

Wide-Area Control Schemes to Improve Small Signal Stability in Power Systems

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*To my parents, Monir and Reza
for their countless sacrifices and
my husband and best friend, Ali,
for his endless love and belief in me*

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Abstract

One of the main concerns for the secure and reliable operation of power systems is the small signal stability problem. In the complex and highly interconnected structure of future power systems, relying solely on operator responses and conventional controls cannot assure reliability. Therefore, there is a need for advanced Wide-Area Control Schemes (WACS) that can automatically respond to degradation of reliability in the system.

The main objective of this dissertation is to address two key challenges regarding the design and implementation of wide-area control schemes for damping inter-area oscillations. First is the high communication cost associated with optimal centralized control approaches. As power networks are large-scale systems, both the synthesis and the implementation of centralized controllers suggested by most of the previous studies are often impossible in practice. Second is the difficulty of obtaining accurate system-wide dynamic models for initiating and updating the control design.

In this research, we introduced wide-area damping control strategies that not only ensure the small signal stability with the desired performance but also consider communication and model information limitations in the design. A state feedback formulation is proposed that aims to simultaneously optimize a standard Linear Quadratic Regulator (LQR) cost criterion and induce a pre-defined communication structure. We solved the proposed problem with three different objectives to target a specific wide-area damping control design challenge in each setting. First, the communication structure is enforced as a constraint in the optimization and solved for a large idealized power network with information symmetry. Second, to make the method suitable for systems with arbitrary structures and information patterns, we proposed a group-sparse regularization to be added to the optimization cost function. Applications of the method for inducing the desired communication network and

finding effective measurement and control signal combinations were also investigated. Third, we paired the proposed optimal control with a real-time model identification approach, to create a wide-area control framework that is capable of dealing with model information limitations and inaccuracies in online implementation. The performances of the proposed wide-area damping control architectures are validated through nonlinear simulations on different test systems.

Table of Contents

1	Introduction	1
1.1	Emerging Challenges in Power System Operation and Control	1
1.2	Motivation	2
1.3	Contributions	3
1.4	Dissertation Outline	6
2	Literature Review	8
2.1	Low Frequency Oscillations in Power Systems	8
2.2	Wide-Area Damping Control Design	10
2.3	Distributed and Decentralized Control Design	11
2.4	Measurement-Based Models in Power Systems	12
3	Wide-Area Damping Control Design: Large Idealized Network	14
3.1	Introduction	14
3.2	Continuum Representation of Large Power Networks	15
3.3	Distributed Damping Control Design For Large Power Networks	17
3.3.1	Power System Model with Distributed LQR Control	18
3.3.2	Distributed LQR Control Design	20
3.4	Evaluation of The Proposed Distributed Controller	23
3.4.1	Test System Overview	24
3.4.2	Simulation Results	25
3.5	Concluding Remarks	28

4	Wide-Area Control Design with Limited Communication	31
4.1	Introduction	31
4.2	Power System Electromechanical Model with Distributed Control Input . . .	32
4.3	Distributed Control Design Using Group Sparse Regularization Functions . .	34
4.3.1	Distributed Linear Quadratic Control Design Using Group Sparse Regularization Functions	37
4.4	Application I: Inducing a Desired Communication Structure for Damping Inter-area Oscillations in Power Networks	40
4.4.1	Illustration on the Two-Area Four-Machine System	41
4.4.2	New England 39-bus 10-machine System	47
4.5	Application II: Control And Communication Co-Design For Damping Inter- area Oscillations In Power Networks	56
4.5.1	Two-Area Four-Machine System	56
4.6	Conclusion	61
5	Power System Model Validation and Enhancements: Current Industry Practice in Western Interconnection	63
5.1	Introduction	63
5.2	Overview of Real-time Transient Stability Assessment at Peak Reliability . .	65
5.3	Model Enhancements for Real-Time Transient Stability Assessment Tool at Peak Reliability	67
5.4	Cases of Model Validation in Western Interconnection	68
5.4.1	Event-Based Model Validation	68
5.4.2	No Disturbance Test	74
5.4.3	Real-Time Transient Stability Analysis Results	75
5.4.4	External Resources	75
5.5	Implementation and Testing of RAS Models using online DSA Tools	77
5.5.1	RAS User-defined Models	78
5.5.2	Simulation Results	79

5.5.3	Impact of Modeling RAS on Transient Stability Limits and Limiting Contingencies	79
5.5.4	Benefits of Modeling RAS in Transient Stability	82
5.6	Concluding Remarks	83
6	Wide-Area Control Design with Limited Model Information	84
6.1	Introduction	84
6.2	Problem Statement	85
6.2.1	Power System Modeling	85
6.2.2	Wide-area Control Design Using Measurement-Based Models	86
6.3	Evaluation of the Proposed Wide-area Control	90
6.3.1	Test System Overview and Simulation Considerations	90
6.3.2	Case 1: Out of Service Power System Stabilizer	91
6.3.3	Case 2: Excitation System Models	94
6.3.4	Case 3: Loads	95
6.4	Concluding Remarks	96
7	Conclusions and Future Directions	97
7.1	Concluding Remarks	97
7.2	Future Directions	98
	Bibliography	100
	Vita	113

List of Tables

3.1	Synchronous Machine Parameters	25
3.2	Network Parameters	25
4.1	Two-area system modes (base-case)	42
4.2	Inter-area modes for different communication structures	45
4.3	New England system inter-area modes (base-case)	48
4.4	New England system inter-area modes percentage damping for different communication structures	51
4.5	Centralized Structure	53
4.6	Ring Structure	54
4.7	Star Structure at G_1	54
4.8	Star Structure at G_7	54
4.9	Local Structure	54
5.1	Largest peak to peak angle deviations (deg) for base case and modified cases	74
5.2	Path X RAS enabling and triggering conditions	78
6.1	Local and inter-area modes for different control designs in case study 1. . . .	92
6.2	Inter-area modes for different control designs in case study 2.	95
6.3	Inter-area modes for different control designs in case study 3.	96

List of Figures

1.1	Dissertation areas of contribution	4
3.1	Information exchange between a distributed control agent on a generator with its two neighbors. Two generators are considered neighbors if there is a communication link between them.	18
3.2	General structure of the two-dimensional mesh grid test system from [36]. . .	24
3.3	A sequence of time snapshots of rotor angle responses in a 30x30 grid of generators without controllers.	26
3.4	A sequence of time snapshots of rotor angle responses in a 30x30 grid of generators with proposed distributed LQR controller.	27
3.5	Rotor Angles for selected generators with different controllers.	29
3.6	Rotor speed deviation for selected generators with different controllers. . . .	30
4.1	Two-stage power system stabilizer model.	33
4.2	Proposed distributed control agent and its information exchange pattern at k_{th} generator.	34
4.3	Categories of non-centralized controllers.	35
4.4	Two-Area, Four-Machine Test System [48].	41
4.5	Communication structures and grouping graphs for (a) Centralized ,(b) Decentralized, (c) Local and (d) Star communication networks and the predicted sparsity pattern of the feedback matrix.	43
4.6	Communication structures and their respective designed feedback control matrix sparsity patterns (a) Centralized ,(b) Decentralized, (c) Local, (d) Star and (e) Ring.	44

4.7	Nonlinear simulation results for different control structures: (a) Frequency deviation (Hz) and (b) Rotor Angles (degree)	46
4.8	Modified New England 39-bus 10-machine System	47
4.9	New England System inter-area mode shapes	49
4.10	Pre-defined communication structures for New England System	50
4.11	Feedback matrix sparsity patterns for different communication structures . .	52
4.12	Collective controllability of the generators of all local and inter-area modes in New England system	53
4.13	Nonlinear simulation results for different control structures: (a) Frequency deviation (Hz) and (b) Rotor Angles (degree)	55
4.14	Communication structures and respective feedback control sparsity patterns for (a) Scenario 1, (b) Scenario 2.	57
4.15	Geometric measure of speed deviation measurements and excitation control inputs for inter-area mode for two scenarios in two-area four-machine test systems, Scenario1: (a) Controllability measure, (b) Observability measure, (c) Joint controllability/observability measure, Scenario 2: (d) Controllability measure, (e) Observability measure, (f) Joint controllability/observability measure.	59
5.1	Peak real-time TSAT architecture.	66
5.2	TSAT Model Accuracy Checkpoints at Peak Reliability.	68
5.3	Frequency response at bus M1 for Event 1 (PMU Measurement vs. Operation Model).	70
5.4	Frequency response at bus M2 for Event 1 (PMU Measurement vs. Operation Model).	70
5.5	Impact of unit status changes on frequency response of bus M1.	71
5.6	Impact of change in governor settings on frequency response of bus M1. . . .	72
5.7	Frequency response at bus M3 for Event 2 (PMU Measurement vs. Operation Model).	73

5.8	Voltage response at bus M4 for Event 3 (PMU Measurement vs. Operation Model).	73
5.9	Reactive power response for generator P1 with and without CCOMP model.	76
5.10	Comparison of voltage responses at bus M5 before and after updating the PDCI model.	76
5.11	RAS basic structure.	77
5.12	Logic diagram of Path X RAS.	79
5.13	Line loading and Path X RAS threshold.	80
5.14	Stability limit differences with and without RAS Models.	81
5.15	Limiting contingency percentages over a one day study: (a) Without RAS model and (b) With RAS models included.	81
6.1	Block diagram of the proposed wide-area control design using measurement-based model.	87
6.2	Component-based models versus measurement-based models for control design.	89
6.3	Kundurs two-area four-machine test system [48].	89
6.4	Nonlinear time domain simulation results.	93
6.5	Comparison of electric power output at G_4 for case study 2.	94
6.6	Comparison of electric power output at G_2 for case study 3.	95

Chapter 1

Introduction

1.1 Emerging Challenges in Power System Operation and Control

Power grid is evolving toward a larger, more complex and geographically distributed network with uncertain generation and load patterns. Increased penetration of renewable energy recourses and deployment of distributed generation have introduced uncertainty and variability on the supply side. Accommodating these variations and maintaining system balance, requires additional operational flexibility. Integration of renewables also affects power systems dynamic behavior. Renewable generations are most often connected to the load centers remotely through weak ties which can enhance power system instability risks. In addition, these units are mainly interfaced with power electronic devices, characterized by less short circuit power and lack of natural inertia, which further complicates power system operation. Power grid demand side is also undergoing significant changes. New types of loads like electric transportation are transforming the traditional consumption trends. In addition, smart metering technology and demand response programs are making portions of loads, controllable.

Aside from changes in power system generation and loads, restructuring and deregulation on one hand and economical and environmental restrictions for transmission expansion, on the other hand, are driving power systems to operate closer to their stability limits.

Therefore, critical modes of the system which are near stability or required performance limits can be influenced by unpredictable contingencies and even lead to cascading failures and blackouts. Consequently, maintaining sufficient security margins will be highly dependent on a robust and reliable control infrastructure.

Changes in power system operational needs have fundamentally changed the expectations from control mechanisms and have exposed their weaknesses. Power system control has been primarily local and suffers from the fact that local controllers are not designed to handle system-wide effects of disturbances. With the introduction of Phasor Measurement Units (PMUs) and advanced communication technologies, wide-area monitoring has enhanced operators situational awareness and provided a platform for a more flexible and adaptive detection and control. However, relying solely on operator responses in the face of events cannot assure reliability in the complex and highly interconnected structure of future power systems. Therefore, there is a need for advanced wide-area control schemes that can be applied on the basis of the modern wide-area monitoring system and automatically take actions to ensure a secure and reliable operation.

1.2 Motivation

The next generation of the electricity grid, also known as “Smart Grid”, is one of the most complex systems due to its extreme dimension, geographic reach, and high-reliability requirements. One of the main concerns for the secure and reliable operation of power systems is the small signal stability problems caused by inter-area oscillations. In the future grid, enhancing the transfer capability while maintaining system stability requires a significant enhancement of the existing control infrastructure to damp these oscillations. Due to the highly interconnected nature of the power grid, deployment of wide-area control is essential toward building a self-healing smart grid.

During the past decade, extensive research has been done to address different aspects of wide-area damping control design for improving small signal stability [103]. These studies have been mainly focused on : (1) different choices of actuators like PSS [104, 101, 102, 97], HVDC [76, 78, 90] or FACTS devices [96, 20], (2) feedback signal and input placement

selection [52, 56, 70], (3) control design methods like the residue method [105], pole placement [20, 14] and robust control strategies [104, 57] and (4) effects of time delays on the performance of the controller [61, 95, 6]. However, as power networks are large-scale systems, both the synthesis and the implementation of centralized controllers suggested by most of the previous studies are often impossible in practice [53]. One of the main challenges for deployment of centralized controllers in a large system is the high amount of information exchange. Very few researchers have considered communication constraints and information limitations in Wide-Area Damping Control (WADC) design [24]. Also, the impact of different communication structures on the damping performance have not been studied.

Another obstacle toward WADC design is the assumption of having access to accurate system-wide dynamic models of the system. Historically, controls in power system were designed and operated using component-based models derived from linearizing nonlinear differential equations governing the system. With recent trends toward deployment of renewable distributed generation and introduction of new types of loads and various load controls, power system models are becoming increasingly inadequate for representing the system. Therefore, highly reliable controls, required for the future power grid, cannot be built upon inaccurate models. Measurement-based models, estimated online directly from the measurements, can serve as an excellent complement to conventional models. With available phasor measurements increasing and model estimation techniques maturing, there is still a need for methods to bridge the gap between online model estimation and power system control design.

The aim of this dissertation is to propose wide-area damping control strategies that not only ensure the small signal stability of the system with the desired performance but also consider communication and model information limitations in large power networks.

1.3 Contributions

The main objective of this research is to address two key challenges regarding the design and implementation of wide-area control schemes for damping inter-area oscillations in large power networks. First is the high communication cost associated with optimal

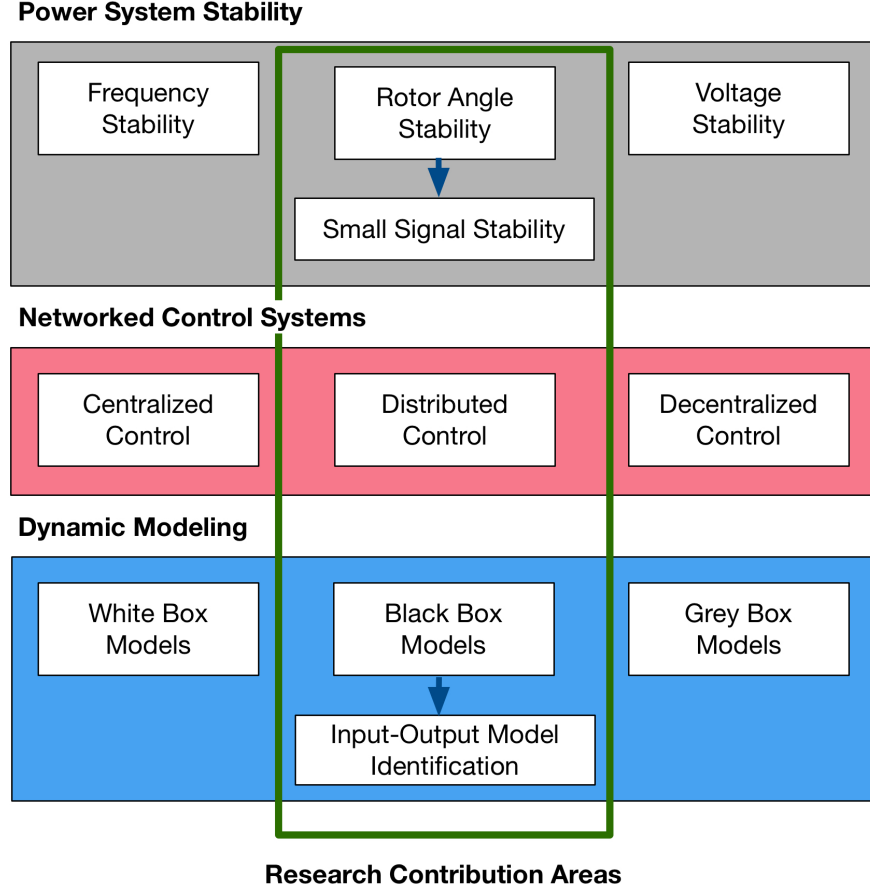


Figure 1.1: Dissertation areas of contribution

centralized control approaches. Second is the difficulty of obtaining accurate system-wide dynamic models for initiating and updating the control design. Achieving this goal requires methodologies which span different areas of power system stability, control systems, and dynamic modeling. Figure 1.1 highlights the research contribution areas. The dissertation contributions can be summarized as follows:

- A distributed excitation control is designed and implemented on a large idealized power network with 900 generators to mitigate the electromechanical disturbance propagations. The performance of the proposed controller is then compared to centralized and decentralized schemes.
- A distributed linear quadratic optimal control framework is developed using group sparse regularization function. The proposed control aims to optimize a standard cost criterion while penalizing the number of communication links. The group sparse

regularization approach is used to induce the desired sparsity pattern and encode prior information about the underlying system into the control design. This new approach is described in a general form and can be applied to different applications other than improving small signal stability.

- Distributed controls with different communication structures are designed and compared for wide-area damping control application in power systems. The proposed method not only provides flexibility to explore different communication structures but also creates a platform for finding the information exchange pattern that best fits the system constraints and satisfies the required performance criteria.
- A control and communication co-design framework is implemented to find the most critical communication links in a distributed control structure. It has been shown that the proposed method is consistent with the conventional geometric controllability and observability approaches in the search for the efficient measurement-control loops.
- Current dynamic model validation and enhancement practices in the power system industry are studied using real test cases to demonstrate the importance of model accuracy for real-time stability analysis applications. These studies resulted in significant improvements in renewable generation, PDCI, governor and exciter and Remedial Action Scheme (RAS) models throughout Western Interconnection.
- A new wide-area control framework is proposed using online model estimation techniques to improve small signal stability. The proposed controller updates the control design based on a model estimated online using the numerical subspace state-space system identification (N4SID) algorithm.
- Three common cases of dynamic model inaccuracies, selected based on previous model validation studies, are used to compare component-based and measurement-based models for the control design. It is demonstrated that inaccurate models degrade the performance of the controller while the proposed control using measurement-based model can successfully capture small signal dynamics of the system and provide satisfactory performance.

1.4 Dissertation Outline

This dissertation is organized as follows:

Chapter 2 reviews the low-frequency oscillation problem in power systems and conventional control methods for limiting its consequences. Then it provides an extensive review of wide-area damping control designs and categorizes the challenging aspects that already covered in the literature. Distributed and decentralized control methods are also summarized. Approaches for finding power system dynamic models from the measurements are reported as well.

Chapter 3 proposes a distributed wide-area control scheme to mitigate electromechanical disturbance propagations. The method is suited for systems with structure and information symmetry and is applied to a large, idealized power network with 900 generators. The performance of the controller is then compared with centralized and decentralized schemes. The work in this chapter is inspired by the continuum representation of large power systems.

Chapter 4 proposes a distributed optimal control framework using group sparse regularization function. The proposed control aims to optimize a standard cost criterion while penalizing the number of communication links. The group sparse regularization approach is used to induce the desired communication structure and encode prior information about the underlying system into the control design. Two applications of the proposed algorithm for damping inter-area modes are explored and evaluated using the two-area four-machine and New England test systems.

Chapter 5 describes current industry practices in model validation and some of the recent model enhancements implemented to improve the operation model for real-time stability analysis applications using case studies and system events in Western Interconnection. The study results provide insight into insufficiencies, which need to be addressed for real-time operation models and demonstrate the need for online measurement-based models in future power system analysis and control.

Chapter 6 introduces a wide-area control scheme using online model estimation to improve small signal stability. The proposed controller updates the control design based on a model estimated online using a numerical subspace state-space system identification (N4SID)

algorithm. Based on previous model validation studies, we use three common cases of model inaccuracies as case studies to compare component-based and measurement-based models for the control design.

Chapter 7 presents the conclusions drawn from the research.

Chapter 2

Literature Review

2.1 Low Frequency Oscillations in Power Systems

One of the main concerns for the secure and reliable operation of power systems is the small signal stability problem. In the highly interconnected structure of power systems, an unstable mode can have immediate impacts over a wide area and may even lead to cascading failures and blackouts [51]. Most of the previous blackout events exhibited sustained low-frequency oscillations [38]. The notable breakup of the Western Electricity Coordinating Council (WECC) system on August 10, 1996, was due to undamped oscillations [47]. Other major oscillation events include a generation loss on October 9, 2003, multiple line trippings on June 4, 2003 [33], and the BC-Alberta separation event on August 4, 2000 [32]. These events raised great concerns about the adverse effect of oscillations on power system operation. Local and inter-area oscillations are two distinct types of oscillations which have presented problems in power systems. Local mode oscillations are caused by a generator or group of generators swinging against the rest of the system. Local plant modes are usually induced by the action of Automatic Voltage Regulators (AVRs) operating at high output [41]. Local modes generally have natural frequencies in the range of 1 to 2 Hz. Their characteristics are fairly well understood and can be analyzed adequately using a detailed representation only in the vicinity of the plant [50]. Power system stabilizers (PSS) can be used to achieve a satisfactory damping for local modes.

Inter-area oscillations involve groups of machines in one part of the system oscillating against groups of machines in other parts of the system. They may be caused by either high-gain exciters or groups of machines closely coupled but interconnected by weak ties [48]. Inter-area modes have frequencies typically in the range of 0.1 to 1 Hz. Characteristics of these modes and factors influencing them are not fully understood which makes them far more complex to study and to control. A detailed model of the entire system is required to study inter-area modes [49].

Large power systems typically exhibit multiple dominant inter-area modes. Insufficient damping of this type of oscillation may lead to a limitation of power transfer capability or, worse than that, a growth in amplitude of the oscillations which could even cause a system to collapse. With highly increasing power exchange between utilities over the existing transmission network, power systems are driven closer to their limits, especially those of transmission capacity. Therefore, enhancing the transfer capability, while maintaining system stability, greatly relies on damping these inter-area oscillations.

