (i.e. voltages and current phasors), and mode shape. The outcome is a proposed signal combination to be used as inputs to the damping controller for mitigation of inter-area oscillations in interconnected power systems.

5.1 Contingency Studies and Analysis Methodology

5.1.1 Contingency Studies

Contingencies considered in this study are loss of transmission lines, including those directly connecting to the dominant inter-area path, and are
CHAPTER 5. PERSISTENCE OF DOMINANT INTER-AREA PATHS
AND CONSTRUCTION OF CONTROLLER INPUT SIGNALS

42
denoted by far, near, and on. The classification of each event is determined
by how “close” the line to be removed is to the pre-determined dominant
path. The path persistence is then examined by using the aforementioned
concept: network modeshape. These three scenarios are as listed below.

1. Loss of a corridor FAR from the main path.
2. Loss of a corridor NEAR the main path.
3. Loss of a corridor ON the main path.

Locations for each scenario are illustrated in Fig. 5.1 where symbols “X”,
“Δ”, and “O” represent the far, near and on cases, respectively. To develop
a fundamental understanding, the detailed model in [13] is stripped from
controllers and the generators have no damping. Since the same methodology
can be applied to the dominant path of Mode 2, only the persistence of the
dominant path of Mode 1 (heavy flow scenario) is investigated.

5.1.2 Methodology
A step-by-step procedure performed in this contingency study is described
as follows.

1. Perform a power flow of the nominal, i.e. unperturbed, system to
obtain initial conditions of all network variables.
2. Perform linearization to obtain the network sensitivities ($C_V$ and $C_θ$).
3. Perform eigenanalysis to obtain mode shapes ($W(A)$) and identify the
inter-area modes and the corresponding dominant path.\(^1\)
4. Compute network modeshapes ($S_V$, $S_θ$).
5. Plot $S_V$ and $S_θ$ of the dominant inter-area path.
6. Implement a contingency by removing a line.
7. Repeat 1-5 (excluding the dominant path identification) and compare
the results with that of the original case.
8. Reconnect the faulted line and go to step 6 for subsequent contingency.

\(^1\)The deduction of dominant paths will be presented in another publication. Here, the
dominant path is known a priori.
Figure 5.1: KTH-NORDIC32 System: Dominant Inter-Area Paths: Mode 1
CHAPTER 5. PERSISTENCE OF DOMINANT INTER-AREA PATHS
AND CONSTRUCTION OF CONTROLLER INPUT SIGNALS

5.2 Simulation Results and Discussions

In Figs. 5.2 - 5.4, the y-axis of the upper and lower figures display the voltage magnitude and voltage angle modeshapes of the dominant inter-area oscillation path for each contingency, respectively. The x-axis represents the bus number in the dominant path; the distance between buses are proportional to the line impedance magnitude. For every scenario, the removal of corridors are compared to the nominal system denoted by black dots to determine the path’s persistence.

5.2.1 Loss of a corridor FAR from the dominant path

Figure 5.2 shows the three selected corridors: 23-24, 36-41, and 45-46, which are located the farthest from the dominant path as indicated by “X” in Fig. 5.1. The results show that the voltage magnitude modeshapes ($S_V$) remains consistent both in magnitude and direction, although there are small but insignificant variations. However, despite maintaining nearly the same magnitude as that of the nominal case, the voltage angle oscillations ($S_\theta$) have opposite directions when the corridors 23-24 and 45-46 are disconnected. Similar results are obtained with the removals of some other “FAR” corridors.
5.2. SIMULATION RESULTS AND DISCUSSIONS

5.2.2 Loss of a corridor NEAR the dominant path

Figure 5.3 shows the three selected corridors: 38-39, 40-43, and 44-49, which are directly connected to the dominant path as indicated by “Δ” in Fig. 5.1. It can be observed that the removal of corridor 44-49 results in a significant reduction in the voltage magnitude modeshape, particularly, that of Bus 40. This is due to the following reasons: (1) Bus 49 is connected close to $G_{18}$ (Generator No.18) in which its speed variable is the most associated state in the 0.49-Hz inter-area mode, and (2) Bus 40 is directly connected with $G_{13}$ which is a synchronous condenser.

The removal of the other corridors “NEAR” the main path has similar results to that of the removal of corridor 38-39; only small variations in both $S_V$ and $S_θ$. The change in direction of $S_θ$ (given by a sign inversion) only occurs with the disconnection of corridors 40-43 and 44-49.

5.2.3 Loss of a corridor ON the dominant path

Figure 5.4 shows the three selected corridors: 35-37, 38-40, and 48-49, which belong to the dominant path as indicated by “O” in Fig. 5.1. The removal of corridor 35-37 has a trivial effect, in terms of magnitudes, on both $S_V$ and
CHAPTER 5. PERSISTENCE OF DOMINANT INTER-AREA PATHS
AND CONSTRUCTION OF CONTROLLER INPUT SIGNALS

Figure 5.4: Voltage magnitude and angle modeshapes: Loss of a corridor ON the dominant path.

$S_{V}$. On the contrary, the removal of corridors 38-40 or 48-49 has detrimental effects on $S_{V}$ and/or $S_{\theta}$. Particularly, that of the latter, the $S_{\theta}$ elements are close to zero in most of the dominant transfer path buses (except Bus 49 and Bus 50), although $S_{V}$ elements are still visible. In addition, although not shown here, the removal of corridor 37-38 results in non-convergent power flow solution while the removal of corridor 49-50 results in the disappearance of the “known” inter-area mode.

5.2.4 Discussions

The contingency studies above allow to recognize the following attributes of dominant paths:

- In most of the contingencies, the dominant path is persistent; the network modeshapes of voltage magnitude and angles maintain their visibility and strength (amplitude) as compared with the nominal scenario.

- In nearly all of the contingencies, despite small variations in the voltage magnitude modeshapes, the voltage angle modeshapes maintain their strength. However, the signs are in opposite direction in some of the cases.
5.3. CONSTRUCTING CONTROLLER INPUT SIGNALS

Based on the results in the previous section, suitable network variables from the dominant path to construct PSSs input feedback signals are proposed here. Block diagram representations of how the signals could be implemented in practice are illustrated in Fig. 5.5. Latencies, e.g. communication and process delays, are omnipresent and play a role in damping control design. Nevertheless, in order to build a fundamental understanding they are neglected in this study, but will be considered in a future study.

To justify signal selection, a small disturbance is applied at linearized test system and the time responses of the selected outputs are simulated and analyzed. The perturbation is a variation of 0.01 p.u. in mechanical power ($\Delta P_M$) at selected generators and applied at $t = 1$ s, and the system response is simulated for a period of 20 s. The signals considered here are:

This sign change can be explained by a reversal in the direction of their corresponding mode shapes.

- In some contingencies such as the removal of corridor 49-50, the system topology is severely changed and the mode of interest disappears. The dominant path loses its persistence, and, due to the topological change, it ceases to exist giving rise to a different dominant path with different mode properties (frequency and damping). This indicates that $G_{18}$ is the origin of the 0.49 Hz mode. Thus, it can be inferred that corridor 49-50 is one of the most critical corridors for this inter-area mode distribution.

5.3 Constructing Controller Input Signals

(a) Voltage magnitudes. (b) Voltage angles.

Figure 5.5: Block diagrams for the feedback signals.
• Voltage magnitude deviation: $V_{23}, V_{37}, V_{38}, V_{48}, V_{50}, \text{ and } V_{37} + V_{48}$
• Voltage angle difference: $\Delta \theta_{37,23}, \Delta \theta_{37,38}, \Delta \theta_{37,48}, \text{ and } \Delta \theta_{37,50}$.

Bus 23 represents a non-dominant-path bus whereas the rest belong to the dominant path. The deviation in the voltage magnitude is the difference between the steady state and the simulated response, while that of the voltage angle is the variation among the simulated output signals, bus voltage angle $\theta_{37}$ is used as a reference. The set $V_{37} + V_{48}$ is used as an example of a signal combination of voltage magnitudes, while all the angle differences are inherently signal combinations.

To implement the network modeshape concept, the multi-modal decomposition framework [84] is employed. It is an approach used to assess a complex multi-machine system with multiple swing modes. Mode shapes of the synchronizing coefficient matrix $A_{21}$ (see (4.2)) are incorporated with the linearized state-space model, thereby reconstructing the system. In this study, a partial multi-modal decomposition [42] concept is used to evaluate one mode at a time, namely, the inter-area oscillation modes. With this approach, the network modeshape, a product of mode shapes and sensitivities, is used as a filter allowing only the mode of interest to be evaluated.

Partial Multi-Modal Decomposition

The mathematical representations of the partial multi-modal decomposition are described in the following. From (4.2), $M$, the mode shapes of the matrix $A_{21}$, are obtained from the relationship $A_{21} \lambda_{21} = \lambda_{21} M, M^{-1} A_{21} M = \Lambda$ where $\Lambda$ is a matrix containing normalized modal synchronizing coefficients on the diagonal. Then, the system (4.1) is transformed into

$$\begin{align*}
\Delta \dot{x}_m &= A_m \Delta x_m + B_m \Delta u \\
\Delta y &= C_m \Delta x_m + D \Delta u
\end{align*}$$

where

$$\Delta x_m = T^{-1} \Delta x, \quad T = \begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix}$$

$$A_m = T^{-1} A T, B_m = T^{-1} B, \quad \text{and, } C_m = C T.$$ 

The mode of concern ($\lambda_i$), which is chosen from the eigenvalues of $A_{21}$, corresponds to the lowest damping frequency of oscillation: 0.49-Hz mode.
5.3. CONSTRUCTING CONTROLLER INPUT SIGNALS

Finally, the system with a single mode \( i_{th} \) to be evaluated can be expressed as

\[
\begin{bmatrix}
\Delta \delta_{mi} \\
\Delta \omega_{mi}
\end{bmatrix} = \begin{bmatrix}
a_{i11} & a_{i12} \\
a_{i21} & a_{i22}
\end{bmatrix} \begin{bmatrix}
\Delta \delta_{mi} \\
\Delta \omega_{mi}
\end{bmatrix} + \begin{bmatrix}
0 \\
b_{i2}
\end{bmatrix} u
\]

\( y = \begin{bmatrix}
c_{i1} & c_{i2}
\end{bmatrix} \begin{bmatrix}
\Delta \delta_{mi} \\
\Delta \omega_{mi}
\end{bmatrix} + Du. \tag{5.3} \]

The perturbed generators are \( G_{18} \) and \( G_6 \). The time responses of the perturbed KTH-NORDIC32 linear system are shown in Fig. 5.6 - 5.9. The first two figures, Fig. 5.6 and 5.7, illustrate the responses of the voltage magnitude deviation after the disturbance at \( G_{18} \) and \( G_6 \), respectively, while the last two, Fig. 5.8 and 5.9, the voltage angle differences. Figures (a) and (b) in each figure refer to the responses before and after filtering through network modeshapes, respectively. Note that we select the 0.49-Hz mode for this analysis.

![Figure 5.6: Voltage magnitude responses after a perturbation at \( G_{18} \).](image)

According to Fig. 5.6 and 5.7, the most observable signal is the signal combination \( V_{37} + V_{48} \), descendingly followed by \( V_{38}, V_{37}, V_{23}, V_{48}, \) and \( V_{50} \) with the least observability except for Fig. 5.7a where \( V_{23} \) is the least visible. Overall, the magnitude of the signals are in accordance with the network modeshape of the nominal system as previously shown in Fig. 5.2 - 5.4. In other words, the voltage magnitude modeshapes indicate that the
Chapter 5. Persistence of Dominant Inter-Area Paths and Construction of Controller Input Signals

The strongest signal is located at Bus 38, followed by Bus 37, Bus 48, and Bus 50, respectively.