The traditional approach for damping inter-area oscillations is by installing PSS to provide supplementary control action through the excitation of the generators. The increased use of high-response exciters, while improving transient stability, adversely affected the damping of local plant modes and shifted the focus for PSS tuning to local mode stability [73]. In addition, due to the lack of observability of certain inter-area modes in local measurements, conventional PSS with local measurements as input, cannot always effectively damp these type of oscillations. For instance, under certain operating conditions an inter-area mode may be controllable from one area and observable from another [2]. Moreover, the performance of conventional PSS is sensitive to operating point changes in the system which presents significant challenges in the design [94]. The practical feasibility of PSS is also limited due to the fact that power system models have been found inadequate for describing real-time operating conditions [47]. To overcome the weaknesses of conventional methods, new control methodologies needs to be developed for improving the damping of inter-area oscillations.

2.2 Wide-Area Damping Control Design

Introduction of Phasor Measurements Units (PMUs) offers the possibility of control based on Wide-area Measurements (WAMs) and provides great potential to overcome the shortcomings of conventional local controllers. North America Synchrophasor Initiative (NAPSI) has identified real-time automated and adaptive wide-area grid controls for inter-area oscillation damping as one of the highest priority applications to be developed using phasor data [18]. Wide-area Damping Control design involves three main steps [103]. Prior to the design of the control, the feedback signal and control inputs are selected based on the observability and controllability of the dominant oscillation modes, respectively. In the next step, the system model defining the input-output relationships is identified. Then, the control can be designed using desired control methodologies.

Researchers achieved promising results by applying WAMs to Wide-area Damping Control (WADC) of inter-area oscillations. Generator PSSs, FACTS devices and HVDC are three main actuators used in WADC design. A Linear Matrix Inequality (LMI) based centralized wide-area damping control was proposed in [104] that provides supplementary damping signals to AVRs of selected generators in addition to their local PSS signal. In the proposed design procedure, only a few measurements with high observability of inter-area modes are selected and only a few generators with the high controllability of those modes are chosen as control locations. A novel control inversion framework was proposed in [11] which can invert PMU-based control designs developed for reduced-order power systems to controllers in actual higher-order systems via optimization methods. In practice, to enhance the damping performance of inter-area oscillations, a WADC framework was designed to modulate multiple HVDC systems and was implemented in China Southern Power Grid (CSG) [76].

Although several other studies also confirm that the use of remote measurement signals could increase damping of inter-area modes beyond that attainable by local signals [25, 71, 42], wide-area damping control is still in its infancy due to many difficulties associated with its design and implementation. As power networks are large-scale systems, the centralized framework for wide-area control suggested by most of the previous studies

[104, 98, 99], despite exhibiting optimal performance, are very challenging to implement in practice. Therefore, there is a lack of research efforts in using distributed control schemes for wide-area damping control design that can provide near optimal performance by exploiting limited communication and limited model information [62].

2.3 Distributed and Decentralized Control Design

Limitations for information exchange and communication constraints in a system motivate the use of decentralized and distributed controllers that only need access to a subset of state measurements. Decentralized and distributed control for large-scale systems is a well-studied problem in the control literature.

It has been shown in [93] that the necessary and sufficient condition for stabilizing a linear time-invariant dynamic system using a decentralized control structure is the absence of fixed modes. While decentralized controllers are blind to the widespread effects of disturbances and centralized controllers are practically difficult to implement, distributed controllers can achieve a trade-off between performance and required communications. In a distributed control scheme, limited communication between different controllers is used to improve the control performance. In a distributed architecture, the controller is composed of several interconnected units. Each local control agent can only access a subset of the global information (e.g., sensor measurements, model parameters) and actuate on a subset of the inputs, perhaps in its vicinity. Distributed controllers have received considerable attention since the early 2000s [9, 19, 26, 62]. Motivation for designing localized controllers comes from [9], where it was shown that optimal controllers for spatially-invariant systems, although centralized, have an inherent spatial-decay property. For these systems, dependence of the controller agent on remote measurements decays exponentially with increasing distance from the controller [28].

Since in a distributed control problem, the information set that each controller has access to, is different, the problem is difficult to solve. One of the main approaches for solving distributed control design problems is by defining special conditions for the underlying system and the information pattern [10]. Therefore, most of the distributed

control strategies proposed in the literature are not suitable for application to real power systems with arbitrary physical structure and dynamic features. Identifying sub-optimal solutions is a good alternative when the distributed control problem cannot be solved optimally. Designing distributed control schemes for power system applications is still in its infancy and extensive research is required to establish an efficient, reliable and economically viable control framework. Therefore, introducing new distributed design algorithms that can adapt to power system conditions will provide a great insight for future wide-area control design.

2.4 Measurement-Based Models in Power Systems

Due to the complex nature of the power grid, wide-area control design is one of the key challenges toward a self-healing smart grid. Conventional controls in power system were designed and operated based on component-based models. However, power system models are increasingly viewed as inadequate for representing system-wide effects of disturbances and describing real-time operating conditions [47]. Therefore, highly reliable controls, required for future power grid, cannot be built upon inaccurate models. In an effort to improve the models to more accurately replicate system events, the North American Reliability Corporation (NERC) recommended model validation and benchmarking following the August 14, 2003 blackout [5]. Model validation has significantly improved the models in Western Electricity Coordinating Council (WECC) during the past decade [7] and NERC is aiming at bringing validation mandates to bear nation wide [77]. However, model validation is a very time consuming process and cannot fully accommodate applications like automated control which deals with real-time changes in the system.

With the deployment of Phasor Measurement Units (PMUs) and advanced communication technologies, wide-area monitoring became a platform for a more flexible and adaptive detection and control for power systems. Measurement-based modal analysis, uses real-time phasor measurements to identify a linear model of the system and estimates oscillation modes and their damping [39]. In previous research, different methods have been proposed for identifying power system models using selected measurements from the system. These

methods include but are not limited to, subspace state-space system identification (N4SID) [43, 91, 107], Prony Analysis [29, 72] and Prediction Error Method (PEM) [60]. Applying such approaches, provide an input-output model of the system that cannot be used for state feedback control design and is commonly paired with phase-compensating lead-lag control where each device is tuned for a specific oscillation mode. Very few studies [27] have been dedicated to the usage of real-time model identification and state feedback control design for coordinating all controllable devices for damping the critical inter-area modes. With available phasor measurements increasing and model estimation techniques maturing, there is still a need for methods to bridge the gap between online model estimation and power system control design.

Chapter 3

Wide-Area Damping Control Design: Large Idealized Network

3.1 Introduction

Power system engineers have long recognized that disturbances propagate in power network with finite speed [82]. Different models were developed to capture the spatio-temporal effects of these propagations [82, 74, 16]. These models provide a new understanding of the large scale system dynamics by taking a global view of the problem, while neglecting some of the details in the system behavior [37]. This broader view of the system dynamics can be used to gain valuable insights for designing new control schemes. However, very few studies have explored the effects of control design in limiting the widespread propagations [4, 54, 55]. Reference [4] uses disturbance propagation speed to improve power system stabilizers (PSS) performance by introducing an extra damping torque simultaneously with the disturbance arrival. References [54] and [55] employ an impedance matching approach to inhibit reflections of electromechanical waves in power systems. Application of distributed control schemes to mitigate disturbance propagations in large power networks has not yet been studied.

Prior to the introduction of real-time Phasor Measurement Units (PMUs), power system control was primarily local. Except for the very slowest of controllers and a few specialized schemes, engineers have designed systems largely through local decisions based on local

measurements [89]. As is all too apparent during blackouts, power system disturbances may have system-wide impacts. When the information of the entire system is available for the design purpose, centralized control schemes can exhibit a great performance [35]. However, as power networks are large-scale systems, both the synthesis and the implementation of centralized controllers are often impossible in practice [53]. While local controllers are blind to the widespread effects of disturbances and centralized controllers are practically challenging to implement, distributed controllers can achieve a trade-off between performance and required communications. In distributed control, limited communication between different controllers is exploited to improve control performance.

In this chapter, a distributed control scheme is proposed to mitigate disturbance propagations in large power networks. For the control design, we follow the distributed LQR control approach developed in [10] and find a linear static state feedback that simultaneously optimizes a standard cost criterion and induces the pre-defined communication structure. Our choice of test system is inspired by continuum modeling work in [36].

This chapter is organized as follows. Section 3.2 introduces the continuum representation of large power networks. Section 3.3 formulates the electromechanical behavior of power system including the proposed controller input and describes the distributed LQR damping control design. In section 3.4, we introduce the test system which represents a large scale power network and evaluate the performance of the proposed distributed controller. Concluding remarks are presented in section 3.5.

3.2 Continuum Representation of Large Power Networks

Consider a two-dimensional mesh network of n generators distributed along a spatial dimension as depicted in figure. At each bus is a generator which supplies a variable current, I_{ij} , at a constant voltage magnitude, E_{ij} . The difference between the mechanical power, P_m , and electrical power, P_e , of a generator is the power that accelerates the generator rotor. The electromechanical behaviour of the generator can be described by the swing equation

below:

$$\left(\frac{2H}{\omega}\right)\ddot{\delta} + \omega D\dot{\delta} = P_m - P_e = P_a \quad (3.1)$$

where δ is the rotor phase angle, H is the inertia constant and ω is the angular frequency of the generator. The mechanical damping constant is D which is typically small.

The supplied current from the generator divides into four branch currents labeled $I_{i+1,j}$, $I_{i-1,j}$, $I_{i,j+1}$ and $I_{i,j-1}$. Each branch current is a function of the line impedance and the voltage difference between the two nodes. The current flowing from node i to $i+1$ is given by :

$$I_{i+1,j} = \frac{E_{i,j} - E_{i+1,j}}{Z} \quad (3.2)$$

where $Z = R + jX$ is the line series impedance. The expression for the net current flowing out of the ij^{th} machine then becomes:

$$I_{i,j} = I_{i+1,j} - I_{i-1,j} + I_{i,j+1} - I_{i,j-1} + \Delta Y E_{i,j} \quad (3.3)$$

where ΔY is the shunt admittance and $G = Re\{Y\}$.

Each node (i, j) is associated with a Cartesian coordinate (x, y) and the distance between adjacent nodes is defined as Δ . So that $(i+1, j) \longrightarrow (x + \Delta, y)$, $(i, j-1) \longrightarrow (x, y - \Delta)$, etc. Substituting (3.2) in (3.3) and using the Taylor series expansions of $E(x + \Delta, y)$, $E(x - \Delta, y)$, $E(x, y + \Delta)$, $E(x, y - \Delta)$ around $E(x, y)$, results in:

$$I(x, y) = -\frac{\Delta^2}{Z}(\nabla^2 E(x, y)) + \Delta Y E(x, y) \quad (3.4)$$

The electrical power of the generator as a function of spatial coordinates is :

$$P_e(x, y) = Re\{\tilde{E}(x, y)\tilde{I}^*(x, y)\} \quad (3.5)$$

In taking the continuum limit of the swing equation, the inertia constant, damping coefficient, mechanical power and the line impedance are defined as distributed parameters which are

functions of the spatial coordinates x and y :

$$H \longrightarrow \Delta h(x, y) \quad D \longrightarrow \Delta d(x, y) \quad (3.6)$$

$$Z \longrightarrow \Delta z(x, y) \quad P_m \longrightarrow \Delta p_m(x, y) \quad (3.7)$$

The source voltage is considered to be constant in magnitude and equal to one per unit which becomes $E(x, y) = \exp(j\delta(x, y))$. The line impedance is also defined as $z(x, y) = |z|(\cos \theta + j \sin \theta)$, with the phase angle θ being close to $\frac{\pi}{2}$ for high voltage transmission lines. By substituting (3.5) into (3.1) all the dependence to Δ cancels and we obtain the following damped hyperbolic wave equation in terms of the aggregate angle δ :

$$\frac{\partial^2 \delta}{\partial t^2} + \nu \frac{\partial \delta}{\partial t} - v^2 \nabla^2 \delta + u^2 (\nabla \delta)^2 = P \quad (3.8)$$

where

$$\begin{aligned} v^2 &= \frac{\omega \sin \theta}{2h |z|} \\ u^2 &= \frac{\omega \cos \theta}{2h |z|} \\ P &= \frac{\omega(p_m - G)}{2h} \\ \nu &= \frac{\omega^2 d}{2h} \end{aligned}$$

Assuming the line impedance angle $\theta \approx \frac{\pi}{2}$ and the electrical frequency is 60 Hz, the wave speed can be defined as:

$$v = \sqrt{\frac{377}{2h |z|}} \quad (3.9)$$

3.3 Distributed Damping Control Design For Large Power Networks

In this section, we design a distributed LQR damping control based on the work presented in [10]. The distributed control agent for each generator receives the full state information

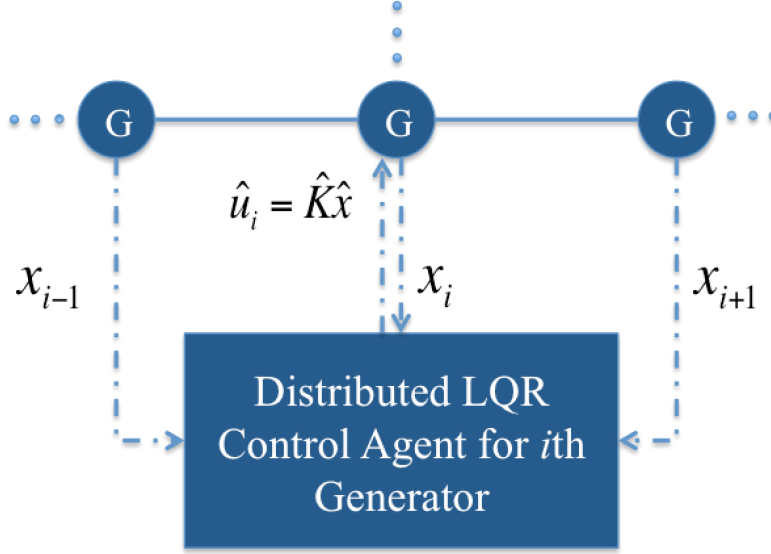


Figure 3.1: Information exchange between a distributed control agent on a generator with its two neighbors. Two generators are considered neighbors if there is a communication link between them.

of that generator and its neighbors. Figure 3.1 shows the information exchange between a distributed control agent on a generator with its two neighbors. Two generators are considered neighbors if there is a communication link between them. The controller output is the damping signal that goes to the Automatic Voltage Regulator (AVR). Here, it is assumed that the graph of physical layer and communication layer coincide.

3.3.1 Power System Model with Distributed LQR Control

We initially use the detailed, nonlinear, standard Differential Algebraic Equation (DAE) model to describe the power system electromechanical behavior. Let $x(t) \in \mathcal{R}^n$ denote a vector that contains the dynamic states of synchronous generators; $y(t) \in \mathcal{R}^q$ denote the system algebraic states, including bus voltage magnitudes and angles; and $u(t) \in \mathcal{R}^m$ denote the control action. Then, power system electromechanical behavior can be described by a set of DAEs of the form:

$$\dot{x}(t) = f(x(t), y(t), u(t)) \quad (3.10a)$$

$$0 = g(x(t), y(t), u(t)) \quad (3.10b)$$

Here, the dynamic equation (3.10a) accounts for the electromechanical dynamics of the synchronous generators and their excitation control. The algebraic equation (3.10b) accounts for load flow and generator stator equations. The control action $u(t)$ can represent the input to generator excitation, governor or power electronic devices. Each generator is modeled using third-order flux-decay model along with its excitation:

$$\begin{aligned}
\frac{d}{dt}w_i(t) &= \frac{\pi f_s}{H_i}(P_{m_i} - P_{e_i} - P_{D_i}) \\
\frac{d}{dt}\delta_i(t) &= w_i(t) - w_s(t) \\
\frac{d}{dt}E'_{q_i}(t) &= \frac{1}{T'_{d0_i}}[E_{fd_i}(t) - E'_{q_i}(t) - (X_{d_i} - X'_{d_i})I_{d_i}(t)] \\
\frac{d}{dt}E_{fd_i}(t) &= \frac{1}{T_{A_i}}[-E_{fd_i}(t) + K_{A_i}(V_{ref_i} - E_{t_i}(t) + V_{DLQR_i}(t))]
\end{aligned} \tag{3.11}$$

In (3.11), $V_{DLQR_i}(t)$ is the supplementary damping control signal designed by the proposed distributed controller. Next we linearize system (3.10) at a stationary operating point and derive the linear state-space model:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.12}$$

where $A \in \mathcal{R}^{n \times n}$ and $B \in \mathcal{R}^{n \times m}$. This linearized full model of the system is used to design the centralized controller. The detailed model (3.12) of a large power network is of large scale. Practically, a large-scale system may have a huge number of states, inputs and outputs, and classical optimal centralized control design algorithms usually cannot handle such a design problem. For the distributed control design described in the next section, only the linearized model of each generator is needed.

3.3.2 Distributed LQR Control Design

We consider a set of N identical generators, described by the linear continuous-time time-invariant state-space model as below

$$\begin{aligned}\dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) \\ x_i(0) &= x_{i0}\end{aligned}\tag{3.13}$$

where $x_i(t) \in \mathcal{R}^n$ and $u_i(t) \in \mathcal{R}^m$ are states and inputs of the i th generator at time t , respectively. The interested reader is referred to [81] for detailed calculations of the state-space models for single and multi-machine cases. Let $\hat{x}(t) \in \mathcal{R}^{Nn}$ and $\hat{u}(t) \in \mathcal{R}^{Nm}$ be the vectors which collect the states and inputs of the N generators at time t , then

$$\begin{aligned}\dot{\hat{x}}(t) &= \hat{A}\hat{x}(t) + \hat{B}\hat{u}(t) \\ \hat{x}(0) &= \hat{x}_0 \triangleq [x_{10}, \dots, x_{N0}]'\end{aligned}\tag{3.14}$$

with

$$\hat{A} = \begin{bmatrix} A_1 & 0 & \cdots & 0 \\ 0 & A_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & A_N \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} B_1 & 0 & \cdots & 0 \\ 0 & B_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & B_N \end{bmatrix}$$

We use a graph to represent the coupling in the communication and the control objective.

A graph $\mathcal{G}$ is defined as:

$$\mathcal{G} = (\mathcal{V}, \mathcal{A})\tag{3.15}$$

where $\mathcal{V}$ is the set of nodes (or vertices) $\mathcal{V} = \{1, \dots, N\}$ and $\mathcal{A} \subseteq \mathcal{V} \times \mathcal{V}$ the set of edges (i, j) with $i \in \mathcal{V}, j \in \mathcal{V}$. The degree d_j of a graph vertex j is the number of edges which start from j . Let $d_{max}(\mathcal{G})$ denote the maximum vertex degree of the graph $\mathcal{G}$. The continuum test system in our study has a finite mesh grid interconnection as depicted in fig. The maximum vertex degree of such an interconnection graph is four, as the nodes located at the corners

of the rectangular grid have two neighbors, those along the edges of the rectangle have three neighbors and the ones in the middle have four each. We associate the i th generator with the i th node of the graph $\mathcal{G}(\mathcal{V}, \mathcal{A})$. If an edge (i, j) connecting the i th and j th node is present, then the controller at i th generator has full state information about the states of the j th generator. To represent the communication network the class of $\mathcal{K}_{n,m}^N(\mathcal{G})$ is defined as:

$$\begin{aligned} \mathcal{K}_{n,m}^N(\mathcal{G}) &= \{M \in \mathcal{R}^{nN \times mN} | M_{ij} = 0 \text{ if } (i, j) \notin \mathcal{A}, \\ M_{ij} &= M[(i-1)n : in, (j-1)m : jm], i, j = 1, \dots, N\} \end{aligned} \quad (3.16)$$

where $M[i : j, k : l]$ denotes a matrix of dimension $(j - i + 1) \times (l - k + 1)$ obtained by extracting rows i to j and columns k to l from the matrix M . The distributed LQR optimal control problem is then defined as follows [10]:

$$\begin{aligned} \min_{\hat{K}} \hat{J}(\hat{u}, \hat{x}_0) &= \int_0^\infty (\hat{x}(\tau)' \hat{Q} \hat{x}(\tau) + \hat{u}(\tau)' \hat{R} \hat{u}(\tau)) d(\tau) \\ \text{subject to} & \\ \text{dynamics:} & \quad \dot{\hat{x}}(t) = \hat{A} \hat{x}(t) + \hat{B} \hat{u}(t) \\ \text{feedback control:} & \quad \hat{u}(t) = \hat{K} \hat{x}(t) \\ \text{stability:} & \quad \hat{A} + \hat{B} \hat{K} \text{ is Hurwitz} \\ \text{communication:} & \quad \hat{K} \in \mathcal{K}_{n,m}^N(\mathcal{G}) \\ \text{initial condition:} & \quad \hat{x}(0) = \hat{x}_0 \end{aligned} \quad (3.17)$$

with $\hat{Q} \geq 0$ and $\hat{R} > 0$. Weighting matrices $\hat{Q}$ and $\hat{R}$ have a special structure and can be decomposed into N^2 blocks of dimension $n \times n$ and $m \times m$, respectively

$$\hat{Q} = \begin{bmatrix} Q_{11} & Q_{12} & \cdots & Q_{1N} \\ Q_{21} & Q_{22} & \cdots & Q_{2N} \\ \vdots & \ddots & \ddots & \vdots \\ Q_{N1} & Q_{N2} & \cdots & Q_{NN} \end{bmatrix}, \quad \hat{R} = \begin{bmatrix} R & 0 & \cdots & 0 \\ 0 & R & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & R \end{bmatrix} \quad (3.18)$$

where

$$\begin{aligned} Q_{ii} &= Q_1 & \forall i = 1, \dots, N \\ Q_{ij} &= Q_2 & \forall i = 1, \dots, N, \quad i \neq j. \end{aligned}$$

We also refer to problem (3.17) with full state-space model of the system (3.12) and without communication constraint as a centralized optimal control problem. In general, computing the solution to (3.17) is an NP-hard problem. We proposed a framework based on the method in [10] to design the distributed suboptimal controller for the special case of homogenous two-dimensional mesh grid.