Comparing the responses before and after filtering through network modes, more than one mode exist in the former while only one mode (0.49 Hz) is present in the latter. Observing Fig. 5.6a and 5.7a, the mode appear-

Figure 5.7: Voltage magnitude responses after a perturbation at $G_6$.

Figure 5.8: Voltage angle difference responses after a perturbation at $G_{18}$.
5.3. **CONSTRUCTING CONTROLLER INPUT SIGNALS**

Figure 5.9: Voltage angle difference responses after a perturbation at $G_6$.

The disturbance at $G_{18}$ mostly excites one mode whereas that of $G_6$ considerably affects the other mode resulting in signal distortion. On the other hand, the responses in Fig. 5.6b and 5.7b are proportionally scaled; the un-concerned modes are removed, leaving only the mode of interest. Because of this network modeshape filter, not only is it possible to distinguish one mode from the rest, but also able to signify the distribution of the mode content among the signals.

For the voltage angle difference responses in Fig. 5.8 - 5.9, the largest element corresponds to $\Delta \theta_{37,50}$, descendingly followed by $\Delta \theta_{37,48}$, $\Delta \theta_{37,38}$, and $\Delta \theta_{37,23}$ with the smallest amplitude. This is in agreement with the voltage angle modeshape of the nominal system (Fig. 5.2 - 5.4) whereby the angle differences of the two edges (Bus 35 and Bus 50) yield the largest magnitude. Comparing among the figures, the use of network modeshape filtering helps not only scaling the contents of the mode onto the signals (the voltage angle difference) as shown in Fig. 5.8a - 5.8b but also screening the undesirable modes out as illustrated in Fig. 5.9a - 5.9b. The network modeshape filter is, therefore, precisely extracting the specific modal contributions at each bus angle, and their combination. This is the true inter-area mode content that should be expected from the resulting signals.

It has been suggested in [36] to use bus voltage angle differences as input...
CHAPTER 5. PERSISTENCE OF DOMINANT INTER-AREA PATHS AND CONSTRUCTION OF CONTROLLER INPUT SIGNALS

signals for damping purposes. However, this is only valid when the smaller angle is lower enough; in other words, the difference should be sufficiently large to be observable which is the case with the buses on the dominant path. When a signal from a non-dominant path is used, such as in the case with $\Delta \theta_{37,23}$, amplitude of the response is much smaller than that of other signals from the dominant path. Hence, a proper choice of the bus angles used for this angle difference should consider the underlying inter-area mode distribution reflected on the network modeshapes. Otherwise, it is likely that the feedback signal will have a poor inter-area mode content that is not robust under different contingencies.

Although the signals $V_{38}$, $V_{23}$, and $\Delta \theta_{37,50}$ are among the most observable, they might not be practically available since it is less likely for the PMUs to be located at generator buses. The more prospective signals could be $V_{37}$, $V_{37} + V_{48}$, and/or $\Delta \theta_{37,48}$ because they are located at the high-voltage buses of the dominant path. This is consistent with the current field practice for deployment of PMUs [16]. Depending on the availability of PMU measurements, different signal combinations, which will be investigated in a future study, can be made available. Using these proposed signals as the inputs to PSS, it is further hypothesized that effective damping will be achieved. This hypothesis will be corroborated in the next chapter.
Chapter 6

Damping Control Design using PMU signals from Dominant Paths

The aim of this chapter is to carry out a fundamental study on feedback control using PMU signals from a dominant path. As such, a conceptualized two-area system is used to illustrate PSS control design for damping enhancement.

The concept of dominant inter-area oscillation paths, as explained in previous chapters, has important implications for damping control design. This will be illustrated for a PSS control design to damp an inter-area mode in a conceptualized two-area system shown in Fig. 6.1. Here, $G_1$ and $G_2$ represent the main clusters of machines involved in the inter-area swing and the elements interconnecting them which are involved in the dominant inter-area path for the mode of interest.

This conceptual system is modelled as follows. Generator 1 ($G_1$) is represented by a sixth-order machine model and a static excitation system model whereas Generator 2 ($G_2$) is represented by a third-order machine model. Both generators have no mechanical damping. The power transfer from $G_1$ to $G_2$ is 1100 MW. The inter-area mode of the system is $-0.0162 \pm j2.3485$.

---

1Electrical damping is included by the use of a sixth-order generator ($G_1$), which considers damping windings.
which has a frequency and damping ratio of 0.3738 Hz and 0.6908%, respectively.

The objective of the design is to improve damping of the inter-area mode by installing a PSS at $G_1$ modulating the AVR error signal. The structure of the PSS includes lead/lag compensators in the form

$$PSS = K_d \left[ \frac{s + z}{\alpha s + p} \right]^n \frac{T_w s}{1 + T_w s}$$ (6.1)

where $n$ is the number of compensator stages and $T_w$ is the washout filter having the value of 10 s. Note that generator speed, as well as angle difference, has high component of torsional mode [40]. Therefore, a torsional filter is added to the PSS structure when generator speed and angle differences are used as feedback input signals. The torsional filter used has the form

$$G_{tor}(s) = \frac{1}{0.0027s^2 + 0.0762s + 1}$$ (6.2)

$\alpha$, poles ($p$), and zeros ($z$) can be computed from the following equations.

$$\phi_m = \frac{180^\circ - \theta_{dep}}{n}, \quad \alpha = \frac{1 + \sin(\phi_m)}{1 - \sin(\phi_m)}$$

$$p = \sqrt{\alpha \omega_c}, \quad z = p/\alpha$$ (6.3)

where $\theta_{dep}$, $\phi_m$, and $\omega_c$ represent angle of departure of the inter-area mode, angle compensation required, and the frequency of the mode in rad/sec.

Conceptualization of the dominant path

Recalling the network modeshape concept described in Chapter 4, the voltage magnitude and angle modeshapes of the only transfer path in the two-area system are computed and illustrated in Fig. 6.2. These results coincide with the dominant inter-area path features and, thus, the transfer path in the
system model is indeed a dominant inter-area oscillation path. It is then expected that using signals having high network modeshapes as feedback input signals can aid in achieving better damping improvement than the ones with lower values.