Let $\mathcal{A}(\mathcal{G})$ denote the adjacency matrix of the graph $\mathcal{G}$. Assuming $\mathbf{A}_{ij} \in \mathcal{R}$ be its i, j element, then $\mathbf{A}_{ii} = 0, \forall i = 1, \dots, N$, $\mathbf{A}_{ij} = 0$ if $(i, j) \notin \mathcal{A}$ and $\mathbf{A}_{ij} = 1$ if $(i, j) \in \mathcal{A}, \forall i = 1, \dots, N, i \neq j$. The focus of this chapter is on undirected graphs, for which adjacency matrix $\mathcal{A}(\mathcal{G})$ is symmetric. The Laplacian matrix of a graph $\mathcal{G}$ is defined in the following way:

$$L(\mathcal{G}) = \mathbf{D}(\mathcal{G}) - \mathbf{A}(\mathcal{G}) \quad (3.19)$$

where $\mathbf{D}(\mathcal{G})$ is the diagonal matrix of vertex degrees d_i . For undirected graphs, $L(\mathcal{G})$ is a symmetric, positive semi-definite matrix, which only has real eigenvalues. Define $N_L = d_{\max}(\mathcal{G}) + 1$ and let $M \in \mathcal{R}^{N \times N}$ be a symmetric matrix with the following property:

$$\lambda_i(M) > \frac{N_L}{2}, \forall \lambda_i(M) \in \mathcal{S}(M) \setminus \{0\} \quad (3.20)$$

then the feedback controller can be calculated as:

$$\hat{K} = -I_N \otimes R^{-1}B'P + M \otimes R^{-1}B'\tilde{P}_2 \quad (3.21)$$

where P is the symmetric positive definite solution of the ARE associated with a single node local problem:

$$A'P + PA - PBR^{-1}B'P + Q_1 = 0 \quad (3.22)$$

and $\tilde{P}_2$ is the solution of the ARE below:

$$(A - XP)' \tilde{P}_2 + \tilde{P}_2(A - XP) + (N_L) \tilde{P}_2 X \tilde{P}_2 - Q_2 = 0 \quad (3.23)$$

where matrix X is defined as $X = BR^{-1}B'$.

Let $0 = \lambda_1(\mathcal{G}) < \lambda_2(\mathcal{G}) < \dots < \lambda_N(\mathcal{G})$ be the eigenvalues of the Laplacian $L(\mathcal{G})$. We choose M in (3.21) as:

$$M = aL(\mathcal{G}) \quad (3.24)$$

if

$$a > \frac{N_L}{2\lambda_2(\mathcal{G})} \quad (3.25)$$

which leads to distributed suboptimal controller solution. The distributed controller for the grid of N interconnected generators on a mesh grid, has the same structure as the underlying graph and considering homogeneity, the controller will have the following structure:

$$\hat{K} = I_N \otimes K_{ii} + \mathbf{A} \otimes K_{ij} \quad (3.26)$$

where I_N denotes the identity matrix of dimension N and $\mathbf{A}$ denotes the adjacency matrix of the interconnection of the generators. K_{ii} is the block diagonal element representing each generators local control and K_{ij} represents the interconnection gains.

3.4 Evaluation of The Proposed Distributed Controller

In this section, the design and implementation of the proposed distributed controller is presented using a test system from [36]. The distributed controller performance is then compared with local and centralized control designs. Simulation results demonstrate the effectiveness of the proposed controller in mitigating oscillation propagations in large power

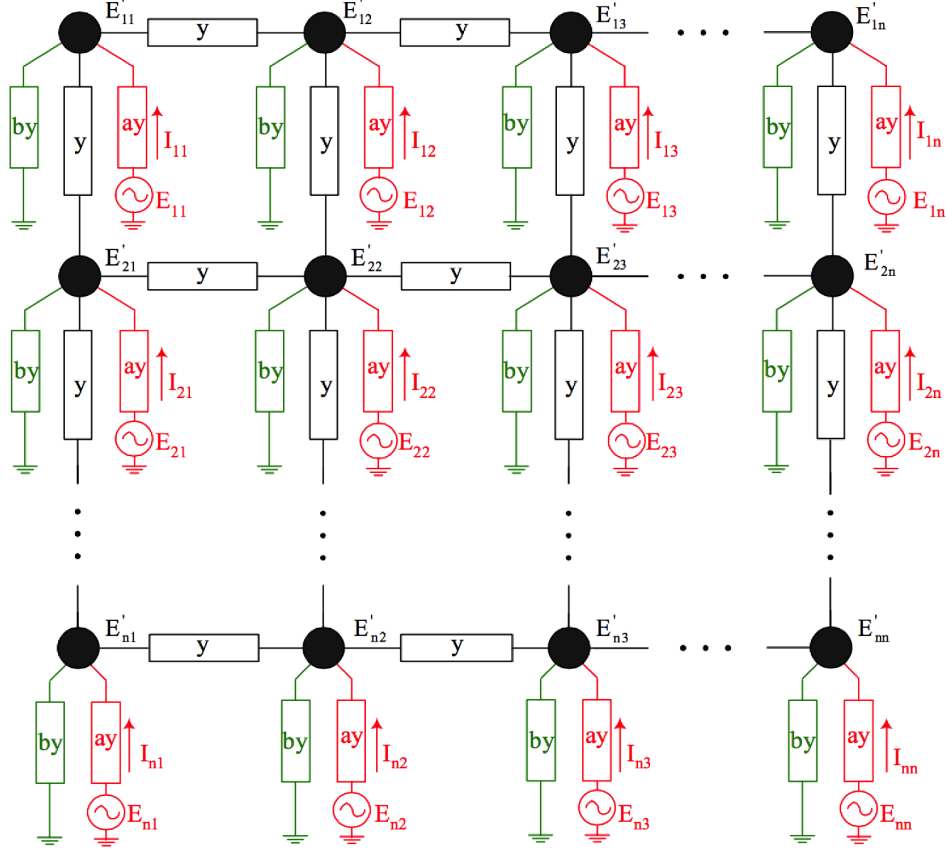


Figure 3.2: General structure of the two-dimensional mesh grid test system from [36].

networks and indicates a trade-off between communication and computation cost and controller performance.

3.4.1 Test System Overview

In order to evaluate the performance of the proposed distributed LQR damping controller, a 30x30 two-dimensional mesh grid system is considered as the study system in this section. Figure 3.2 shows the general structure of the test system. The system under study consists of 900 generator buses and a shunt load connected to each bus. The generators are modeled using detailed third-order flux-decay model with excitation. All loads are modeled as constant impedance loads. The system parameters are kept homogeneous throughout the network. While this test system loses some of its ability to accurately model the detailed behavior of the power system because of the parameters homogeneity assumption, the global behavior of the system which is the subject of our study remains preserved. Furthermore,

Table 3.1: Synchronous Machine Parameters

Parameters		Parameters	
H	2.5 s	K_D	0.01
X_d	0.146 pu	T_A	0.02 s
X_q	0.0608 pu	K_A	200
X'_d	0.0608 pu	E_{fdmin}	-5
T'_{d0}	10 s	E_{fdmax}	5

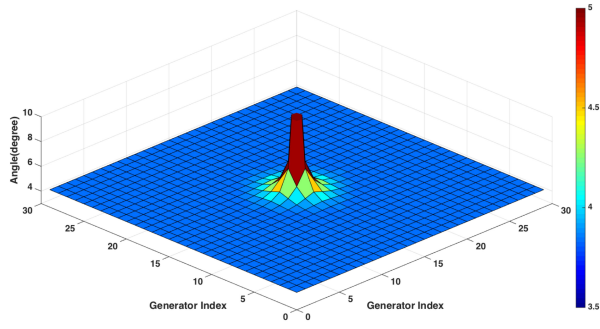
Table 3.2: Network Parameters

Network Parameters	
Transmission Line Reactance in pu	$0.1j$
Constant Impedance Load in pu	$0.55 + 0.414j$

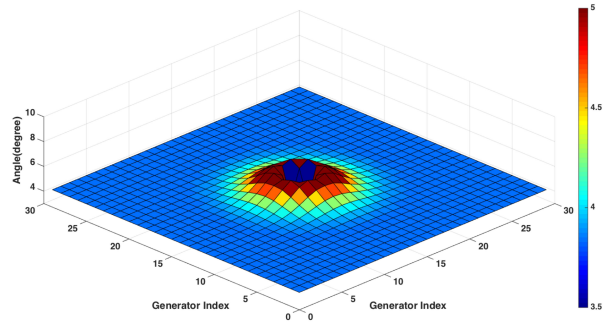
the electromechanical wave propagation behavior observed in actual power systems is readily recognized from this test system [74]. Test system machine and network parameters are illustrated in Table 3.1 and Table 3.2. For simulation of dynamic behavior, the disturbance scenario considered is a step change of mechanical power input by 1 p.u. for the generator at the center of the mesh grid for duration of 0.5 s.

3.4.2 Simulation Results

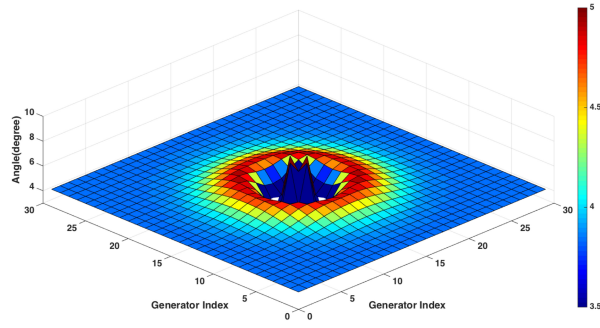
The nonlinear time domain simulation of the power network is carried out using MATLAB. Figure 3.3 shows a sequence of time snapshots of the open-loop generators rotor angle responses. The uncontrolled open-loop test system is unstable and the disturbance initially started at the center of the mesh structure, unit (15,15), propagates through the whole system. Next, we apply the proposed distributed controller. The design of the controller has been described earlier in section 3.3. Figure 3.4 shows a sequence of time snapshots of the rotor angle responses with distributed controller.



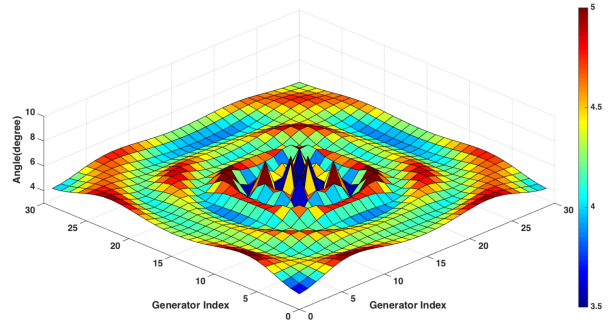
(a) $t = 1 \text{ s}$



(b) $t = 2 \text{ s}$

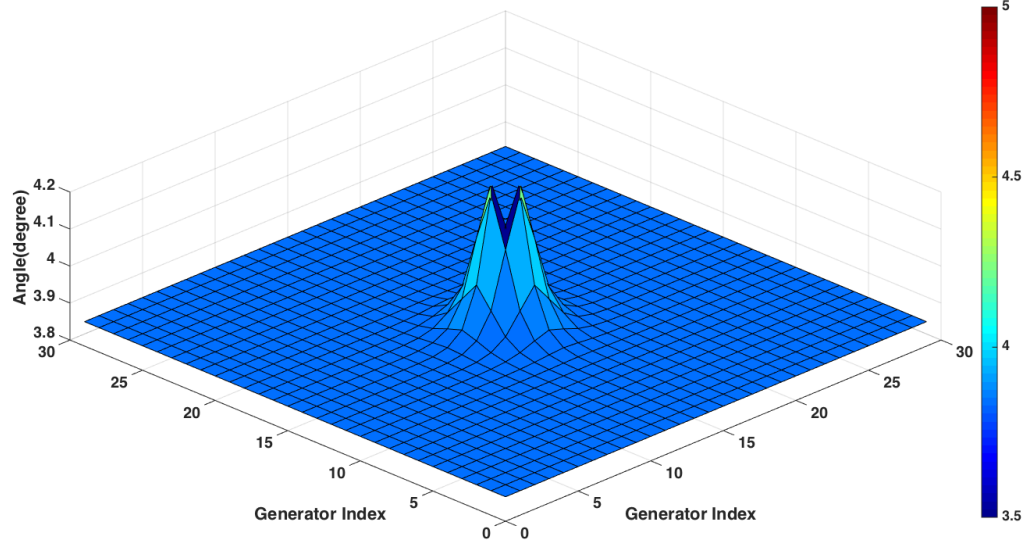


(c) $t = 5 \text{ s}$

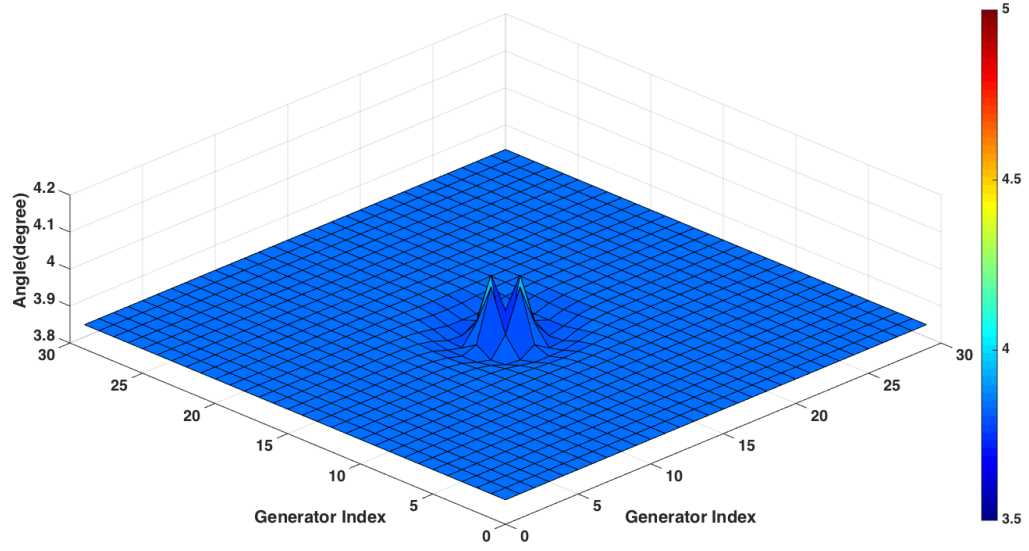


(d) $t = 10 \text{ s}$

Figure 3.3: A sequence of time snapshots of rotor angle responses in a 30x30 grid of generators without controllers.



(a) $t = 1s$



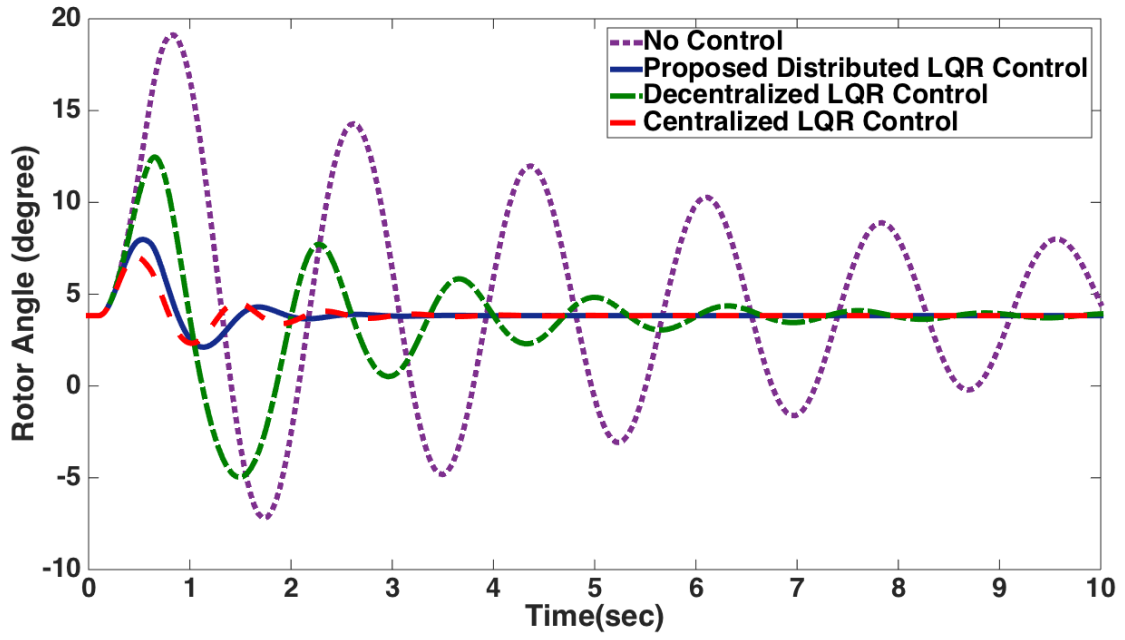
(b) $t = 2s$

Figure 3.4: A sequence of time snapshots of rotor angle responses in a 30x30 grid of generators with proposed distributed LQR controller.

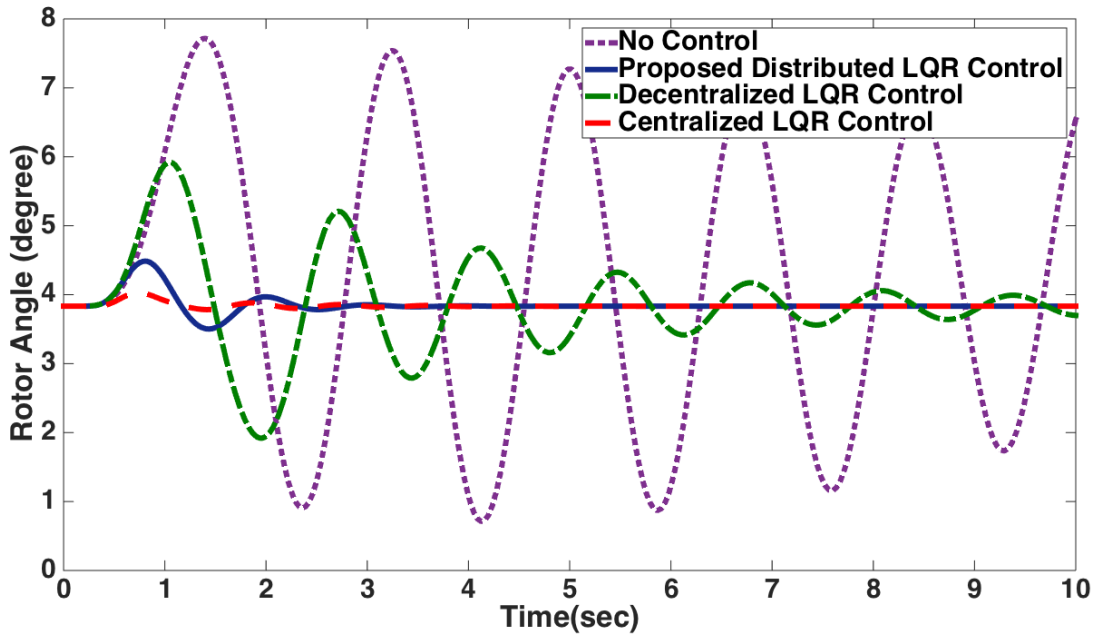
Note that we decreased the upper limits of the Z axis from 10 degrees to 4.2 degrees for the controlled case so that the smaller deviations can be visible. The color bar scaling is remained constant for the sake of comparison. As illustrated in the figure, the distributed controller effectively damps the oscillations and prevents it from propagating and effecting the whole system. Since in the controlled case the oscillation will damp in less than 3 seconds, the time snapshots for after that are not included in the figure. Next, we compare the performance of the proposed distributed controller with local and centralized LQR designs. In each of the designs, R and Q in (3.17) were tuned to provide maximum achievable damping. Figure 3.5 and figure 3.6 illustrate the rotor angle and speed deviation responses for selected generators respectively.

3.5 Concluding Remarks

This chapter presents a distributed control approach to mitigate disturbance propagations in large power networks. The proposed controller provides a supplementary damping through the excitation of the generators. The main advantage of this approach lies in the limited communication and limited model information required for the design which makes it practically applicable for large scale systems. We evaluated the proposed control strategy on a mesh structure test system representing a large power grid, which demonstrated nearly optimal performance. However, implementing distributed type control design on actual power grid will require further studies that use spatially irregular parameters and connections and more realistic test cases. A significant and important challenge is solving the distributed control design problem for arbitrary physical and communication structures.