![Figure 6.2: Voltage magnitude and angle modeshapes of the dominant path in the two-area system.](image)

### 6.1 Feedback Input Signals

As mentioned in Chapter 1, one major challenge in damping control design is the selection of feedback input signals. Conventionally, PSSs use local measurements as input signals. They are active power in the outgoing transmission line, generator speed, and frequency at the terminal bus. With the availability of signals from synchrophasors, choices of inputs are not only limited to those local but now include wide-area signals. Direct measurements from PMUs are voltage and current phasors, i.e. both magnitude and phase of currents and voltages. They are prospective signals to be implemented in WADC. Generator speeds, the commonly used input signal, are not available from PMUs [68], [17]. The main issue is which signal, among all the available signals, would give satisfactory damping performance.
In this section, the impact of different feedback input signals on the damping of the two-area test system will be evaluated. Each signal requires different controller (PSS) parameters, as well as different structures. As such, two analyses are carried out to assess damping performance. The first one being controller design for maximum damping. For each input signal, PSS parameters will be tuned such that the system achieves its highest damping possible. The second analysis is controller design using fixed-structure controllers. In practice, PSS parameters and structures are fixed, therefore, corresponding system performance (using different signals) should be evaluated.

For each analysis, voltage magnitude, voltage angle, and generator speeds will be used as feedback input signals. Controller performance is evaluated considering the following factors.

• Distance from zeros close to the inter-area mode \(d_\lambda\): it is desirable for the zeros to be far from the inter-area mode [17].

• Effective gain: the cumulative gain of the PSSs which can be computed from \(\alpha^nK_d\).

• Damping ratio \((\lambda)\).

• Overshoot \((M_p)\).

• Rise time \((t_r)\).

The monitored signal is the bus voltage terminal at \(G_1, V_1\), whereby its response is evaluated by the above factors. Before going into the analyses, an example of how to design a PSS controller is illustrated here.

**Controller Design Illustration**

Signal \(V_3\), the voltage magnitude at Bus 3, is used as the feedback input signal. A root-locus plot of the open-loop system (no phase compensation) including the washout filter is shown in Fig. 6.3a. The angle of departure \((\theta_{dep})\) of the inter-area mode is \(-23.03^\circ\). Using this angle, PSS parameters are computed using equations (6.1-6.3). Adding the designed controller to the system, the root-locus plot is shown in Fig. 6.3b which shows an inverse direction of the inter-area mode; i.e., the inter-area mode is moving in a stable direction. Gain \(K_d\) is obtained when moving along the branch of the
6.1. FEEDBACK INPUT SIGNALS

root loci of the inter-area mode until the desired damping ratio, or maximum damping in this case, is reached. Finally, for the signal used, the obtained PSS has the form

$$0.00372 \left[ \frac{98 s + 0.2372}{s + 23.249} \right]^2.$$  \hspace{1cm} (6.4)

Figure 6.3: Root-locus plots of the system with $V_3$ as feedback input signal.

Responses of the terminal voltage at Bus 1 with and without PSS are compared in Fig. 6.4.

Figure 6.4: Damping control performance using $V_3$ as feedback input signal.
CHAPTER 6. DAMPING CONTROL DESIGN USING PMU SIGNALS FROM DOMINANT PATHS

Table 6.1: System Performance using Voltage Magnitudes as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>( d_\lambda )</th>
<th>Effective gain</th>
<th>( \xi ) (%)</th>
<th>( M_\rho ) (%)</th>
<th>( t_r ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_1 )</td>
<td>0.09</td>
<td>53.55</td>
<td>2.73</td>
<td>-</td>
<td>2.35</td>
</tr>
<tr>
<td>( V_4 )</td>
<td>0.44</td>
<td>48.44</td>
<td>7.41</td>
<td>14.79</td>
<td>0.83</td>
</tr>
<tr>
<td>( V_3 )</td>
<td>1.21</td>
<td>35.73</td>
<td>22.5</td>
<td>14.54</td>
<td>0.64</td>
</tr>
<tr>
<td>( V_5 )</td>
<td>1.97</td>
<td>123.72</td>
<td>20.2</td>
<td>17.77</td>
<td>0.69</td>
</tr>
<tr>
<td>( V_2 )</td>
<td>»</td>
<td>478.43</td>
<td>6.83</td>
<td>15.82</td>
<td>0.61</td>
</tr>
</tbody>
</table>

6.1.1 Controller Design for Maximum Damping

Voltage Magnitude

The system’s damping performance using voltage magnitudes as feedback input signals is summarized in Table 6.1. Note that they are arranged in the order of the dominant path in Fig. 6.1. All voltage magnitude signals use 3-stage lead compensator.

According to the results in Table 6.1, it can be concluded that damping performance, together with effective gain, correspond to the voltage mode shape \( S_V \) (see Fig. 6.2) where \( V_3 \) having the largest \( S_V \) achieves the highest damping performance and requires the least amount of gain.

Table 6.1’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.5.

Sets of possible signal combinations using voltage magnitude are shown in Table 6.2. This selection is an analogy to the KTH-NORDIC32’s dominant path of Mode 1 where Bus 4 is used to represent Bus 37 (see Fig. 4.1). Here, different combinations of Bus 4 with Bus 3 and Bus 5 are investigated. Note that “” in the distance column indicates that the distance is much larger than 100.

Comparing to only using a single signal \( (V_4) \), using signal combination improves the damping of the system. Furthermore, the effective gain is considerably reduced, to more than half, as a result of combining signals. Comparing the sets \( V_3 + V_4 \) to \( V_3 + V_4 + V_5 \), both combinations require relatively about the same gain, however, the latter achieves higher damping. On the other hand, if this set of signals \( (V_3 + V_4 + V_5) \) were to be implemented, when one of the signals is lost and the controller parameters are fixed for the combined signal \( V_3 + V_4 + V_5 \), the resulting damping will decrease, as shown
6.1. FEEDBACK INPUT SIGNALS

Figure 6.5: Damping control performance using $V_i$ as feedback input signal: Maximum Damping Case.

Table 6.2: System Performance using Combination of Voltage Magnitude as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$d_\lambda$</th>
<th>Effective gain</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_4$</td>
<td>0.44</td>
<td>48.44</td>
<td>7.41</td>
<td>14.79</td>
<td>0.83</td>
</tr>
<tr>
<td>$V_3 + V_4$</td>
<td>0.73</td>
<td>15.11</td>
<td>12.95</td>
<td>18.1</td>
<td>0.65</td>
</tr>
<tr>
<td>$V_4 + V_5$</td>
<td>0.69</td>
<td>22.11</td>
<td>12.3</td>
<td>17.41</td>
<td>0.66</td>
</tr>
<tr>
<td>$V_3 + V_4 + V_5$</td>
<td>0.87</td>
<td>13.15</td>
<td>14.86</td>
<td>16.54</td>
<td>0.65</td>
</tr>
</tbody>
</table>

in the forthcoming analysis.

Table 6.2’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.6.

Angle Differences

The system performance using voltage angle differences as feedback input signals is summarized in Table 6.3. All angle differences in Table 6.3 use a 1-stage lag compensator. Note that $\theta_4$ is used as a reference and $\Delta \theta_{ij}$ represents the difference between two angles: $\theta_i - \theta_j$.

According to the results in Table 6.3, it can be concluded that both damping performance and effective gain correspond to the voltage angle
Figure 6.6: Damping control performance using \( \sum V_i \) as feedback input signal: Maximum Damping Case.

Table 6.3: System Performance using Angle Differences as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals ( \Delta \theta )</th>
<th>( d_1 )</th>
<th>Effective gain</th>
<th>( \xi ) (%)</th>
<th>( M_p ) (%)</th>
<th>( t_r ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \theta_{41} )</td>
<td>1.54</td>
<td>0.86</td>
<td>14.2</td>
<td>71.1</td>
<td>0.54</td>
</tr>
<tr>
<td>( \Delta \theta_{34} )</td>
<td>2.357</td>
<td>0.21</td>
<td>16.63</td>
<td>40.89</td>
<td>0.55</td>
</tr>
<tr>
<td>( \Delta \theta_{54} )</td>
<td>2.359</td>
<td>0.12</td>
<td>17.74</td>
<td>40.28</td>
<td>0.56</td>
</tr>
<tr>
<td>( \Delta \theta_{24} )</td>
<td>2.360</td>
<td>0.09</td>
<td>18.85</td>
<td>30.94</td>
<td>0.56</td>
</tr>
</tbody>
</table>

modeshape \( (S_\theta) \) in which \( \Delta \theta_{24} \) having the largest \( S_\theta \) achieves the highest damping ratio with smallest gain.

Table 6.3’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.7. Note that, in order to have the same sign, \( \Delta \theta_{41} \) is used instead of \( \Delta \theta_{14} \).

Sets of possible signal combinations using angle differences between the two areas are shown in Table 6.4 where the average angle differences \( \Delta \theta_{\text{avg},1} \) represents \((\theta_1 + \theta_4) - (\theta_2 + \theta_5)\) and \( \Delta \theta_{\text{avg},2} \) represents \((\theta_{14} + \theta_4) - (\theta_{23} + \theta_5)\). Note that Bus 14 is a bus in the middle between Bus 4 and Bus 3, whereas Bus 23 is a bus in the middle between Bus 3 and Bus 5. The aim of using the average angle differences in the two areas is to reduce the effect of the local oscillations [17]. All two-area angle difference combinations use a 2-stage lead compensator.
6.1. FEEDBACK INPUT SIGNALS

Table 6.4: System Performance using Angle Differences as Feedback Input Signals: Two-Area Case.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$d_\lambda$</th>
<th>Effective gain</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta_{12}$</td>
<td>42.08</td>
<td>85.37</td>
<td>20.32</td>
<td>21.04</td>
<td>0.61</td>
</tr>
<tr>
<td>$\Delta \theta_{\text{avg},1}$</td>
<td>33.82</td>
<td>44.87</td>
<td>20.00</td>
<td>19.25</td>
<td>0.61</td>
</tr>
<tr>
<td>$\Delta \theta_{\text{avg},2}$</td>
<td>26.12</td>
<td>91.40</td>
<td>21.24</td>
<td>27.82</td>
<td>0.63</td>
</tr>
</tbody>
</table>

By combining signals from both areas, the damping performance does not increase significantly but the overshoot is greatly reduced, as compared to those in Table 6.3. For example, the overshoot of $\Delta \theta_{24}$ is larger those that of $\Delta \theta_{\text{avg},1}$ and $\Delta \theta_{\text{avg},2}$ while the damping ratio improves about 1-2 % when using the averaging signals. However, the effective gain increases as a result of using two-area combinations. In practice, $\theta_1$ and $\theta_2$ are generator buses and thus not usually available from PMUs (see [16]). Hence, for any practical implementation, the most feasible combination is $\Delta \theta_{\text{avg},2}$, for which similar damping performance can be achieved, although, notice that, a higher gain is the price to pay.

Table 6.4’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.8.
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Figure 6.8: Damping control performance using two-area $\Delta \theta_{ij}$ as feedback input signal: Maximum Damping Case.

Generator Speed

For comparison purposes, we consider speed signals from generators—although, only available locally, and not available from PMUs [16]. The system performance using generator speed as feedback input signals is summarized in Table 6.5. All signals in Table 6.5 use a 2-stage lead compensator except for $\omega_2$ which requires a 3-stage lead compensator.

According to the results in Table 6.5, overall, using speed as feedback input signals requires considerably larger gain than using other signals, especially using $\omega_2$.

Contrary to expectations founded in common practice, that of speed being the most effective signal for damping control, it is demonstrated here that using $\Delta \theta_{ij}$ as input signals, higher damping performance can be obtained while using much lower effective gain. The maximum damping obtained from speed signals is lower than the maximum damping that can be obtained from $\Delta \theta_{ij}$. Compare $\Delta \theta_{12}$ to $\omega_1 - \omega_2$, the angle difference outperforms the speed signals in damping performance, gain required and overshoot\(^2\).