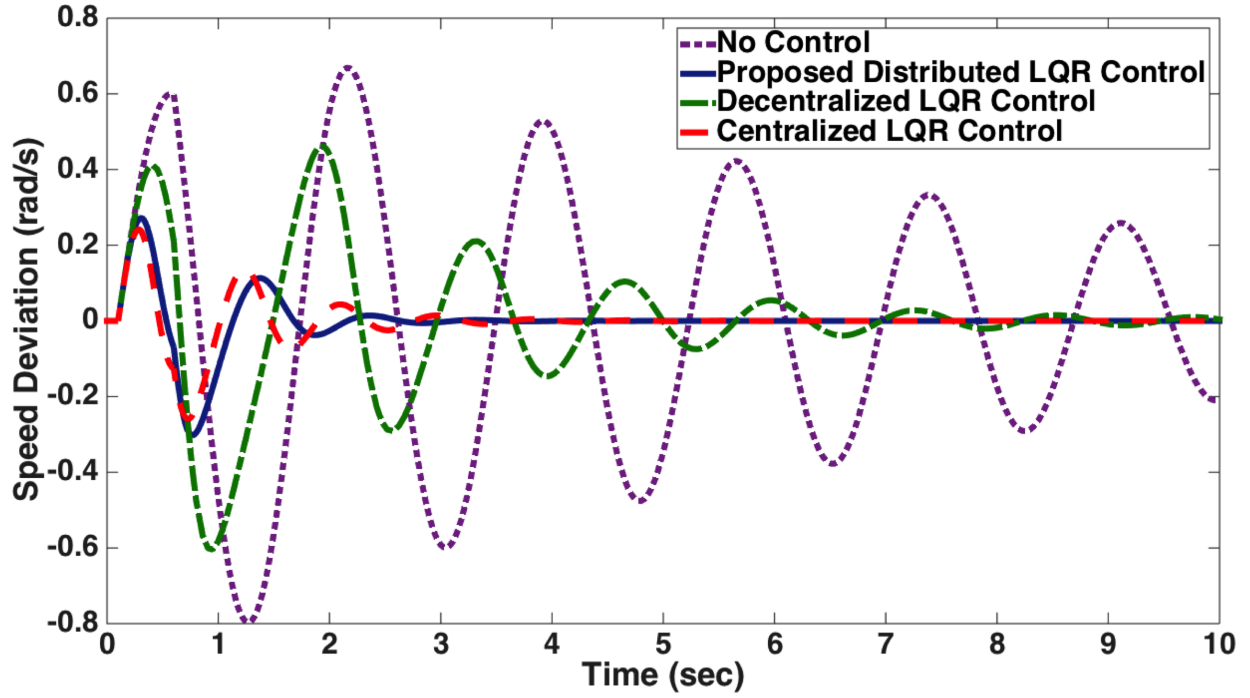


(a) Generator unit located at position (15, 15) in mesh grid

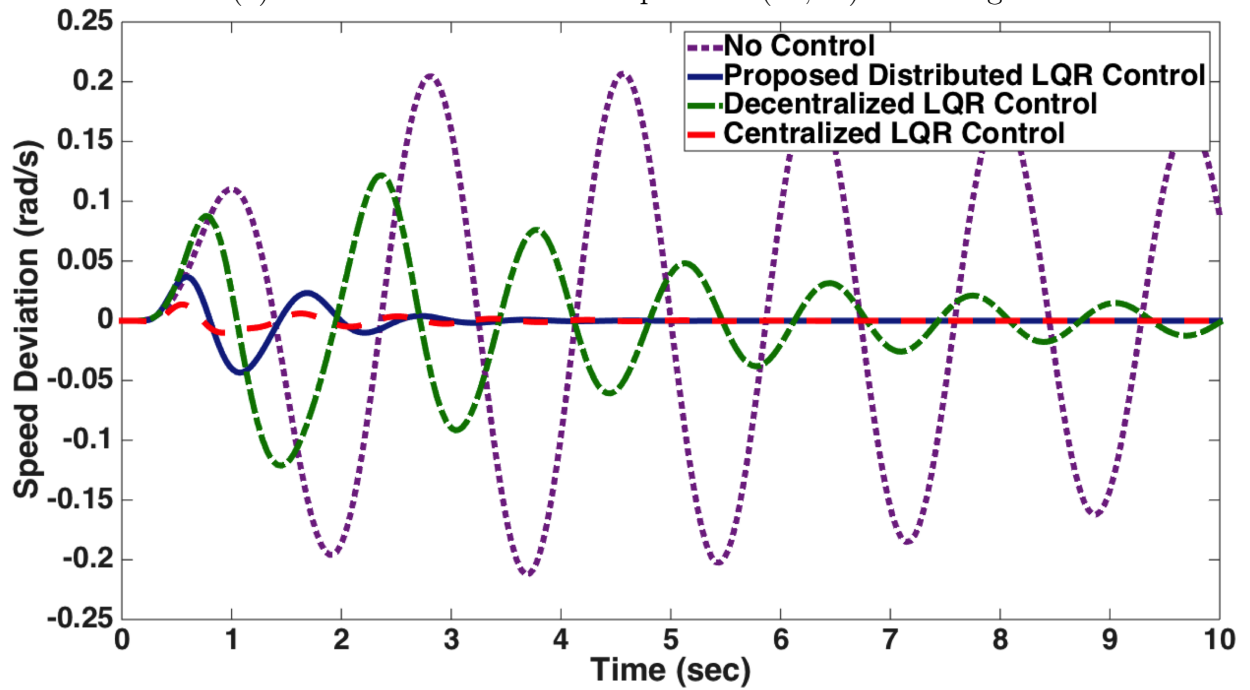


(b) Generator unit located at position (14, 14) in mesh grid

Figure 3.5: Rotor Angles for selected generators with different controllers.



(a) Generator unit located at position (15, 15) in mesh grid



(b) Generator unit located at position (14, 14) in mesh grid

Figure 3.6: Rotor speed deviation for selected generators with different controllers.

Chapter 4

Wide-Area Control Design with Limited Communication

4.1 Introduction

In this chapter, inspired by recent advances in the field of compressive sensing and the sparsity-promoting optimal control design in [24], we propose a distributed linear quadratic optimal control framework using group sparse regularization function. The proposed control aims to optimize a standard cost criterion while penalizing the number of communication links. The group sparse regularization approach is used to induce a desired sparsity pattern and encode prior information about the underlying system into the control design. We then present two applications of the proposed algorithm for damping inter-area modes in power networks:

1. Inducing a desired communication network based on system constraints and
2. Control and communication co-design to find efficient measurement and control signal pairs that improve the damping of inter-area modes.

The proposed optimal control design is then evaluated using the two-area four-machine test system. Our results suggest that the proposed method provides increased flexibility in designing wide-area type controls by allowing for a pre-defined communication structure.

It also can act as an alternative approach to modal analysis methods in finding effective measurement-control loops in the system. The ability to encode system constraints in the control design objective is another major advantage of the method.

The remainder of the chapter is organized as follows. Section 4.2 describes the power system electromechanical model with the proposed distributed control input. The distributed control design algorithm using group sparse regularization functions is presented in Section 4.3. Sections 4.4 and 4.5 illustrate two applications for the proposed method in designing control for damping inter-area modes in power networks. Section 4.6 concludes the chapter.

4.2 Power System Electromechanical Model with Distributed Control Input

To capture the electromechanical oscillations in power systems, we initially use the detailed, nonlinear, standard Differential Algebraic Equation (DAE) model to describe the power system dynamic behavior. Let $x(t) \in \mathbb{R}^n$ denote a vector that contains the dynamic states of synchronous generators; $y(t) \in \mathbb{R}^q$ denote the system algebraic states, including bus voltage magnitudes and angles; and $u(t) \in \mathbb{R}^m$ denote the control action. Then, power system dynamic behavior can be described by a set of DAEs of the form:

$$\dot{x}(t) = f(x(t), y(t), u(t)) \quad (4.1a)$$

$$0 = g(x(t), y(t), u(t)) \quad (4.1b)$$

Here, the dynamic equation (4.1a) accounts for the electromechanical dynamics of the synchronous generators and their excitation control. The algebraic equation (4.1b) accounts for load flow and generator stator equations. The control action $u(t)$ can represent the input to generator excitation, governor, or power electronic devices. Each generator is modeled

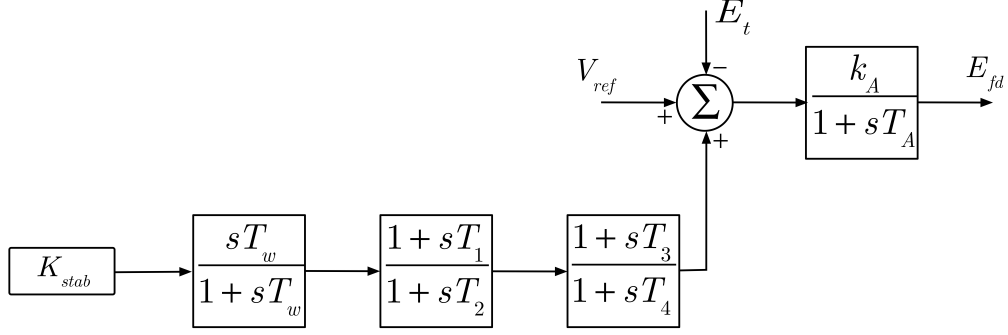


Figure 4.1: Two-stage power system stabilizer model.

using a third-order flux-decay model [81] along with its excitation:

$$\begin{aligned}
\frac{d}{dt}w_i(t) &= \frac{\pi f_s}{H_i}(P_{m_i} - P_{e_i} - P_{D_i}) \\
\frac{d}{dt}\delta_i(t) &= w_i(t) - w_s(t) \\
\frac{d}{dt}E'_{q_i}(t) &= \frac{1}{T'_{d0_i}}[E_{fd_i}(t) - E'_{q_i}(t) - (X_{d_i} - X'_{d_i})I_{d_i}(t)] \\
\frac{d}{dt}E_{fd_i}(t) &= \frac{1}{T_{A_i}}[-E_{fd_i}(t) + K_{A_i}(V_{ref_i} - E_{t_i}(t) + V_{DLQR_i}(t))]
\end{aligned} \tag{4.2}$$

In (4.2), $V_{DLQR_i}(t)$ is the supplementary damping control signal designed by the proposed distributed controller. PSS is modeled as illustrated in figure 4.1. In this chapter, without loss of generality, we assumed that the distributed control design will provide a supplementary signal to the excitation of selected generators. It should be noted, however, that model (4.1) and the proposed control design are sufficiently general to include different control inputs, load models, and renewable generation. Figure 4.2 shows the proposed distributed control agent and its information exchange pattern at k_{th} generator. Next we linearize system (4.1) at a stationary operating point and derive the linear state-space model:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{4.3}$$

where $A \in \mathbb{R}^{n \times n}$ and $B \in \mathbb{R}^{n \times m}$. This linearized full model of the system will be used to design the controller. Practically, a large-scale system may have a large number of states,

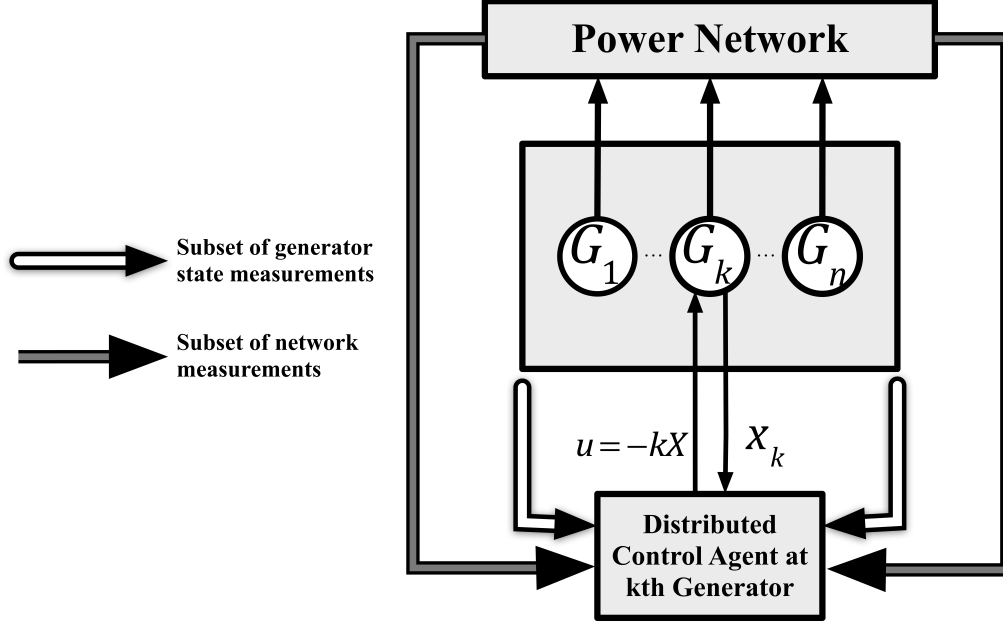


Figure 4.2: Proposed distributed control agent and its information exchange pattern at k_{th} generator.

inputs, and outputs and the detailed model (4.3) of a large power network will be of a large-scale. Thus, one of the challenges for designing wide-area controls for large-scale systems arises from the absence of mathematical models that can capture the electromechanical dynamic couplings in the system [12]. Aggregated and equivalent models have provided a good alternative for wide-area analysis of large-scale power systems since the 1980s [15]. Recently proposed aggregation methods can take advantage of PMU measurements and construct simplified inter-area models of large power systems by using dynamic measurements available from limited points on the transmission lines [13]. System identification techniques can also be used to derive low-order state-space models of a power system [27].

4.3 Distributed Control Design Using Group Sparse Regularization Functions

In modeling and control in networks of dynamical systems, it is crucial to understand the interactions between control network structure and the underlying dynamic properties. Constraints on communication network can limit the control performance. A trade-off exists

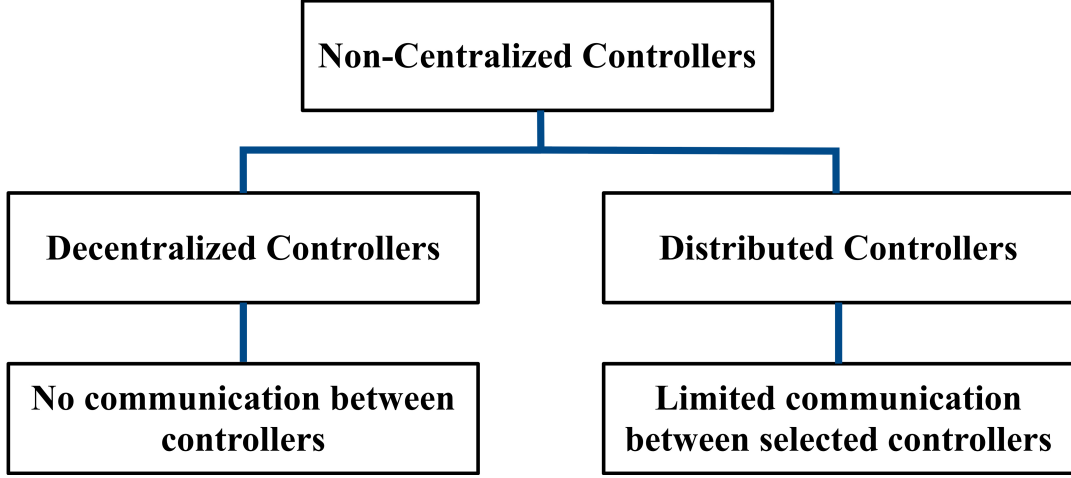


Figure 4.3: Categories of non-centralized controllers.

between the achievable performance and the communication cost. If all controllers can communicate with each other, and decide on the control actions to be applied to each subsystem, the best possible performance is achievable. However, this requires prohibitively excessive communication and computation. On the other hand, in a fully decentralized scenario, every controller acts independently, and applies control actions to its corresponding subsystem solely based on the subsystem's output measurements. Although decentralized control has minimal communication and computation requirement, it may result in poor performance. A desired scenario is the limited exchange of information in a distributed control architecture [58].

Distributed control is a widely used, but not well-defined term. Here, distributed control refers to a control structure where each local control agent can only access a subset of the global information and actuate on a subset of the inputs. Figure 4.3 categorizes non-centralized control structures as they are defined in this chapter. The conventional controller design problem assumes that all the controllers in the system have access to the same information. Thus, the controller design problem is to design a controller K for a plant P such that K stabilizes the plant and meets a certain performance criteria like $\min \|f(P, K)\|$.

A distributed control problem can then be defined generally in the form:

$$\begin{aligned}
& \text{minimize } \|f(P, K)\| \\
& \text{subject to } K \text{ stabilizes } P \\
& K \in S
\end{aligned} \tag{4.4}$$

where S is a subspace. For a general linear time-invariant system P and sub-space S , there is no known tractable algorithm for computing the optimal K . The unique feature that simplifies the conventional control problem is the information pattern. The information pattern represents the information set that each decision maker has access to when it makes the decision and calculates the control input. Since in a distributed control problem the information set for different controllers is different, the problem is difficult to solve. To overcome this design complexity, new approaches have recently been developed that initially design a centralized controller and apply compressed sensing algorithms, [23, 85, 84], to sparsify the control structure while preserving stability [28, 59, 68]. These methods open new possibilities in wide-area control design with limited communication and provide an alternative solution for the major challenge in distributed control design, namely the information pattern constraint. In this chapter, we propose a novel distributed control design for damping inter-area oscillations. The newly developed approach provides the ability to encode prior knowledge about the underlying system into the control design objective using group sparse regularization functions. In power systems, this prior knowledge can be a pre-defined communication structure, measurement availabilities or network variables and dynamic features that can observe or affect the inter-area modes. The grouping approach will greatly expand the application domain of the algorithm and the flexibility of the control design. Details of the proposed method and its applications are described in the following subsection.

4.3.1 Distributed Linear Quadratic Control Design Using Group Sparse Regularization Functions

As discussed in section 4.1, one of the main challenges in designing a practical WADC is selecting the measurements that each controller agent in a distributed architecture needs to have access to. One approach for addressing this issue is the sparsity-promoting linear quadratic control proposed in [59] which simultaneously identifies the optimal control structure and optimizes the closed-loop performance. This method was applied to WADC design in [24]. In [59], to induce a control architecture with limited communication, the standard quadratic performance index was regularized with an ℓ_1 -norm penalty on the feedback matrix. However, use of ℓ_1 -norm regularization encourages sparsity among individual elements of the controller matrix, without considering the potential structural relationships existing in the system. When dealing with a large scale system with a sensor-rich structure and communication constraints, using readily available information or historic data about the system in the control design can greatly enhance the controllers performance, flexibility and practicality. A considerable body of research in the field of compressive sensing has recently been devoted to design regularizations capable of encoding more prior information about the problem in searching for patterns of non-zero elements (e.g., [40]). Inspired by the applications in compressive sensing, we propose a distributed linear quadratic control design using group sparse regularization functions. Group sparse regularizations consider sums of norms of appropriate subsets of measurements, or groups of states, based on the system characteristics. These groupings can influence the sparsity patterns of the resulting control and improve the feedback control performance.

The group-sparse linear quadratic optimal control problem is defined as follows:

$$\begin{aligned}
& \min_K \int_0^\infty (x(\tau)'Qx(\tau) + u(\tau)'Ru(\tau))d(\tau) + \lambda\Omega(K) \\
& \text{subject to} \\
& \text{dynamics:} \quad \dot{x}(t) = Ax(t) + Bu(t) \\
& \text{feedback control:} \quad u(t) = Kx(t) \\
& \text{stability:} \quad A - BK \text{ is Hurwitz} \\
& \text{initial condition:} \quad x(0) = x_0
\end{aligned} \tag{4.5}$$

where, $\lambda \geq 0$ is a regularization parameter and $Q \in \mathbb{R}^{n \times n}$, $R \in \mathbb{R}^{p \times p}$ are positive semi-definite and positive definite matrices that denote the state and control weights, respectively. Ω is a convex, typically non-smooth sparsity-inducing regularization function. The stability condition in (4.5) guarantees that the closed-loop system will be stable [106]. When it is only desired that the solution of optimal control problem have limited number of non-zero elements, Ω is chosen to be ℓ_1 -norm [59]:

$$\Omega(K) \triangleq \sum_{i,j} |K_{i,j}| \tag{4.6}$$

(other norms, such as ℓ_2 and ℓ_∞ can also be used to form different objectives). Regularizing by the ℓ_1 -norm induces sparsity in the sense that, depending on the strength of the regularization parameter, λ , a number of elements in K , will be equal to zero. In the proposed group sparse approach, based on the prior knowledge of the system, we organize the elements of the feedback matrix, K in groups. The objective is then to select or remove all the variables forming a group. A regularization function exploiting this group structure will help in designing controllers which are more flexible to adapt to communication and measurement constraints that we may practically have in the system. The group norm used in our method is the so-called ℓ_1/ℓ_2 -norm:

$$\Omega(K) \triangleq \sum_{g \in \mathcal{G}} \eta_g \|K_g\|_2 \tag{4.7}$$

where $\mathcal{G}$ is a partition of $\{1, \dots, m\}$ and $m = n \times p$ is the total number of elements in K . η_g are strictly positive weights, and K_g denotes the vector in $\mathbb{R}^{|g|}$ recording the coefficients of K indexed by group g in $\mathcal{G}$. As defined in (4.7), Ω is known as a mixed ℓ_1/ℓ_2 -norm. It behaves like an ℓ_1 -norm on the vector $(\|K_g\|_2)_{g \in \mathcal{G}}$ in $\mathbb{R}^{|\mathcal{G}|}$, and therefore, Ω induces group sparsity. In other words, each $\|K_g\|_2$, and equivalently each K_g , is encouraged to be set to zero. On the other hand, within the groups g in $\mathcal{G}$, the ℓ_2 -norm does not promote sparsity.

The proposed group-sparse regularization approach can be used to induce a desired communication structure (e.g., star, ring, hierarchial) or to encode prior information about the underlying system into the control design. In power systems, this prior knowledge can be communication costs and constraints, probability of measurement availabilities, power transfers in critical tie-lines, inertia and damping distributions, and the topology of the system.

The optimization problem (4.5) is difficult in part because of the non-smooth nature of the norm function. To solve the group-sparse optimal control problem, (4.5), we use the Alternating Method of Multipliers (ADMM) [75, 86, 87]. In each iteration of ADMM the required proximal gradient step which induces the group sparsity pattern is solved using SPARSe Modeling Software package (SPAMS) [40, 83]. We incorporated the SPAMS solver into the LQRSP $\tilde{\mathbf{U}}$ (Sparsity-Promoting Linear Quadratic Regulator) toolbox [24], to solve the proposed optimization. Two applications of the proposed method for damping inter-area oscillations in power networks are described in the following sections. Below is a summary of the algorithmic approach for the proposed distributed linear quadratic control design.

Distributed Linear Quadratic Control Design Algorithm Using Group Sparse Regularization Functions

- Step 1. Derive the state-space model of the system (4.3) analytically or by using aggregation or identification methods.
- Step 2. Define grouping structures based on the desired communication network design.
- Step 3. Construct the graphs representing the groups in the system and select their weights based on their grouping objective.

- Step 4. Solve optimal control problem (4.5) with $\lambda = 0$ to obtain the centralized feedback matrix K .
- Step 5. Set the regularization parameter λ based on the application and the desired level of sparsity.
- Step 6. Solve the optimization problem (4.5) using ADMM algorithm implemented in LQRSP toolbox. Enforce grouping structures (4.7) in the proximal gradient step of ADMM using SPAMS software.
- Step 7. Solve the structured optimal control problem based on the final sparsity pattern identified in step 7.