Table 6.5’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.9.

\(^2\)Although, it is noted that none of the signals are actually available from PMUs: $\Delta \theta_{12}$ due to placement practice and $\omega_1 - \omega_2$ due to PMU characteristics
Table 6.5: System Performance using Generator Speed as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$d_\lambda$</th>
<th>Effective gain ($\xi$)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>»</td>
<td>349.19</td>
<td>16.89</td>
<td>27.2</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>2.35</td>
<td>266632.35</td>
<td>15.4</td>
<td>32.49</td>
</tr>
<tr>
<td>$\omega_1 - \omega_2$</td>
<td>»</td>
<td>227.38</td>
<td>16.06</td>
<td>31.31</td>
</tr>
<tr>
<td>$0.5 \times (\omega_1 - \omega_2)$</td>
<td>»</td>
<td>287.68</td>
<td>16.7</td>
<td>22.25</td>
</tr>
</tbody>
</table>

Figure 6.9: Damping control performance using $\omega_i$ as feedback input signal: Maximum Damping Case.

6.1.2 Controller Design for Fixed Parameter PSSs

Voltage Magnitude

The system damping performance using voltage magnitudes as feedback input signals with a fixed controller (both parameters and structure) is summarized in Table 6.6. The PSS parameters are $\alpha = 98$, $K_d = 0.00372$ using a 2-stage lead compensator. The resulting effective gain is 35.73.

The results in Table 6.6 correspond to the voltage magnitude modeshape, $S_V$, where $V_3$ having the largest $S_V$ is the most effective signal (highest damping performance). The important observation is that for a controller designed to use a specific signal, a lower damping should be expected if the original signal is replaced by another.
Table 6.6: System Performance using Voltage Magnitude as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>2.41</td>
<td>25.63</td>
<td>0.67</td>
</tr>
<tr>
<td>$V_4$</td>
<td>9.05</td>
<td>20.37</td>
<td>0.67</td>
</tr>
<tr>
<td>$V_3$</td>
<td>22.5</td>
<td>14.54</td>
<td>0.64</td>
</tr>
<tr>
<td>$V_5$</td>
<td>9.6</td>
<td>18.18</td>
<td>0.59</td>
</tr>
<tr>
<td>$V_2$</td>
<td>1.55</td>
<td>23.39</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 6.6’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.10.

Figure 6.10: Damping control performance using $V_i$ as feedback input signal: Fixed Controller Case.

For the signal combination scenario, a different structure of controller is used: $\alpha = 93$, $K_d = 0.00152$ using a 2-stage lead compensator. The resulting effective gain is 13.15.

If the last combination $V_3 + V_4 + V_5$ with highest damping were to be implemented as input to the PSS, when one of the signals is lost, this results in damping reduction. This has to be carefully taken into consideration when designing a WADC scheme.

Table 6.7’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.11.
Table 6.7: System Performance using Combination of Voltage Magnitude as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_3 + V_4$</td>
<td>11.23</td>
<td>18.75</td>
<td>0.63</td>
</tr>
<tr>
<td>$V_4 + V_5$</td>
<td>7.39</td>
<td>20.24</td>
<td>0.62</td>
</tr>
<tr>
<td>$V_3 + V_4 + V_5$</td>
<td>14.86</td>
<td>16.54</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Figure 6.11: Damping control performance using $\sum V_i$ as feedback input signal: Fixed Controller Case.

**Angle Differences**

The system performance using voltage angle differences as feedback input signals with fixed controller is summarized in Table 6.8. The PSS parameters are $\alpha = 1.4856$, $K_d = 0.0578$ using a 1-stage lag compensator. The resulting effective gain is 0.09.

As can be expected from the angle modeshape, $S_\theta$, result, the combination $\Delta \theta_{24}$ having the largest angle difference modeshape achieves the highest damping performance. As previously stated, $\theta_2$ is not likely to be available from PMUs and, thus, if $\theta_5$ is to replace it, the resulting damping is lower than using $\theta_2$.

Table 6.8’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.12. The responses of $\Delta \theta_{41}$ highlights the fact that
CHAPTER 6. DAMPING CONTROL DESIGN USING PMU SIGNALS FROM DOMINANT PATHS

Table 6.8: System Performance using Angle Difference as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta_{41}$</td>
<td>-0.77</td>
<td>23.81</td>
<td>0.56</td>
</tr>
<tr>
<td>$\Delta \theta_{34}$</td>
<td>6.57</td>
<td>28.92</td>
<td>0.56</td>
</tr>
<tr>
<td>$\Delta \theta_{54}$</td>
<td>15.00</td>
<td>31.12</td>
<td>0.56</td>
</tr>
<tr>
<td>$\Delta \theta_{24}$</td>
<td>18.85</td>
<td>30.94</td>
<td>0.56</td>
</tr>
</tbody>
</table>

controller structure and parameters need to change depending on the input signals. Note that from Table 6.8 when $\Delta \theta_{41}$ is used with the controller designed for $\Delta \theta_{24}$, this results in negative damping, rendering the system unstable.

Figure 6.12: Damping control performance using $\Delta \theta_{ij}$ as feedback input signal: Fixed Controller Case.

Sets of possible signal combinations using angle differences between the two areas with fixed controller are shown in Table 6.9. The PSS parameters are $\alpha = 418.05$, $K_d = 0.000523$ using a 2-stage lead compensator. The resulting effective gain is 91.4.

The results show that using the same amount of gain, similar damping can be obtained when using the angle difference or the average values between the two areas.
Table 6.9: System Performance using Angle Difference as Feedback Input Signals: Two-Area Case.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta_{12}$</td>
<td>14.07</td>
<td>16.79</td>
<td>0.57</td>
</tr>
<tr>
<td>$\Delta \theta_{avg,1}$</td>
<td>20.55</td>
<td>11.11</td>
<td>0.59</td>
</tr>
<tr>
<td>$\Delta \theta_{avg,2}$</td>
<td>21.24</td>
<td>27.82</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 6.9’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.13.

Figure 6.13: Damping control performance using two-area $\Delta \theta_{ij}$ as feedback input signal: Fixed Controller Case.

Generator Speed

The system performance using generator speed as feedback input signals with a fixed controller is summarized in Table 6.10. The PSS parameters are $\alpha = 5.66$, $K_d = 10.9$ using a 2-stage lead compensator. The resulting effective gain is 349.19.

With a fixed controller, using the signal $\omega_2$ as the feedback input signal results in instability; damping is negative. This emphasizes the necessity and importance of choosing the “appropriate” signals as feedback inputs.
CHAPTER 6. DAMPING CONTROL DESIGN USING PMU SIGNALS FROM DOMINANT PATHS

Table 6.10: System Performance using Generator Speed as Feedback Input Signals.

<table>
<thead>
<tr>
<th>Signals</th>
<th>$\xi$ (%)</th>
<th>$M_p$ (%)</th>
<th>$t_r$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>16.89</td>
<td>27.2</td>
<td>0.63</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>-19.25</td>
<td>~100</td>
<td>0.52</td>
</tr>
<tr>
<td>$\omega_1 - \omega_2$</td>
<td>18.64</td>
<td>44.27</td>
<td>1.36</td>
</tr>
<tr>
<td>$0.5 \times (\omega_1 - \omega_2)$</td>
<td>16.83</td>
<td>26.64</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 6.10’s corresponding responses of the terminal voltage at Bus 1 are illustrated in Fig. 6.14.

Figure 6.14: Damping control performance using $\omega_i$ as feedback input signal: Fixed Controller Case.

6.1.3 Conclusion

Results from both analyses indicate that angle difference is the most effective feedback input signals with comparatively superior damping performance and small effective gain required, comparing to voltage magnitude and generator speed. Although one drawback of using angle difference is large overshoot, which can be reduced by combining and averaging signals from two areas.
6.1. FEEDBACK INPUT SIGNALS

Damping performance of each signal of the voltage magnitude and angle differences is in accordance with their corresponding network modeshapes (see Fig. 6.2). That is, signals having high network modeshape achieve higher damping ratios than those with lower network modeshapes. Note that all of these results coincide with the open-loop observability illustrated in the previous chapter.

In the second analysis where the PSS parameters are fixed (as it is today’s practice), it can be concluded that by using different types of inputs, one cannot always expect to attain sufficiently high damping; this depends on the resulting location of the zeros near the inter-area mode. Closed-loop observability of inter-area modes will be different than open-loop observability due to the effect of “$d_\lambda$”: the distance of the zeros of an open-loop system closest to the inter-area mode. This zero is obtained from the root-locus plot of the transfer function

$$\frac{V_s}{V_{ref}} = G(s)G_{tor}(s)G_{WO}(s), \quad (6.5)$$

in which the corresponding block diagram is illustrated in Fig. 6.15.

In the case of voltage magnitude, when a signal with a small $d_\lambda$, e.g. $V_4$ with $d_{\lambda 4} = 0.44$, is combined with a larger $d_\lambda$-signal, e.g. $V_5$ with $d_{\lambda 5} = 0.197$, the combination results in $d_{\lambda 45} = 0.69$ which is larger than that of $d_{\lambda 4}$ but smaller than $d_{\lambda 5}$. Note that, in practice, if PMUs are available at Bus 4 and Bus 5 and Bus 4 is used as a primary signal, complementing $V_4$ with $V_5$ and $V_5$ provides damping enhancement because the distance to zero increases. However, when $V_5$ is a primary signal for damping, $V_4$ should be used only as a backup.
Observe that when combining a signal with a short $d_\lambda$, e.g., $d_{\lambda_4}$ with two signals with larger $d_\lambda$, e.g., $d_{\lambda_3}$ and $d_{\lambda_5}$, the resulting $d_\lambda$ will increase the damping.

We have not yet considered different loading effect in this study. This is relevant because, for different loading scenarios as shown in the previous chapters, the open-loop observability of the dominant path signals shifts depending on loading level. For example, in the case of voltage magnitude modeshape in Fig. 4.2a, $S_V$ increases as the loading increases. This is expected as the inter-area mode becomes excited.

Further work is necessary to determine if the closed-loop observability on different loading levels maintains the same properties as revealed in this study.

The selection of the “right” input signals from PMUs is critical for effective damping control. However, in the case of signal loss (due to communication failures), the controller must be changed even if new signals are to replace a lost signal so that highest damping can be obtained. These changes must occur adaptively and must be initiated by an adequate switch-over logic that guarantees the continued operation of the damping controller. Depending on the types of signals, as well as, signal combination, controller structure must be adapted accordingly to achieve optimal damping possible. As such, “adaptive” controllers, which can automatically adjust their parameters for each input signal feeding in, are promising and desirable.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis has laid out important concepts for power system small signal stability analysis and control design considering the availability and use of synchrophasors. It starts by reviewing the necessary building blocks for PMU-based control of PSSs. The importance of PMUs and their prospective implementation in WADC for inter-area mode damping in large interconnected systems has been highlighted.

A Nordic grid model, namely the KTH-NORDIC32 system, is implemented in a free and open source software: the Power System Analysis Toolbox (PSAT), and used as a test system to illustrate the concepts investigated throughout the work. Small signal stability of the KTH-NORDIC32 system is analyzed; important dynamic behavior of the system, particularly regarding to inter-area oscillations is presented. Using this test system, the concept of dominant inter-area oscillation paths is elaborated. Especially noteworthy is the concept of network modeshape that helps one to understand the behavior of the swing modes within a system; where a mode is from, on which track the mode goes, and how it is distributed among the network variables.