4.4 Application I: Inducing a Desired Communication Structure for Damping Inter-area Oscillations in Power Networks

Based on the report from North American Synchrophasor Initiative (NASPI) the total number of PMUs installed in the North American grid was more than 1100 by year 2014, offering nearly 100 percent observability of the transmission system [17]. PMU measurements are taken at a high speed (30 observations per second) and can be transmitted over a communication network to the control stations. Due to communication limitations and the large scale of the power grid, these sensor measurements cannot instantaneously be available to all the controllers in the system. In practice, each local control agent can only access a subset of the measurements. Limitations on the information exchange pattern in control design in power systems can come from different sources. Control actions being employed by separate utilities, lack of availability of some measurements and privacy considerations are just a few of the reasons. Therefore, it will be highly beneficial if the control design method can consider communication limitations and measurement access constraints and stabilize the system based on a pre-defined communication structure. In the following subsection

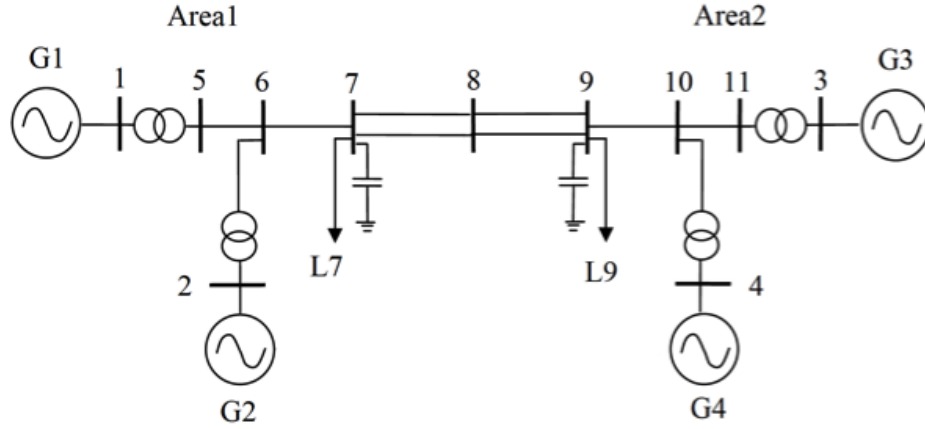


Figure 4.4: Two-Area, Four-Machine Test System [48].

application of our proposed method for inducing a desired communication structure is illustrated on the two-area four-machine test system.

4.4.1 Illustration on the Two-Area Four-Machine System

Consider the two-area four-machine power system in figure 4.4 modeled using (4.2). This test system was created to exhibit different types of oscillations that occur in both large and small interconnected power systems. A detailed description of the system parameters can be found in [48]. We use this test system to validate the performance of the proposed WADC in inducing different pre-defined communication structures and explore the effect of the information patterns on the damping of the inter-area mode. In this configuration, 400 MW of active power exported from area 1 to area 2 causes the transmission lines to be stressed and the inter-area mode to be unstable. All generators are equipped with PSS to provide damping for local and inter-area modes. We modified this test system to create a very low-damped inter-area mode while local modes can be fairly damped using PSS. We doubled the amount of inertia on G_2 and G_4 , setting $H_2 = 13s$ and $H_4 = 12.35s$, to increase the distance between frequencies of the local modes and the inter-area mode. The stabilizer gains of the generators, were decreased to $K_{stab} = [10; 0; 10; 0]$ to allow for lightly damped modes. We linearized this system and derived the linear state-space model representation (4.3). Small signal analysis is then performed to identify system modes and the respective

Table 4.1: Two-area system modes (base-case)

Mode No.	Eigenvalues	Frequency(Hz)	Percentage Damping	Mode Type
1	$-0.0500 \pm 3.1069j$	0.4945	1.61	Inter-area
2	$-0.2574 \pm 6.2966j$	1.0030	4.08	Local
3	$-0.2823 \pm 6.4472j$	1.0271	4.37	Local

mode shapes. Table 4.1 shows the local and the inter-area modes of the system and their frequency and percentage damping. In power networks damping is considered adequate if all electromechanical modes have a damping ratio of around five percent. Damping ratios less than three percent are considered too weakly damped and becomes a cause of concern. Thus, this test system has a too weakly damped inter-area mode that may lead to further instabilities. Our goal is to solve the proposed optimal control problem (4.5) for a pre-defined communication structure using grouping regularization functions. This structure can be defined based on communication cost and constraints in the system. Figure 4.5 shows the communication structures and grouping graphs for centralized, decentralized, local and star communication networks along with the predicted sparsity patterns of their respective feedback matrices.

We use graph representation to show the grouping structures. Each grouping graph contains one white vertex which represents the root of the graph depicted by R and a set of black vertices that represent the generators labeled by the generator number. A desired grouping structure is created by adding a path to the graph which starts from the root and connects the black vertices that are included in that group. The sequence of black vertices in the path can be chosen arbitrarily and will not affect the grouping definitions but it should not create a loop. For example, the grouping graph in figure 4.5 (a) contains only one path, i.e., $(R, 1, 2, 3, 4)$ which indicates that all the generators are grouped together. In other word, in the centralized design all the generators can communicate with each other. The grouping graph in figure 4.5 (b) contains four paths, $(R, 1)$, $(R, 2)$, $(R, 3)$ and $(R, 4)$ which shows that the generators are not allowed to communicate in the decentralized design. In the matrix representation, the 16 divided blocks represent generator gains. The block diagonal elements of the matrix are the generator self-gains, and off-diagonal blocks are correlation

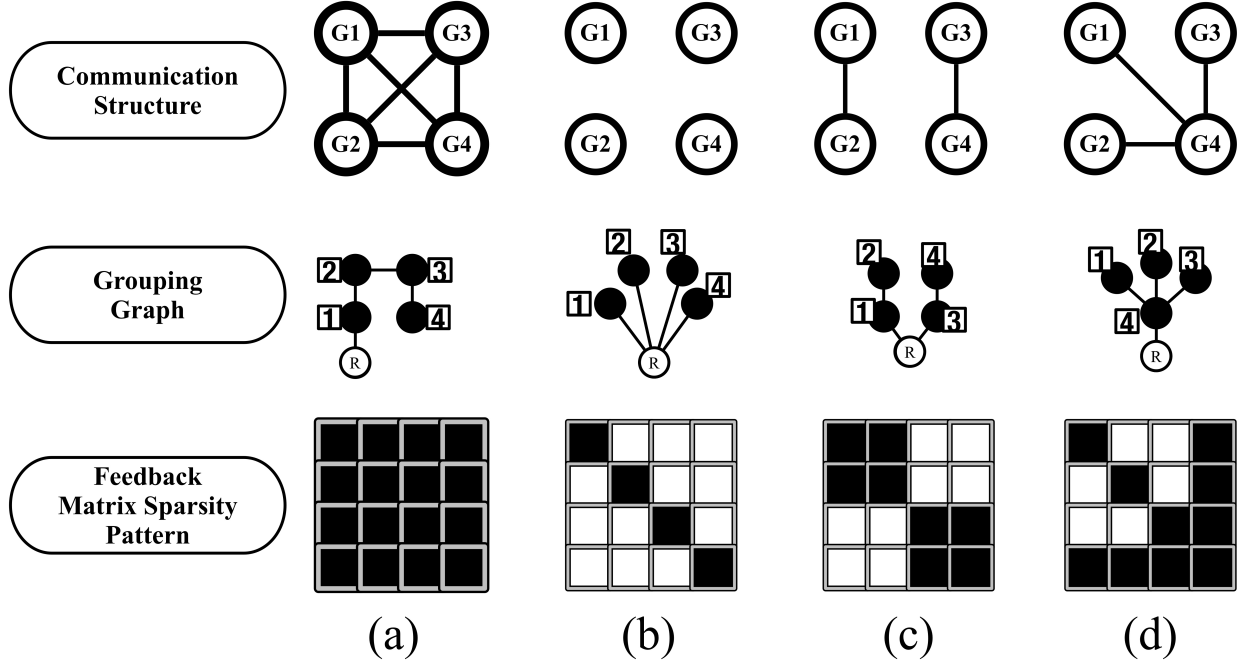


Figure 4.5: Communication structures and grouping graphs for (a) Centralized, (b) Decentralized, (c) Local and (d) Star communication networks and the predicted sparsity pattern of the feedback matrix.

gains between the four generators in the system. Black blocks represent vectors of non-zero elements. Figure 4.5 only shows the groupings between different generators, but it should be noted that all seven states of each generator (*i.e.*, $[\Delta\omega_i, \Delta\delta_i, \Delta E'_{qi}, \Delta E_{fdi}, \Delta V_1, \Delta V_2, \Delta V_s]$) are also treated as a group. The feedback matrix K , is a N by $(N \times n)$ matrix where N is the number of generators and n is the number states for each generator. For the two-area system with four generators modeled with seven states, K is a 4×28 matrix. The blue dots represent the non-zero elements of the matrix. Below each matrix, the total number of the non-zero elements is indicated by nz . As illustrated in figure 4.6 (a), for the centralized case where all the generators are allowed to communicate the resulting feedback control matrix is a full matrix.

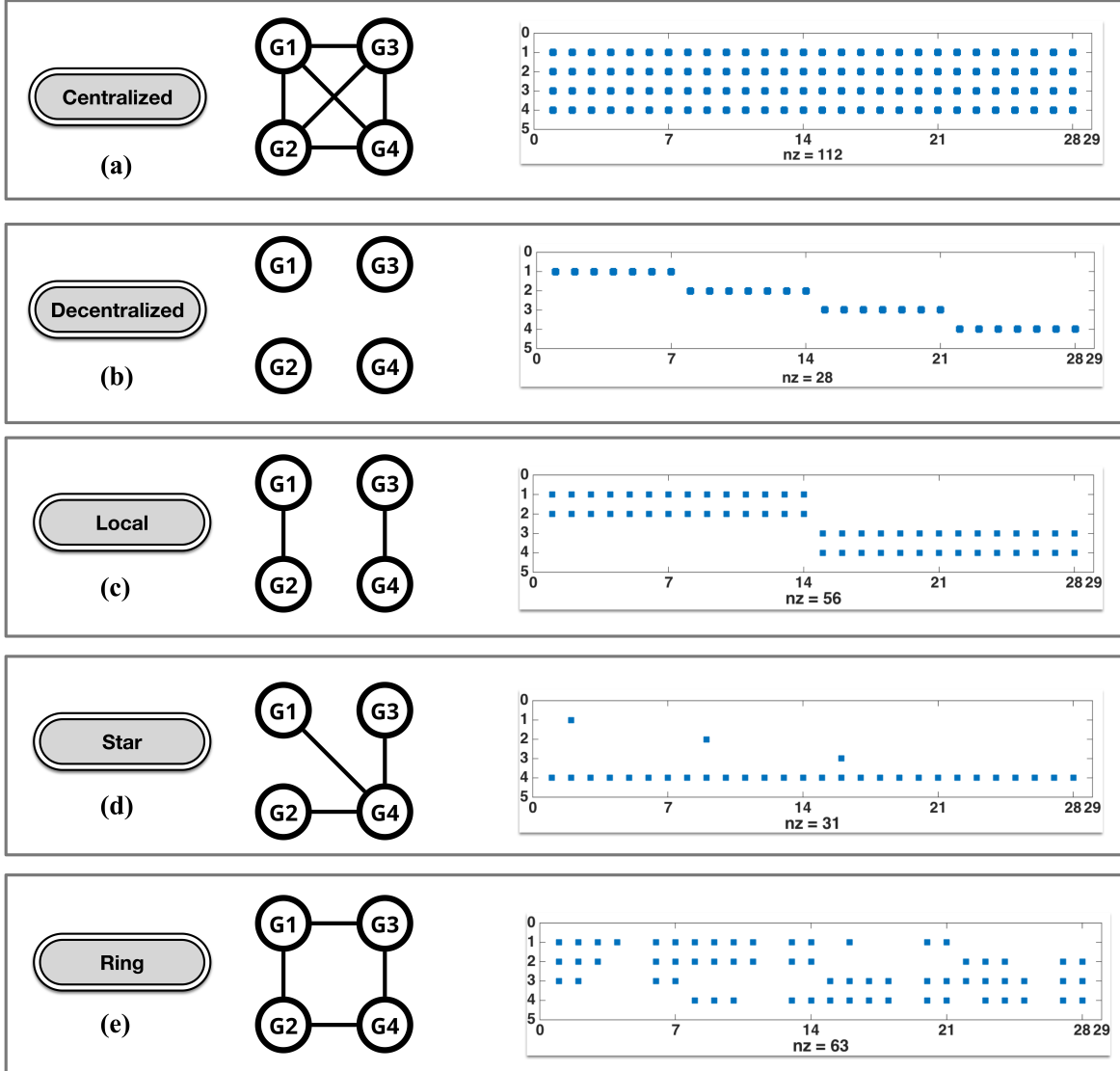
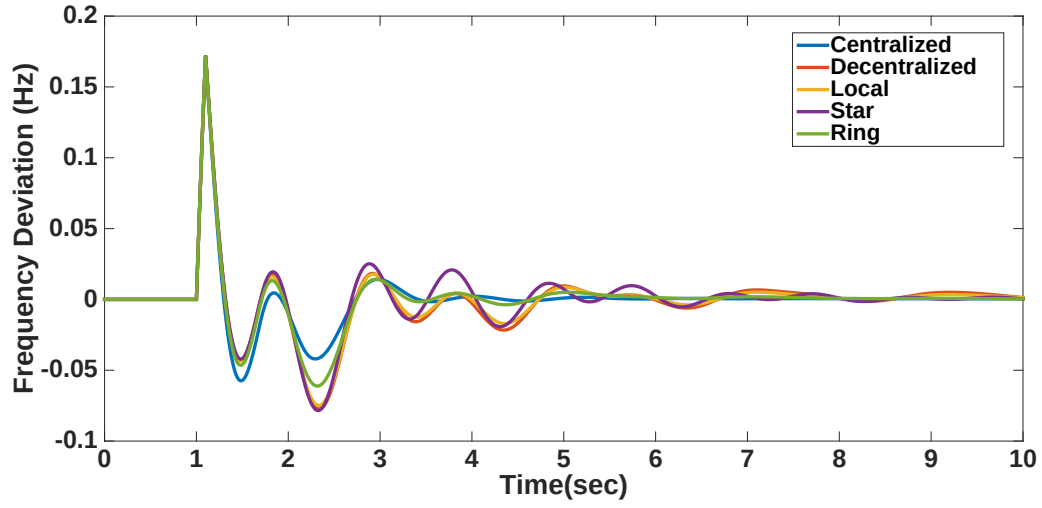


Figure 4.6: Communication structures and their respective designed feedback control matrix sparsity patterns (a) Centralized, (b) Decentralized, (c) Local, (d) Star and (e) Ring.

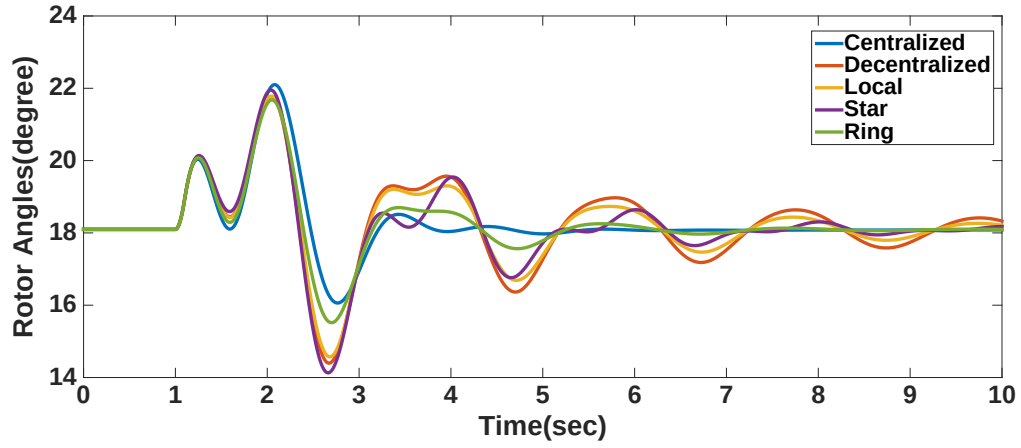
Table 4.2: Inter-area modes for different communication structures

Case	Inter-area Mode	Frequency (Hz)	Percentage Damping
Base Case	$-0.0500 \pm j3.1069$	0.4945	1.61
Centralized	$-0.4603 \pm j3.0790$	0.4900	14.78
Decentralized	$-0.1322 \pm j3.1299$	0.4981	4.22
Local	$-0.1429 \pm j3.1383$	0.4994	4.54
Star	$-0.2202 \pm j3.1300$	0.4981	7.01
Ring	$-0.3755 \pm j3.1478$	0.5009	11.84

In figure 4.6 (b), i.e., the decentralized case, there is no communication between the generators; thus, the resulting control matrix has the block diagonal pattern with nz exactly equal to 28 non-zero elements which shows that each generator only uses its own state information for the control purpose. Table 4.2 compares the inter-area modes for different communication structures. In this test system, the ring structure has the next best damping after the optimal centralized case which was predictable due to the high level of information exchanged between the controllers. For simulation of the dynamic behavior, the disturbance scenario considered is a three phase fault at bus 8 at time $t = 1s$ that is cleared after six cycles. The nonlinear time domain simulation of the power network is carried out using MATLAB. Figure 4.7 shows frequency deviations and rotor angles for G_1 for the five communication structures. The nonlinear simulation also confirms the results obtained in linear analysis. Here, we provided examples of design and implementation of the distributed control with pre-defined communication structures to show the effectiveness of the proposed algorithm. However, it should be noted that our objective is not to find the best performing controller. The performance of these controllers cannot be compared while they have different amount of data communicated and different levels of optimality. Here, the proposed method provides a framework to find the controllers that best fit communication costs and constraints.



(a)



(b)

Figure 4.7: Nonlinear simulation results for different control structures: (a) Frequency deviation (Hz) and (b) Rotor Angles (degree)

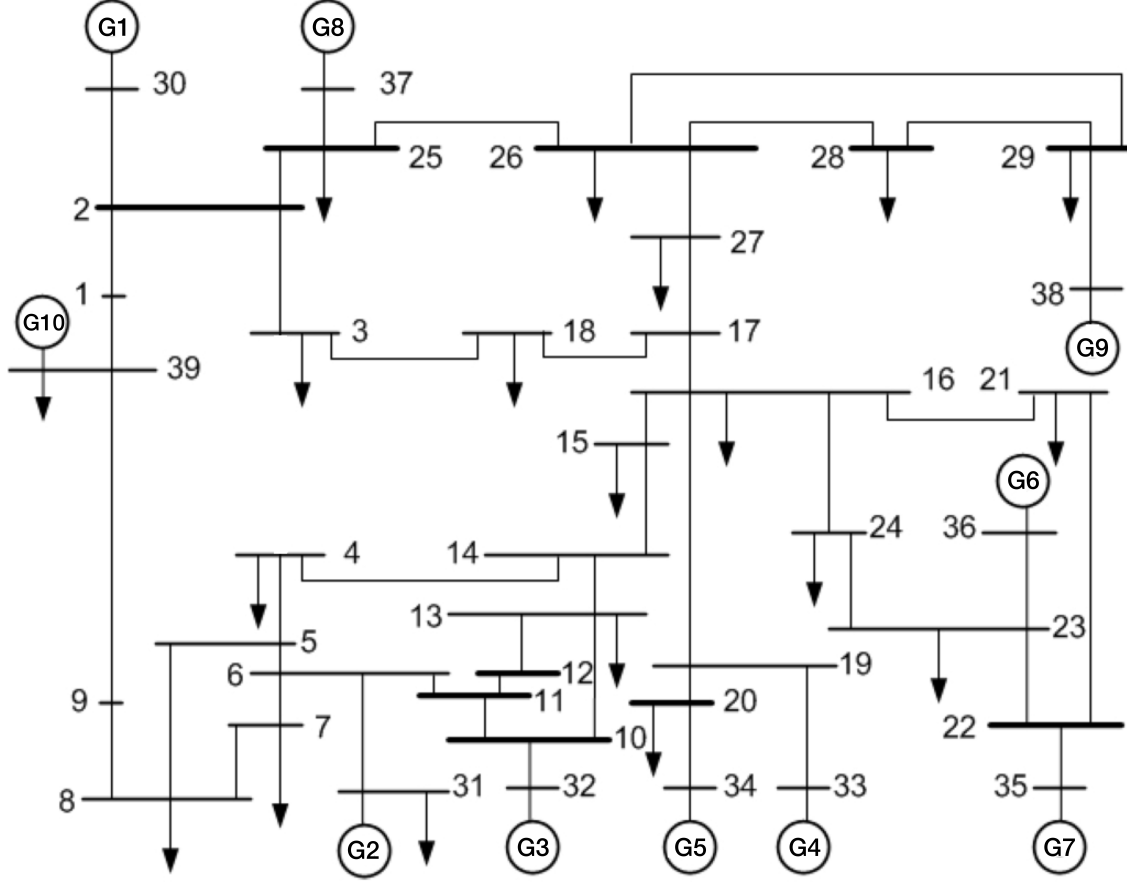


Figure 4.8: Modified New England 39-bus 10-machine System

4.4.2 New England 39-bus 10-machine System

In this section, we use the New England 39-bus 10-machine test system displayed in figure 4.8 to further investigate the performance of the proposed WADC in inducing different pre-defined communication structures and explore the effect of the information patterns on the damping of the inter-area modes. In this test system, all synchronous machines except G_{10} , which is an equivalent unit, are equipped with conventional PSS. We modified this test system to create low-damped inter-area modes while local modes can be fairly damped. Detailed descriptions of the models and parameters for generators, excitation systems and PSSs can be found in Appendix. We linearized this system and derived the linear state-space model representation (4.3). Small signal analysis is then performed to identify system modes and the respective mode shapes. Table 4.3 shows the inter-area modes of the system and their frequency and percentage damping. Mode 3 and 4 have damping

Table 4.3: New England system inter-area modes (base-case)

Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping	Coherent Groups
Mode 1	$-0.29 \pm j 6.42$	1.02	4.55	2, 3 vs. 4, 5
Mode 2	$-0.16 \pm j 5.24$	0.83	3.20	1, 8, 9, 10 vs. 2, 3, 4, 5, 6, 7
Mode 3	$-0.12 \pm j 4.63$	0.73	2.76	9, 10 vs. all others
Mode 4	$-0.07 \pm j 3.54$	0.56	2.22	10 vs. all others

ratios less than three percent and are considered too weakly damped. Figure 4.9 shows the mode shapes of the inter-area modes. Coherent groups of generators for each inter-area mode are also displayed in Table 4.3. We solved the proposed optimal control problem (4.5) for pre-defined communication structures displayed in figure 4.10 using grouping regularization functions and compared the controller damping performances with the centralized scheme. Having group structures, the proposed optimal control problem (4.5) is then solved for the different information patterns. Figure 4.6 shows the communication structures and their resulting feedback control matrix patterns. To make the controllers comparable in terms of the control effort, for each communication structure, the weighting matrix $\mathcal{R}$ in (4.5) is tuned to maintain the control cost, $u(\tau)'u(\tau)$, within two percent of the control cost for the centralized design. A fully decentralized LQR solution that improves the damping performances of inter-area modes for this system cannot be found. The local design which is defined based on geographical proximity, also needs to use twice the control effort required for other structures to show signs of improvement in the damping performances.