The degree of persistence of dominant paths in the study system is rigorously tested by contingency studies. Based on the results, suitable network variables to be used as PSS input signals are proposed. Time response of the linearized system to a disturbance demonstrates that the proposed signals contain high inter-area modal content which are good candidates as feedback input signals. This is validated through non-linear simulations in [15].
An application of the dominant inter-area oscillation paths concept for feedback controller design using synchrophasor measurements is demonstrated for PSS design in a conceptualized two-area system. Analyses considering maximum damping design objectives with different controller input signals are investigated. The results indicate that voltage angle differences, compared to voltage magnitude and generator speed, are the most effective feedback signals considering damping performance and effective gain required. In any case, depending on the control objective, one signal may be more effective than the others and the controller structure must be adapted accordingly.

7.2 Future Work

One 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, at the same time, adapt their structure to different input signals. Moreover, the effect of time delays should be taken into account.

Observe that the signals of choice are mainly dependent on the locations of PMUs. 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. At present, PMUs are not available everywhere in power systems, and it would be irrational to assume so. On the contrary, if the only available PMU signals were to be used, the concept of dominant inter-area paths could offer an insightful and effective solution to locate the existing sets of signals that contain the highest possible content of inter-area modes.

As such, based on the results from this study, prospective studies to be continued are as follows.

- Closed-loop observability. Effects of different loadings on closed-loop observability has to be investigated to verify if the properties found in this study are preserved.

- Adaptive/selective control schemes. As previously stated, for each input signal, the controller structure has to be adjusted such that effec-
7.2. FUTURE WORK

tive damping performance can be achieved. Adaptive controllers may allow for automatic switching to pre-defined controllers or automatic parameter tuning corresponding to the change in input signals. In case of communication failures, which can occur in WAMS, the controller should be able to switch to the next pre-defined available signals.

- Impact of information and communication technology (ICT) on WADC. Time delays may have certain impact, to some extent, on damping control performance. One issue is how to model or mathematically represent time delays for controller design in a reasonable way. In addition, the choice of flexible communication mechanisms for adaptive control schemes can be investigated.

- Real-time oscillation damping using synchrophasor measurements. Applications of wide-area measurements from PMUs for WAPOD will be implemented using a real-time simulator. Practical issues and feasibility will be taken into consideration for developing control schemes and controller designs.
### Data for the KTH-NORDIC32 System

Table 7.1: Generator model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thermal</th>
<th>Hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_d$ [p.u.]</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>$x_d'$ [p.u.]</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>$x_d''$ [p.u.]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$T_{d0}$ [p.u.]</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>$T_{d0}$ [p.u.]</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>$x_q$ [p.u.]</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>$x_q'$ [p.u.]</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>$x_q''$ [p.u.]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$T_{q0}$ [p.u.]</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>$T_{q0}$ [p.u.]</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>$2H$ [kWs/kVA]</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 7.2: Exciter model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thermal [p.u.]</th>
<th>Hydro [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_0$</td>
<td>120</td>
<td>50</td>
</tr>
<tr>
<td>$T_2$ [s]</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>$T_1$ [s]</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>$T_e$ [s]</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$T_r$ [s]</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$v_{f \text{max}}$ [p.u.]</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>$v_{f \text{min}}$ [p.u.]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$v_0$ [p.u.]</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7.3: Over excitation limiter model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ [p.u.]</td>
<td>10</td>
</tr>
<tr>
<td>$i_{f \text{lim}}$ [p.u.]</td>
<td>3.0-22.0</td>
</tr>
<tr>
<td>$v_{OXL \text{max}}$ [p.u.]</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 7.4: Turbine governor system model parameters: Model 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ [p.u.]</td>
<td>0.04</td>
</tr>
<tr>
<td>$T_g$ [s]</td>
<td>5</td>
</tr>
<tr>
<td>$T_e$ [s]</td>
<td>0.2</td>
</tr>
<tr>
<td>$T_3$ [s]</td>
<td>5</td>
</tr>
<tr>
<td>$T_4$ [s]</td>
<td>0.01</td>
</tr>
<tr>
<td>$T_5$ [s]</td>
<td>6</td>
</tr>
<tr>
<td>$P_{\text{max}}$ [p.u.]</td>
<td>0.95</td>
</tr>
<tr>
<td>$P_{\text{min}}$ [p.u.]</td>
<td>0, -0.5 for $G_{13}$</td>
</tr>
</tbody>
</table>

Table 7.5: Turbine governor system model parameters: Model 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ [p.u.]</td>
<td>0.04, 0.08 (for $G_{19}, G_{20}$)</td>
</tr>
<tr>
<td>$T_1$ [s]</td>
<td>3</td>
</tr>
<tr>
<td>$T_2$ [s]</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_{\text{max}}$ [p.u.]</td>
<td>1</td>
</tr>
<tr>
<td>$P_{\text{min}}$ [p.u.]</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 7.6: Turbine governor system model parameters: Model 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$ [s]</td>
<td>0.2</td>
</tr>
<tr>
<td>$T_p$ [s]</td>
<td>0.04</td>
</tr>
<tr>
<td>$T_r$ [s]</td>
<td>5</td>
</tr>
<tr>
<td>$T_w$ [s]</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma$ [p.u.]</td>
<td>0.04</td>
</tr>
<tr>
<td>$\delta$ [p.u.]</td>
<td>0.3</td>
</tr>
<tr>
<td>$a_{11}$ [p.u.]</td>
<td>0.5</td>
</tr>
<tr>
<td>$a_{13}$ [p.u.]</td>
<td>1</td>
</tr>
<tr>
<td>$a_{21}$ [p.u.]</td>
<td>1.5</td>
</tr>
<tr>
<td>$a_{23}$ [p.u.]</td>
<td>1</td>
</tr>
<tr>
<td>$G_{max}$ (Maximum gate opening) [p.u.]</td>
<td>1</td>
</tr>
<tr>
<td>$G_{min}$ (Minimum gate opening) [p.u.]</td>
<td>0</td>
</tr>
</tbody>
</table>
Bibliography


[77] K. Uhlen, L. Warland, J.O. Gjerde, O. Breidablik, M. Uusitalo, A.B. Leirbukt, and P. Korba. Monitoring Amplitude, Frequency and Damp-