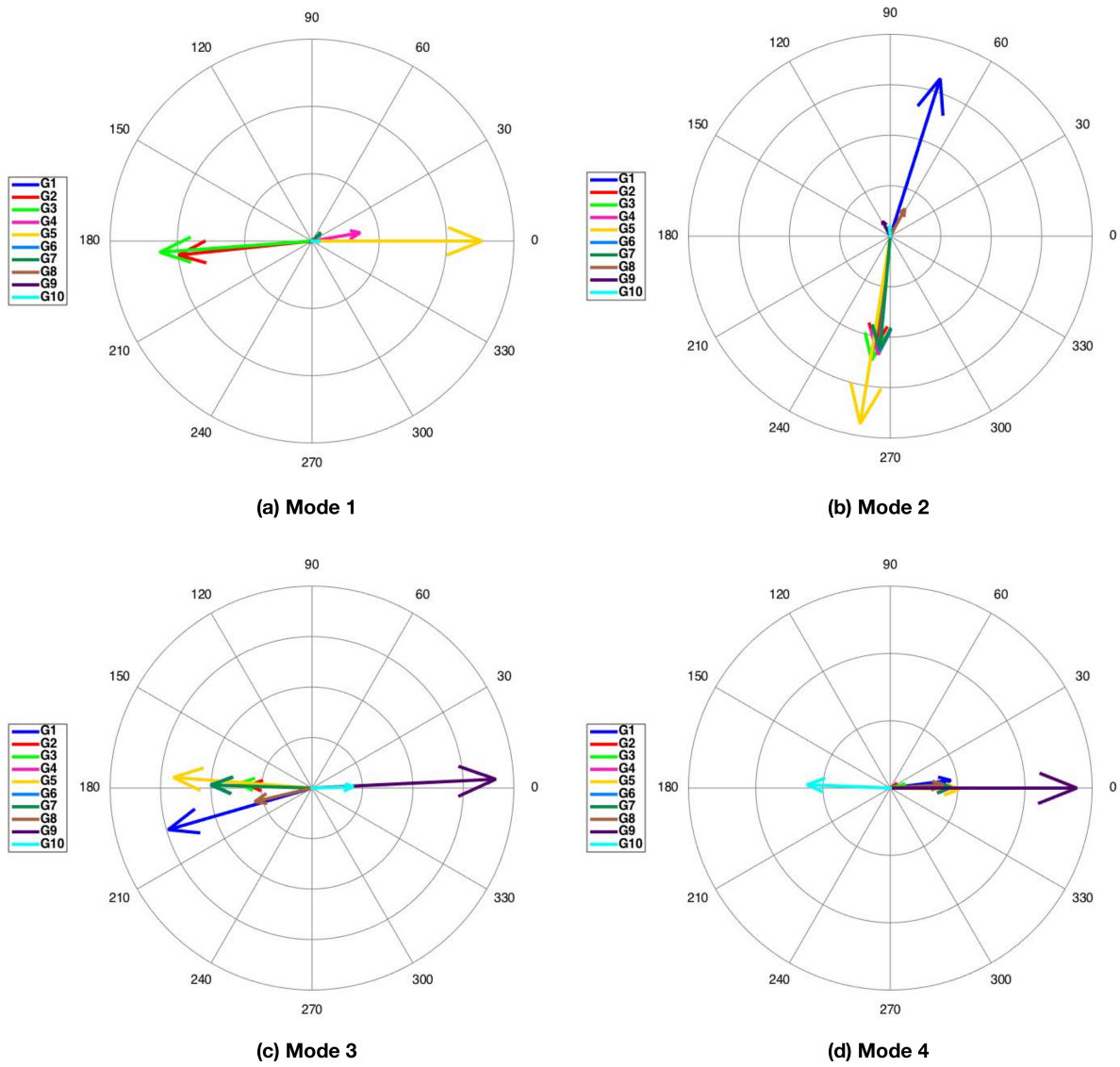


Figure 4.9: New England System inter-area mode shapes

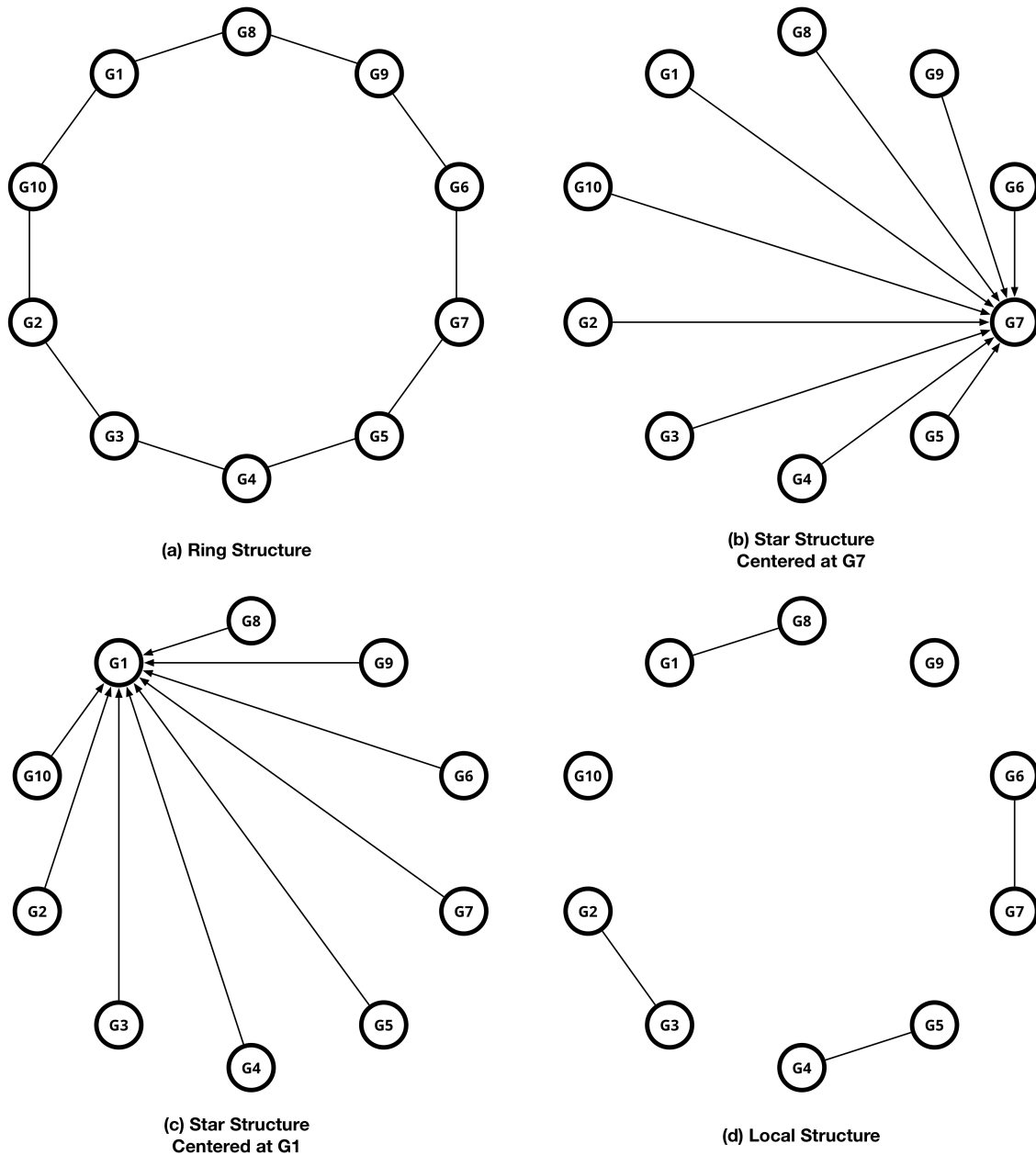


Figure 4.10: Pre-defined communication structures for New England System

Table 4.4: New England system inter-area modes percentage damping for different communication structures

Communication Structures	Inter-area Mode Percentage Damping			
	Mode 1	Mode 2	Mode 3	Mode 4
Centralized	11.85	8.21	7.96	6.57
Ring	10.25	7.58	6.59	5.60
Star Centered at G7	10.42	7.85	7.72	6.30
Star Centered at G1	6.00	4.28	3.91	3.20
Local (double control cost)	5.43	3.83	3.73	2.73
Base Case	4.55	3.20	2.76	2.22

Figure 4.11 shows the resulting feedback control matrix sparsity patterns for each communication structure. Table 4.4 compares the percentage damping of the inter-area modes for different communication structures.

In this system, among all implemented communication structures, only Ring and Star Centered at G7 can provide the sufficient damping for all the inter-area modes. In the star structure, since all control burden is on one controller, the controllability of that generator of the modes will directly affect the performance of the controller. Figure 4.12 shows the collective controllability of the generators of all local and inter-area modes in the New England test system.

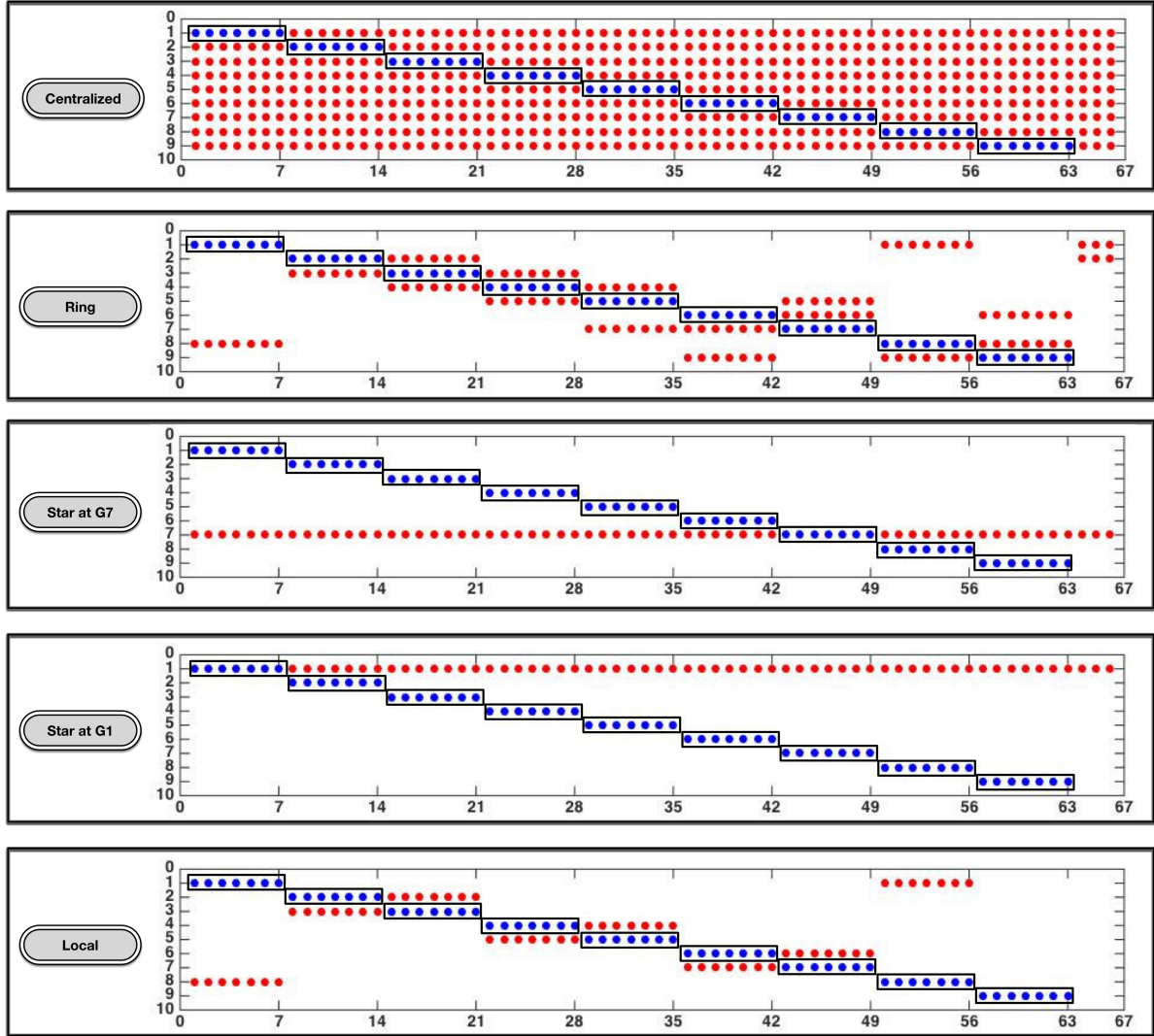


Figure 4.11: Feedback matrix sparsity patterns for different communication structures

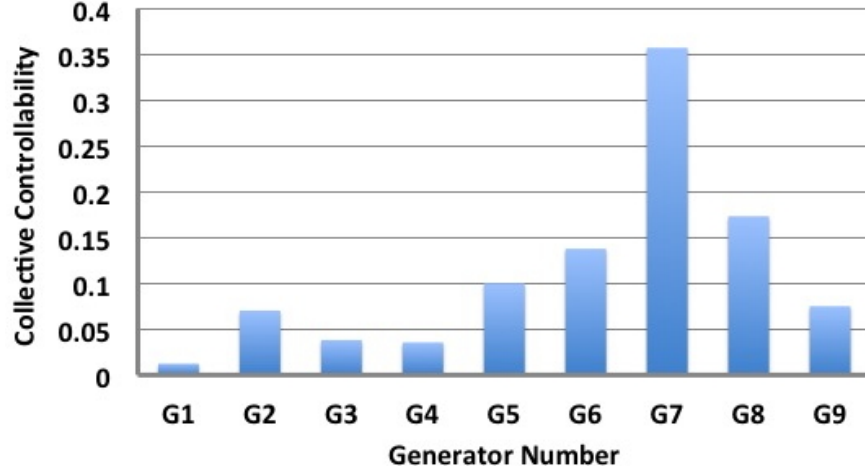


Figure 4.12: Collective controllability of the generators of all local and inter-area modes in New England system

Table 4.5: Centralized Structure

Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping
Mode 1	$-0.76 \pm j 6.41$	1.02	11.85
Mode 2	$-0.42 \pm j 5.15$	0.82	8.21
Mode 3	$-0.37 \pm j 4.68$	0.74	7.96
Mode 4	$-0.23 \pm j 3.52$	0.56	6.57

As displayed, G_7 has the highest controllability while G_1 has the lowest, which is consistent with the results of the proposed control design. In the Tables 4.5, 4.6, 4.7, 4.8, and 4.9 the detailed data for inter-area modes for each structure are presented.

For simulation of the dynamic behavior, the disturbance scenario considered is a three phase fault at bus 15 at time $t = 1s$ that is cleared after three cycles. The nonlinear time domain simulation of the power network is carried out using MATLAB. Figure 4.13 shows frequency deviations and rotor angles for G_2 for the five communication structures. The nonlinear simulation also confirms the results obtained in linear analysis.

Table 4.6: Ring Structure

Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping
Mode 1	$-0.67 \pm j \ 6.57$	1.05	10.25
Mode 2	$-0.39 \pm j \ 5.23$	0.83	7.58
Mode 3	$-0.31 \pm j \ 4.72$	0.75	6.59
Mode 4	$-0.20 \pm j \ 3.56$	0.56	5.60

Table 4.7: Star Structure at G_1

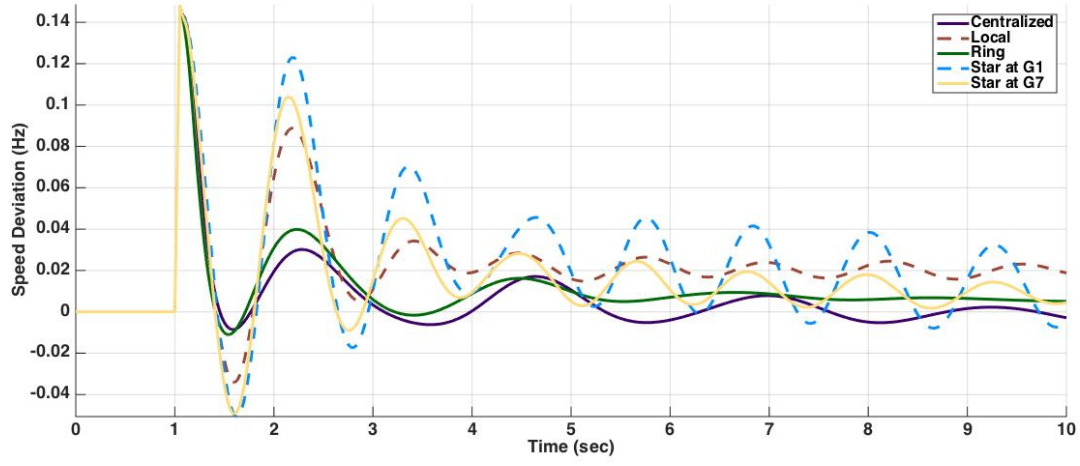
Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping
Mode 1	$-0.38 \pm j \ 6.45$	1.02	6.00
Mode 2	$-0.22 \pm j \ 5.24$	0.83	4.28
Mode 3	$-0.18 \pm j \ 4.65$	0.74	3.91
Mode 4	$-0.11 \pm j \ 3.54$	0.56	3.20

Table 4.8: Star Structure at G_7

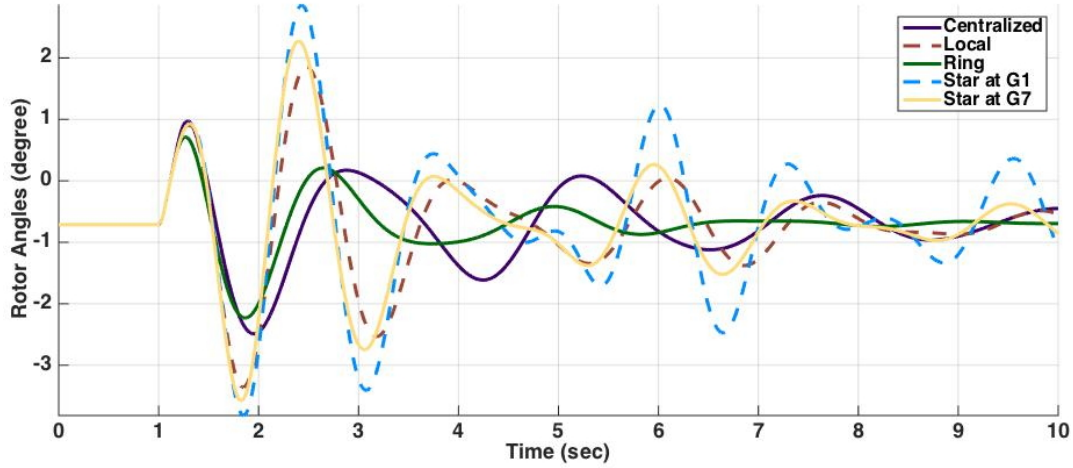
Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping
Mode 1	$-0.68 \pm j \ 6.56$	1.05	10.42
Mode 2	$-0.41 \pm j \ 5.21$	0.83	7.85
Mode 3	$-0.36 \pm j \ 4.71$	0.75	7.72
Mode 4	$-0.22 \pm j \ 3.54$	0.56	6.3

Table 4.9: Local Structure

Inter-area Modes	Eigenvalues	Frequency (Hz)	Percentage Damping
Mode 1	$-0.35 \pm j \ 6.44$	1.02	5.43
Mode 2	$-0.20 \pm j \ 5.24$	0.83	3.83
Mode 3	$-0.15 \pm j \ 4.64$	0.73	3.73
Mode 4	$-0.09 \pm j \ 3.54$	0.56	2.73



(a)



(b)

Figure 4.13: Nonlinear simulation results for different control structures: (a) Frequency deviation (Hz) and (b) Rotor Angles (degree)

4.5 Application II: Control And Communication Co-Design For Damping Inter-area Oscillations In Power Networks

As discussed in section 4.1 several studies confirm that using remote measurements can improve damping of the inter-area modes beyond that obtainable by local signals. The main challenge is then finding a few pairs of measurements and control inputs among all the options that can achieve an effective inter-area oscillation damping. The choice of measurements and control input signals are typically based on modal analysis and frequency response information. Geometric measures and residues are two methods that have been used in power system studies to quantify the observability and controllability of the modes in the system [104]. Geometric measures are proven to be more accurate compared with residues in predicting the contribution of the k_{th} mode of the system in output measurements and the mode's sensitivity to input perturbations [34]. An alternative approach is to use the proposed distributed control design to find the few measurements that when communicated can improve the damping for inter-area modes. For this purpose, the regularization parameter, λ is increased gradually from zero to one to reach a desired level of sparsity in the feedback control matrix. Since some of the generator states are practically difficult to measure, the grouping feature of the algorithm provides the benefit to choose from the available sets of measurements by setting more weights, i.e. higher η_g , on those groups.

4.5.1 Two-Area Four-Machine System

To illustrate the effectiveness of the proposed method we compared two scenarios on the two-area four-machine test system introduced in section 4.5.1 and compared the results with geometric measure approach. In the first scenario, we solved the group-sparse linear quadratic optimal control problem (4.5) for the base case and gradually increased λ from zero to obtain a sparse feedback matrix with one communication link. In grouping the states between different generators equal higher weights were selected for the set of $[\Delta\delta_i, \Delta\omega_i]$ measurements, to emphasize the availability of these measurements compared with other

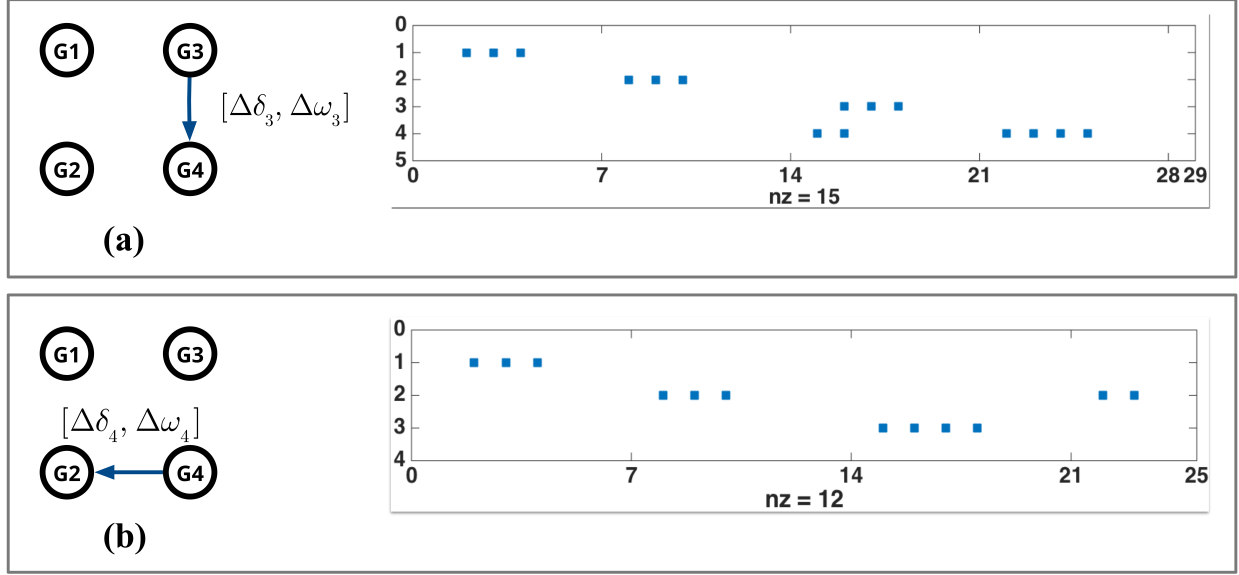


Figure 4.14: Communication structures and respective feedback control sparsity patterns for (a) Scenario 1, (b) Scenario 2.

states. Figure 4.14 (a) shows the resulting communication structure and respective feedback control sparsity pattern. This result suggests measurements $[\Delta\delta_3, \Delta\omega_3]$ and the excitation control input G_4 as the effective measurement-control pair to improve the damping of the inter-area mode. Then the geometric measures for this scenario were calculated. Here we briefly explain the geometric measures and their formulations. The interested reader is referred to [31] for the detailed explanation.

Consider the state-space model of the system described as (4.3). Eigenanalysis of matrix A provides the n distinct eigenvalues $(\lambda_i, i = 1, \dots, n)$ and the corresponding matrices of right and left eigenvectors, $\Phi = [\Phi_1, \dots, \Phi_n]$ and $\Psi = [\Psi_1, \dots, \Psi_n]$, respectively. The geometric measures of controllability m_{ci} and observability m_{oi} associated with mode i are defined as follows:

$$m_{ci}(k) = \cos(\alpha(\Psi_i, b_k)) = \frac{|b_k^T \Psi_i|}{\|\Psi_i\| \|b_k\|} \quad (4.8)$$

$$m_{oi}(l) = \cos(\alpha(c_l, \Phi_i)) = \frac{|c_l \Phi_i|}{\|\Phi_i\| \|c_l\|} \quad (4.9)$$

where b_k is the k_{th} column of input matrix B (referring to the k_{th} input) and c_l is the l_{th} row of output matrix C (referring to the l_{th} output). $|z|$ and $\|z\|$ are defined as the modulus and Euclidean norm of z which sets m_{ci} and m_{oi} between 0 and 1. $\alpha(\Psi_i, b_k)$ is the

geometrical angle between the input vector b_k and the i_{th} left eigenvector, while $\alpha(c_l, \Phi_i)$ is the geometrical angle between the output vector c_l and the i_{th} right eigenvector. Using (8) and (9), the joint controllability/observability measure is defined as :

$$m_{coi}(k, l) = m_{ci}(k).m_{oi}(l) \quad (4.10)$$

It is feasible to control the mode i with the input u_k and the measured value y_l , if $m_{coi}(k)$ is different from zero. Pairs of u_k and y_l with the maximum m_{coi} will be the most efficient choice. Figure 4.15 (a)-(c) shows the observability, controllability, and joint controllability/observability measures of speed deviations and excitation control inputs of inter-area mode for the four generators in the first scenario. Based on the calculated geometric measures the inter-area mode is best controllable and best observable from G_4 . This will result in a decentralized measurement-control loop. However, if we search for a remote measurement, based on the joint controllability/observability measure, $\Delta\omega_3$ and excitation control of G_4 are the second most efficient control loop. Analysis of the geometric measures of rotor angles will also produce the same result. Thus, the control loop suggested by our distributed control design algorithm is compatible with the traditional modal analysis.

In the second scenario, to evaluate the controller ability in finding efficient wide-area control loops we modified the test system. The inertia constant of G_4 is tripled and G_4 is considered as an equivalent area without a definitive point of control. Then we solved the group-sparse linear quadratic optimal control problem (4.5) and gradually increased λ to obtain a sparse feedback matrix with one communication link. Choice of groups and their weights is similar to scenario 1. Figure 4.14 (b) shows the resulting communication structure and respective feedback control sparsity pattern. This result suggests measurements $[\Delta\delta_4, \Delta\omega_4]$ and the excitation control input G_2 as the effective measurement-control pair to improve the damping of the inter-area mode. Then the geometric measures for this scenario were calculated. Figure 4.15 (d)-(f) shows the observability, controllability, and joint controllability/observability measures of speed deviations and excitation control inputs of inter-area mode for the four generators in the second scenario.

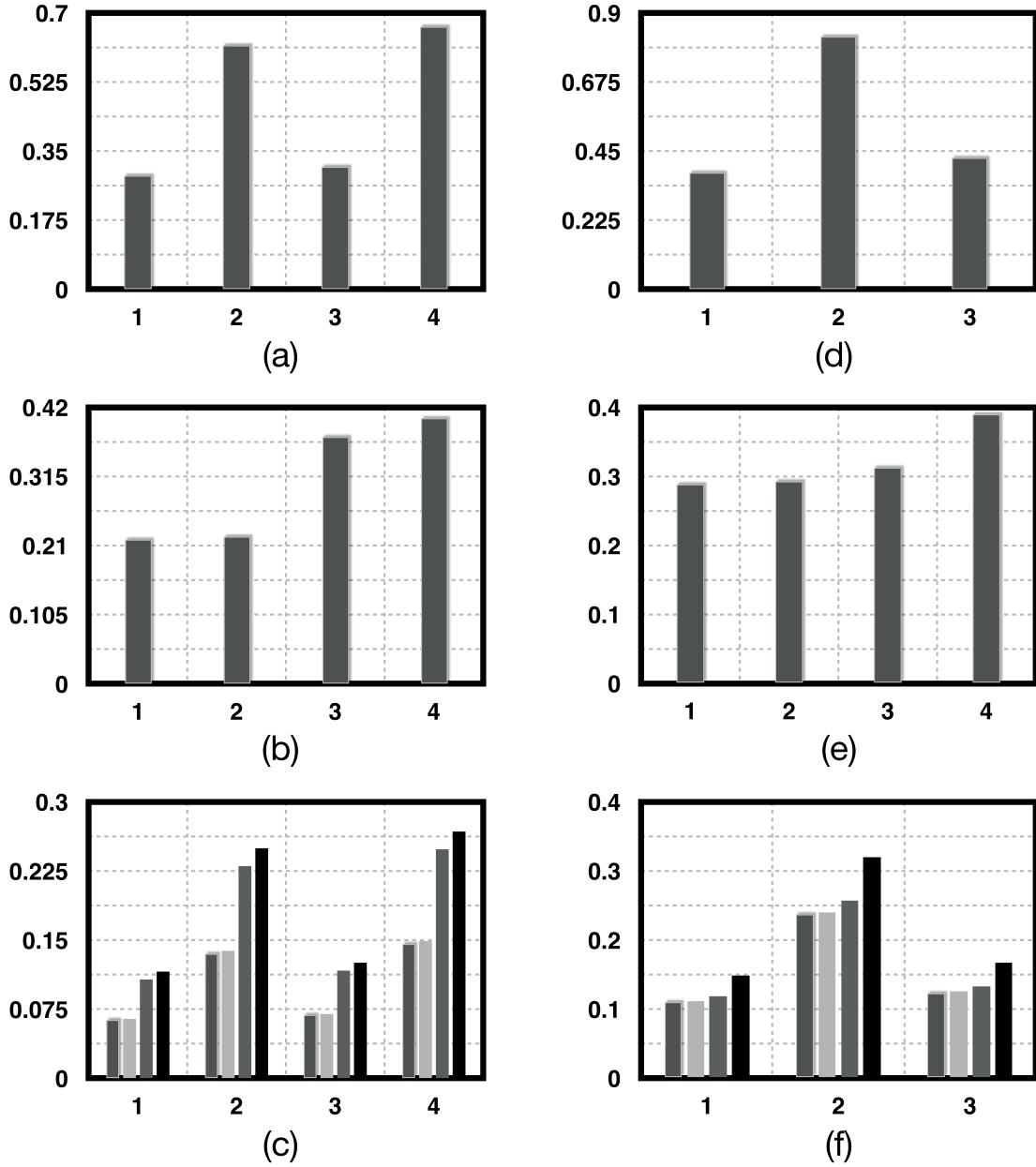


Figure 4.15: Geometric measure of speed deviation measurements and excitation control inputs for inter-area mode for two scenarios in two-area four-machine test systems, Scenario1: (a) Controllability measure, (b) Observability measure, (c) Joint controllability/observability measure, Scenario 2: (d) Controllability measure, (e) Observability measure, (f) Joint controllability/observability measure.

By removing the control on G_4 the inter-area mode has the best controllability from G_2 and best observability from $\Delta\omega_4$. Therefore, the results from the proposed framework are again compatible with the traditional modal analysis. The proposed distributed control design not only considers the communication costs but also eliminates the need to perform additional modal analysis computations for finding best measurement-control pairs for a given system. This will result in a decentralized measurement-control loop. However, if we search for a remote measurement, based on the joint controllability/observability measure, $\Delta\omega_3$ and excitation control of G_4 are the second most efficient control loop. Analysis of the geometric measures of rotor angles will also produce the same result. Thus, the control loop suggested by our distributed control design algorithm is compatible with the traditional modal analysis.

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The results for the two scenarios on two-area four-machine system shows that the proposed algorithm can successfully find the efficient measurement-control loops and has the

potential to be considered as an alternative approach to traditional modal analysis methods for this purpose. Our experience with this method on larger test systems with multiple low-damped or unstable inter-area modes reveals the presence of another important factor in the design which is the interaction between different control loops that may adversely affect each other. In that case, the objective function and group structures should be chosen based on the desired performance that might require damping a particular mode or increasing the overall damping in the system. The interaction measure introduced in [34] provides a good criteria for validating the results.

4.6 Conclusion

This chapter addressed one of the main stability problems in power systems and proposed a new control scheme considering the cyber-physical aspects of the grid. Low-damped inter-area oscillations are one of the major causes of stability concerns in power systems. To improve the damping of these low-frequency oscillations, a novel wide-area control scheme has been presented in this chapter. The proposed distributed optimal control framework optimizes a standard performance criterion while limiting the amount of required communication. The newly developed approach provides the ability to encode prior knowledge about the underlying system into the control design objective using group sparse regularization functions. In power systems, this prior knowledge can be a pre-defined communication structure, measurement availabilities or network variables and dynamic features that can observe or affect the inter-area modes. The grouping approach will greatly expand the application domain of the algorithm and the flexibility of the control design. Two applications of the proposed framework have been introduced and evaluated in this chapter. First, the grouping objective was used to select a communication structure based on system constraints. Second, a control and communication co-design problem was solved to find efficient measurement and control signal pairs to improve the damping of inter-area modes. For this application, groups were defined based on measurement availabilities. Our results suggest that the proposed method opens new possibilities in designing wide-area type controls by including knowledge of the system constraints and characteristics into the design

objective. It can also act as an alternative approach to modal analysis methods in finding effective measurement-control loops in the system. Further investigations can explore the robustness of the designed controller to communication failures.

Chapter 5

Power System Model Validation and Enhancements: Current Industry Practice in Western Interconnection

5.1 Introduction

Models are the foundation for all analysis in power systems. Any inaccuracy present in the models used for planning and operation can significantly impact the outcomes of these studies and lead to inefficient decisions. In particular, model accuracy is critical for real-time stability assessment tools which aim to enhance operators situational awareness and ability to take prompt, effective actions. To improve the models to more accurately replicate system events, the North American Reliability Corporation (NERC) recommended model validation and benchmarking following August 14, 2003, blackout [5]. Model validation has significantly improved the models in Western Electricity Coordinating Council (WECC) during the past decade. However, the power grid is evolving toward a larger, more complex and geographically distributed network [64] with uncertain generation and loads and power system models are increasingly viewed as inadequate for representing real-time operating conditions [67]. Therefore, ensuring consistency between real-time and off-line models is essential for real-time applications like the dynamic assessment of voltage stability and

transient stability limits [45]. Using real-time limits instead of the seasonal limits can improve systems reliability and enhance transmission capacity restricted by conservative limits.

As the Reliability Coordinator (RC) in the Western Interconnection, Peak Reliability needs to address stability risks in real-time to achieve the appropriate level of Bulk Electric System (BES) reliability at the least cost. In addition, following considerations highlight the need for making real-time stability assessments:

- Increased stability risks due to remotely connected generation and load centers in Western Interconnection
- Interconnection-wide impact of Remedial Action Schemes (RAS)
- Growth in renewable generation and the associated integration challenges

Peak has implemented a real-time Transient Stability Assessment Tool (TSAT) to calculate stability limits and operating margins for pre-defined scenarios. The real-time VSA computes voltage stability limits and operating margins in real-time and alarms the operator if the current system state approaches the limit. The real-time TSAT is currently undergoing extensive model validation [45, 88, 67], use-case development and results benchmarking with PMU data as well as results validation with a subset of entities.

Modeling Remedial Action Schemes (RAS) is an essential step in replicating the behaviour of the actual power systems in real-time simulations. RAS sense abnormal or predetermined system conditions and take corrective actions to maintain system reliability. RAS supplement ordinary protection and control devices [65, 64, 79] (fault protection, AVR, PSS, governors, etc) to prevent violations of the NERC (North American Electric Reliability Corporation) reliability standards and limit the impact of extreme events [1]. The most common actions taken by RAS include changes in the generation (MW and Mvar), demand, or system configuration to maintain system stability, acceptable voltage, or power flows [1]. As RAS are becoming more widely used in recent years [22], the impact of these schemes and the potential interaction between RAS systems needs to be considered in real-time power system studies [21]. Transient stability analysis focuses on the power system behavior in the period of 10 seconds after the disturbance. Most RAS schemes usually take action in this time frame

and can affect the transient stability limits in a given study area. Therefore, it is essential to understand and model the effects of these automatic protection systems in real-time transient stability assessments.

In this chapter, we first describe some of the recent model enhancements implemented to improve the operation model for Peaks real-time TSAT. Different model accuracy checkpoints in TSAT are explored using case studies and system events in Western Interconnection. The study results provide a great insight into insufficiencies which need to be addressed for real-time operation models in power systems. Then, we explain the implementation and testing procedure of modeling RAS in real-time transient stability analysis tool at Peak. We also performed a one-day study to investigate the impact of adding RAS models on transient stability limits and limiting contingencies.

5.2 Overview of Real-time Transient Stability Assessment at Peak Reliability

Peak Reliability’s real-time Transient Stability Assessment (TSA) is performed using two software from Powertech’s DSATools package, TSAT and DSA Manager. TSAT (Transient Stability Assessment Tool) is the computation engine that performs transient stability analysis. DSA Manager provides a platform for the dynamic security assessment modules to be integrated into the real-time sequence of an energy management system (EMS). Peak uses a procedure to automatically export the State Estimator (SE) case from EMS to DSA Manager every 15 minutes. The node-breaker model based SE case is then modified to create the TSAT case. TSAT performs “Basecase Analysis” to assess the security of the system at the given operating point for each of the critical contingencies defined. If any of the specified criteria for the stability indices is violated, the system is considered insecure for the contingency. Monitored security indices may include voltage drop/rise duration, frequency drop/rise duration, the rate of change of frequency. TSAT also performs “Transaction Analysis” to calculate the stability limits of the system for five pre-defined transfer scenarios for WECC system under all critical contingencies. A total of around 100 contingencies have

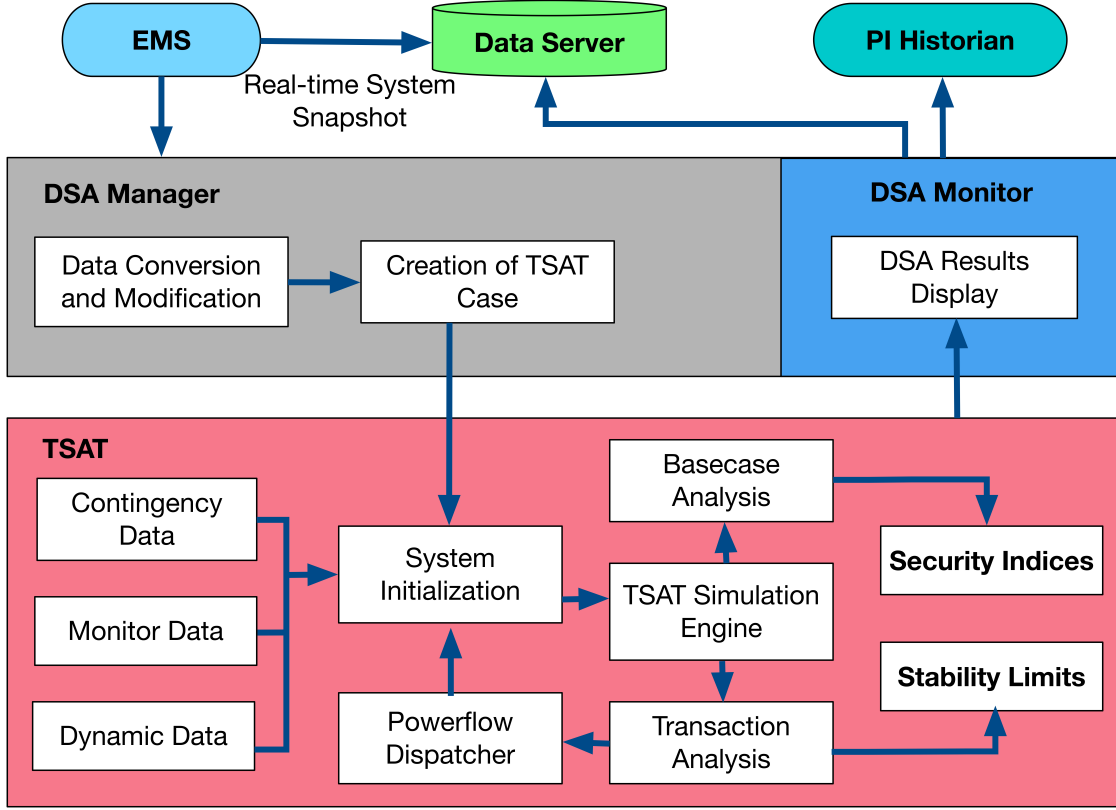


Figure 5.1: Peak real-time TSAT architecture.

been defined for the basecase and transaction analysis which includes both $N - 1$ and $N - 2$ cases. The objective of a transaction analysis is to find the power transfer level where the system is secure for all critical contingencies and will become insecure if the power transfer is increased by an amount equal to a specified threshold. The security can be measured by any or all of the indices available in the basecase analysis. Powerflow unsolvability is also considered as one form of insecurity. The limiting contingency is then defined as the contingency which imposed the most limiting power transfer. Results are displayed locally on DSA Monitor and deposited into a real-time database, PI historian. Figure 5.1 displays Peak's online TSAT architecture. All processed cases are archived and can further be used for off-line studies.

5.3 Model Enhancements for Real-Time Transient Stability Assessment Tool at Peak Reliability

To implement real-time transient stability assessment, Peak uses the West-wide System Model (WSM) [100] linked with WECC dynamic database through EMS labels [45]. WSM is a full-topology, node-breaker model which represents the entire Western Interconnection. Real-time measurements and breaker statuses are automatically mapped from Supervisory Control and Data Acquisition (SCADA) to the model so that it mimics real-time system operating conditions. To associate the WECC dynamic database with WSM, generation units from the two models needs to be matched. The mapping process of the units depends on how their models differ in WSM and the WECC planning base case. Due to the different levels of aggregation, some units might not match one to one. Since WECC dynamic database is created consistent with the WECC planning base case, units with no match in WSM are netted and considered as injections without dynamics. Small units subjected to asynchronism during simulations are also netted. Considering all the required adjustments, approximately 97 percent of the generators from the WECC planning base case has been mapped to the WSM [45].

WSM have been primarily used to perform State Estimation, Real-Time Contingency Analysis (RTCA) and other operational studies [100]. The credibility of all these studies is dependent on the accuracy of the models. Therefore, to improve the accuracy of the model and robustness of the real-time transient stability application, model validations and modifications have been performed continuously using TSAT.

TSAT model enhancement process involve the addition of new dynamic models and modification of the existing ones. New models are mainly added to:

- Accommodate a specific system analysis (e.g., motor load and composite load models for fast voltage collapse detection)
- Replace or improve existing models (e.g., renewable generation dynamic models or High Voltage DC (HVDC))

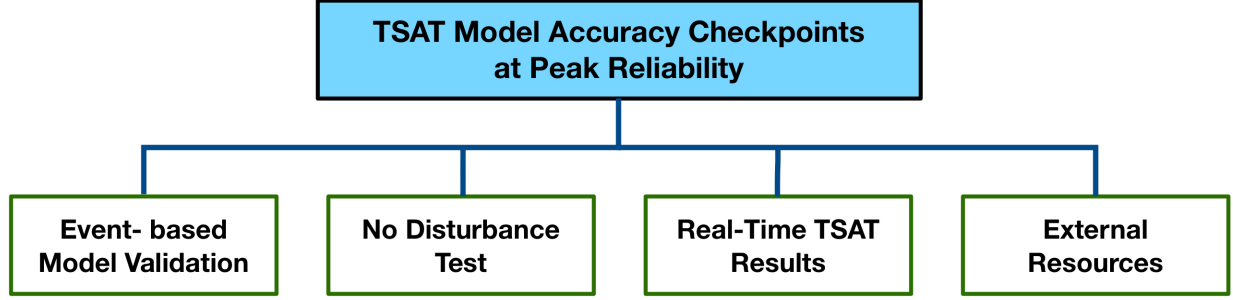


Figure 5.2: TSAT Model Accuracy Checkpoints at Peak Reliability.

- Study system-wide effects and interactions (e.g., Remedial Action Schemes (RAS)[63] and relay models)

Also, Peak uses different checkpoints to validate the models against real-time system measurements and suggests required modifications after extensive off-line and online tests. Figure 5.2 shows TSAT model accuracy checkpoints. In the following section, we describe these model accuracy checkpoints in detail using case studies and system events in Western Interconnection.

5.4 Cases of Model Validation in Western Interconnection

5.4.1 Event-Based Model Validation

The newly enforced NERC MOD-033 standard requires validation of the planning models, but there is no requirement for the operation model validation. Peak Reliability is the first to perform operation model validation (dynamic and steady-state). Following system events, the last TSAT case archived immediately before the event is retrieved and tested to ensure its quality using a “No Disturbance” test. Details of this testing process is described later in section 5.4.2. The event sequence is then replicated as contingencies. The objective of the validation study is to reproduce the key elements of system performance in the transient stability simulator and compare the simulation results against actual

measurements. Therefore, frequency, voltage and active and reactive power responses of major transmission paths and buses are commonly used for the comparison.

Over a one month period in 2016, considered in this section, Peak performed model validation studies for the three following events:

- Event 1: Generator outage on May 31st
- Event 2: Generator outage on June 26th
- Event 3: Substation event on June 27th

PMU measurements and equipment logs in conjunction with the data received from the entities, provide the necessary information to develop the sequence of events for the model validation studies. Below is the sequence of events for Event 1:

18:29:35 – Two circuit breakers were closed and bypassed the capacitor C1 on both 345 kV lines between Bus A and Bus B

18:29:37 – Two circuit breakers were closed and bypassed the series capacitors C2 on both 345 kV lines between Bus A and Bus B

18:29:38 – A circuit breaker was closed and bypassed the series capacitor C3 on 345 kV line between Bus D and Bus E

18:29:40 – Two circuit breakers opened and tripped the generator at Bus A

Real names of the equipment and areas have been changed to maintain confidentiality. Figures 5.3 and 5.4 show the validation results for Event 1 on two major buses M1 and M2.

These figures illustrate a strong agreement between the actual and simulated frequency responses. However, the simulated frequency dip is slightly smaller than what was observed in the measurements. Therefore, additional model sensitivity studies were attempted to improve the match between the operation model and reality. In the following subsections, we explore the sensitivity of the operation model to unit statuses and governor settings and its impact on validation results.

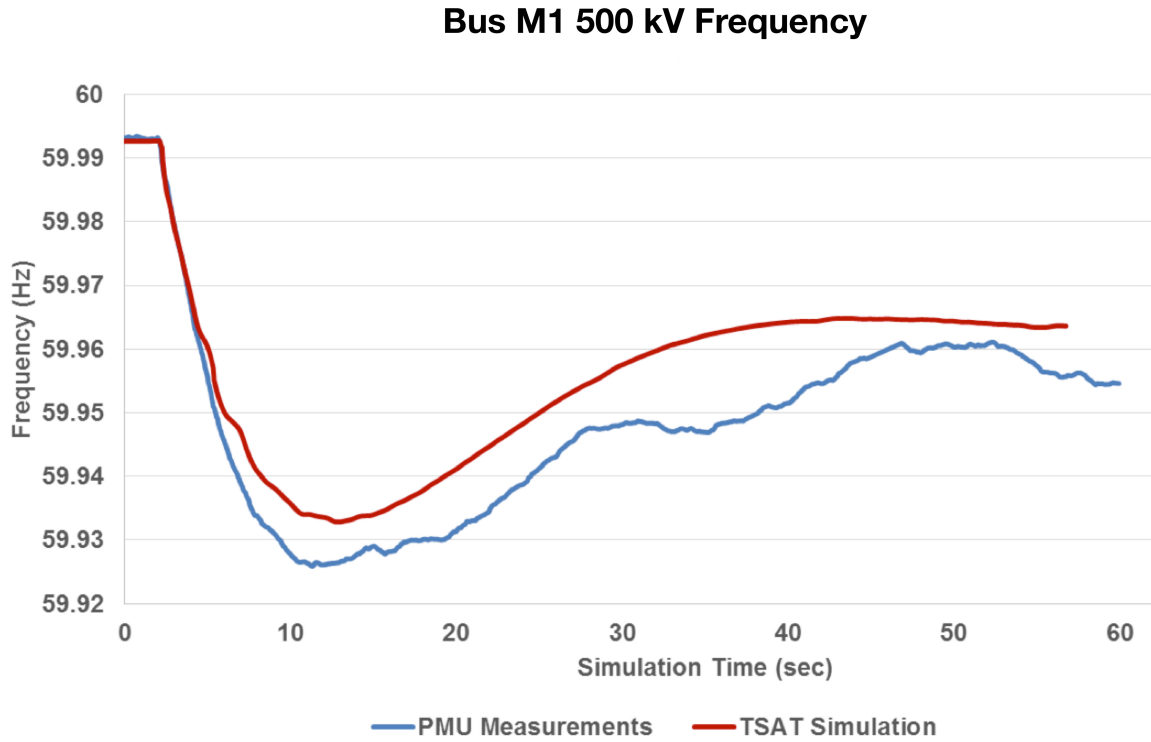


Figure 5.3: Frequency response at bus M1 for Event 1 (PMU Measurement vs. Operation Model).

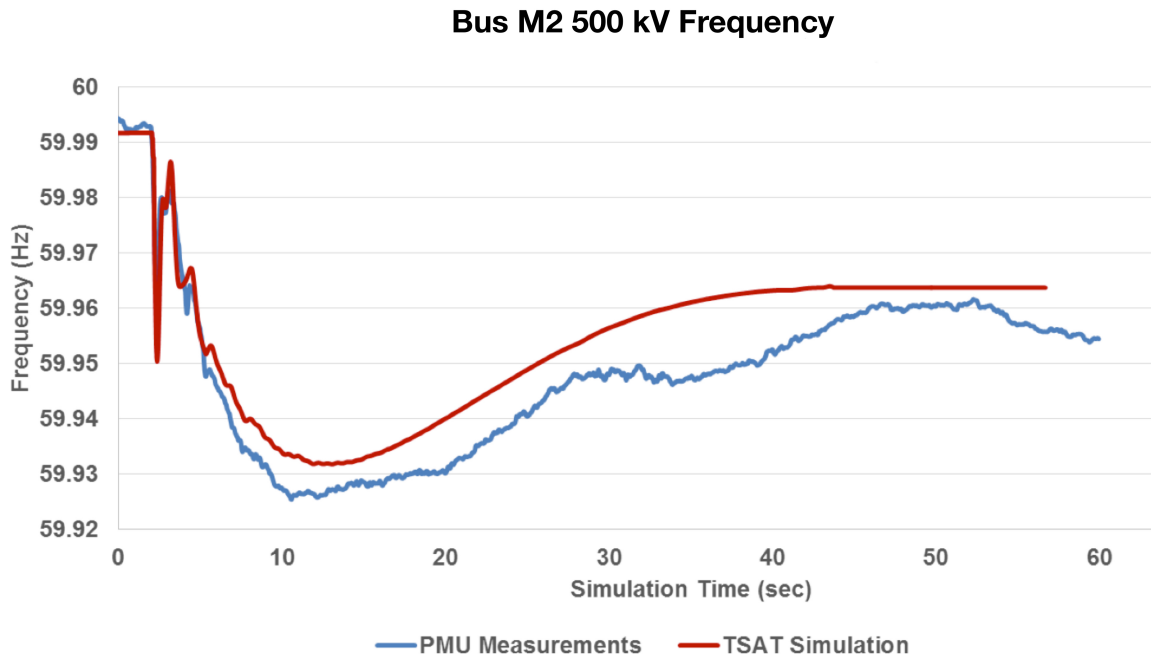


Figure 5.4: Frequency response at bus M2 for Event 1 (PMU Measurement vs. Operation Model).

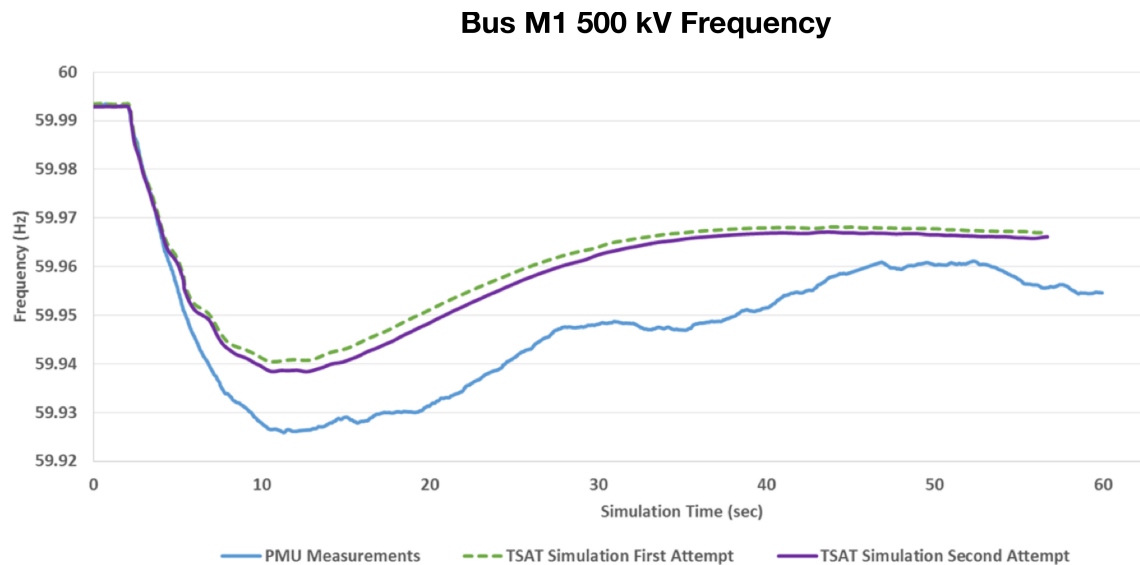


Figure 5.5: Impact of unit status changes on frequency response of bus M1.

Importance of Unit Status Availability

To study the sensitivity of the operation model to unit statuses, we turned off the large units in the simulation base case that were at low output, i.e. less than 10 MW. These units likely should have been off if accurate unit statuses were available. Figure 5.5 shows the frequency response at bus M1 after applying this change. The new frequency response is labeled as “TSAT Simulation Second Attempt” and it shows that the applied change had some, but not significant, impact on the system frequency dip.

Importance of Real-Time Governor Data Availability

To explore the sensitivity of the operation model to governor model settings, we blocked governor responses for units dispatched above 95 percent of their P_{max} in simulation base case. Due to being close to their maximum power output capacity, it is unlikely that these units responded to the decline in frequency. Figure 5.6 shows the frequency response at bus M1 after blocking the governors. The new frequency response is labeled as “TSAT Simulation Third Attempt” and it demonstrates that the applied change had a significant effect on the system frequency dip and the frequency response from the modified model became closer to real-time measurements.

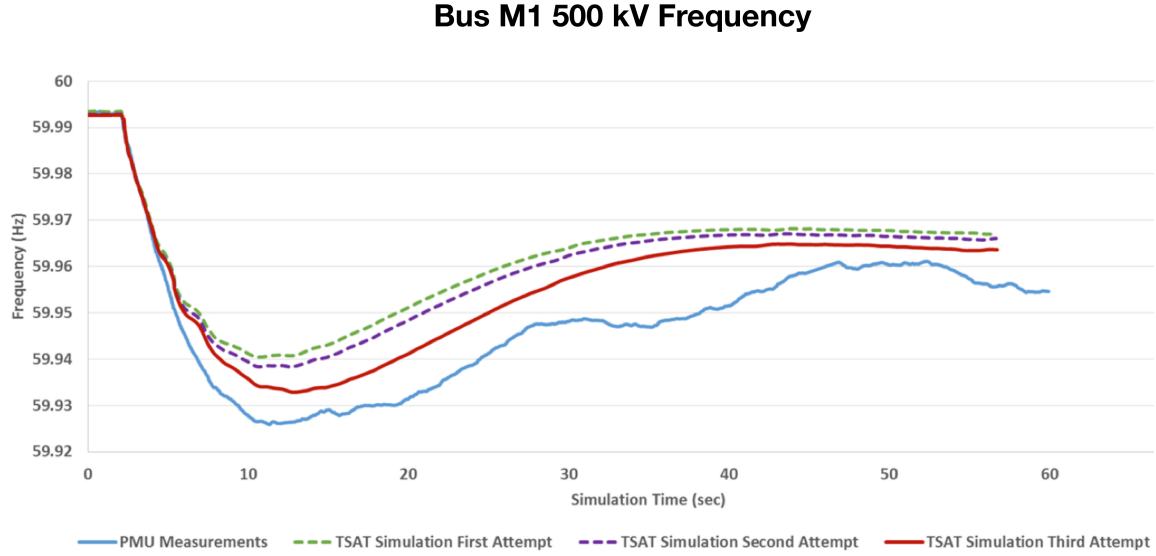


Figure 5.6: Impact of change in governor settings on frequency response of bus M1.

We followed the same model validation process for Event 2 and Event 3. Figure 5.7 shows the frequency response at major bus M3 for Event 2 and figure 5.8 shows the voltage response at bus M4 for Event 3. These results confirm that simulations using WSM and WECC base case match reasonably well against measurements for the studied system events. It can be concluded that steady state and dynamic models used in Peak TSAT are trustworthy for transient stability analysis purposes. Continual model validation studies are needed to maintain the confidence in power system models.

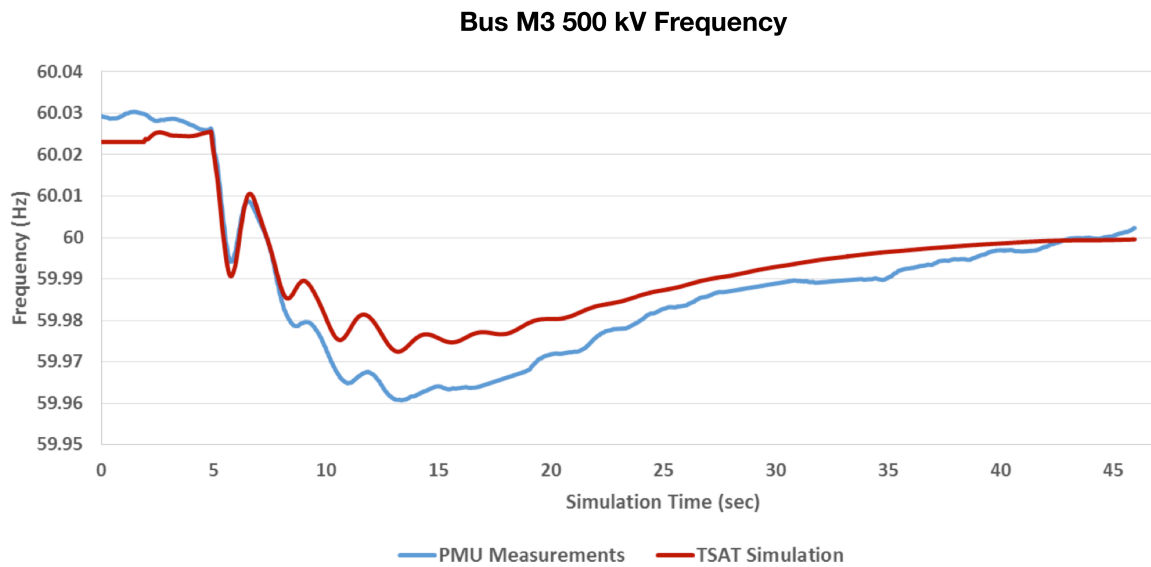


Figure 5.7: Frequency response at bus M3 for Event 2 (PMU Measurement vs. Operation Model).

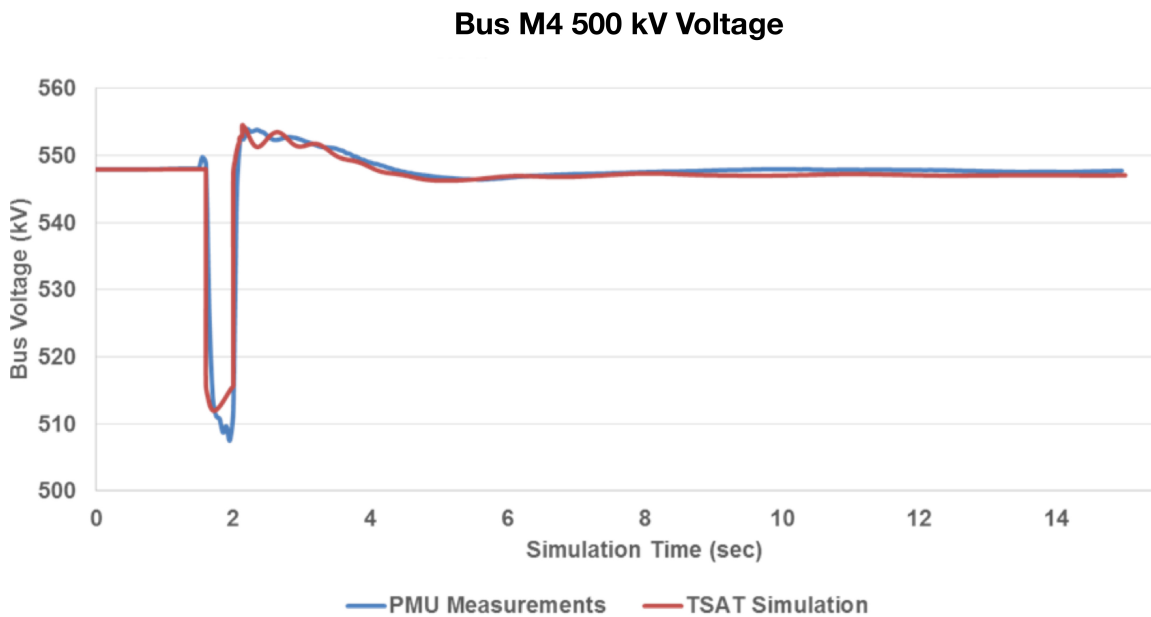


Figure 5.8: Voltage response at bus M4 for Event 3 (PMU Measurement vs. Operation Model).

Table 5.1: Largest peak to peak angle deviations (deg) for base case and modified cases

Rank	Peak to Peak Angle Deviations (deg)		
	Base Case	Case 1: Modified Inertia	Case 2: Modified PWmin
1	5.697	3.015	2.576
2	5.422	2.923	0.703
3	5.381	2.898	0.622
4	5.368	2.897	0.573
5	5.368	2.886	0.529

5.4.2 No Disturbance Test

Peak engineers perform several off-line studies daily using archived TSAT cases from real-time transient stability assessment tool. To ensure the quality of these cases, they initialize each study with a “No Disturbance” test. In this analysis, a simulation is performed with no disturbance applied to the system. TSAT will list the generators with the largest speed and angle deviations from the simulation. Selected case is considered credible if all generator angle deviations after 10 seconds of flat run remain within five degrees. If the largest angle deviations exceed the five-degree limit, further investigations are performed to find potential defects in generator dynamic models. Issues related to renewable generation dynamic models are one of the most common causes of observed large angle deviations. Here, we present the study results for a TSAT case identified as noncredible in “No Disturbance” test. Table 5.1 summarizes the findings of this study. In this table, the five largest peak to peak angle deviations of all the generators in the system are ranked from largest to the smallest. For the base case, the angle deviations are slightly larger than five degrees. For case 1, we modified the inertias for some of the renewable generations that were modeled with unreasonably high inertias. As displayed in the table, this modification decreased the angle deviations and brought them within the defined limits. For case 2, we changed the PWmin value for some of the wind farms modeled using WNDTGE. The PWmin default value for these units was set to -0.4. As a result, the pitch angle limits were violated, and this caused the large rotor angle deviations, as the controllers attempted to bring the pitch angles back to within limits.

After setting the PWmin to 0.05 pu the angle deviations mainly become very close to zero. These findings were reported to WECC and related entities for further investigations.

5.4.3 Real-Time Transient Stability Analysis Results

As described in section 5.3, real-time transient stability analysis at Peak runs approximately every 15 minutes. Some of the real-time alarms and insecure cases can be due to modeling problems. Therefore, engineers at Peak consider this possibility when searching for the underlying causes. For instance, some instability issues among paralleled units in simulations were found to be related to modeling insufficiencies to enable stable reactive power sharing. Therefore, there is a need to implement a Cross-Current Compensation (CCOMP) model [30] for paralleled units with Line Drop Compensation. Line Drop Compensation is a function which provides better high voltage system voltage control, especially when the generator step-up transformer has a large impedance. Figure 5.9 shows the reactive power response for one of the parallel units at a generating station that was initially unstable in simulations. The added CCOMP model can adequately capture the behavior of the excitation systems and resolve the stability issue in simulations.

5.4.4 External Resources

Peak continuously updates the TSAT operation model based on the information obtained from WECC, PowerTech, and other credible resources. For instance, a model modification for Pacific DC Intertie (PDCI) was received from PowerTech in summer 2016. High Voltage DC (HVDC) lines can rapidly control the transmitted power; therefore they are modeled in transient stability analysis. It was observed that the PDCI model used in Peak online TSAT could have poor numerical behavior when a fault caused the PDCI to have commutation failure. To address this issue, the updated PDCI dynamic file modified the DC line reactance in the dynamic model. Most commutation failures are caused by voltage disturbances in the AC system. To test the new PDCI model we applied a load increase contingency to create a severe voltage drop on the AC side. Figure 5.10 shows the voltage response at Bus M5

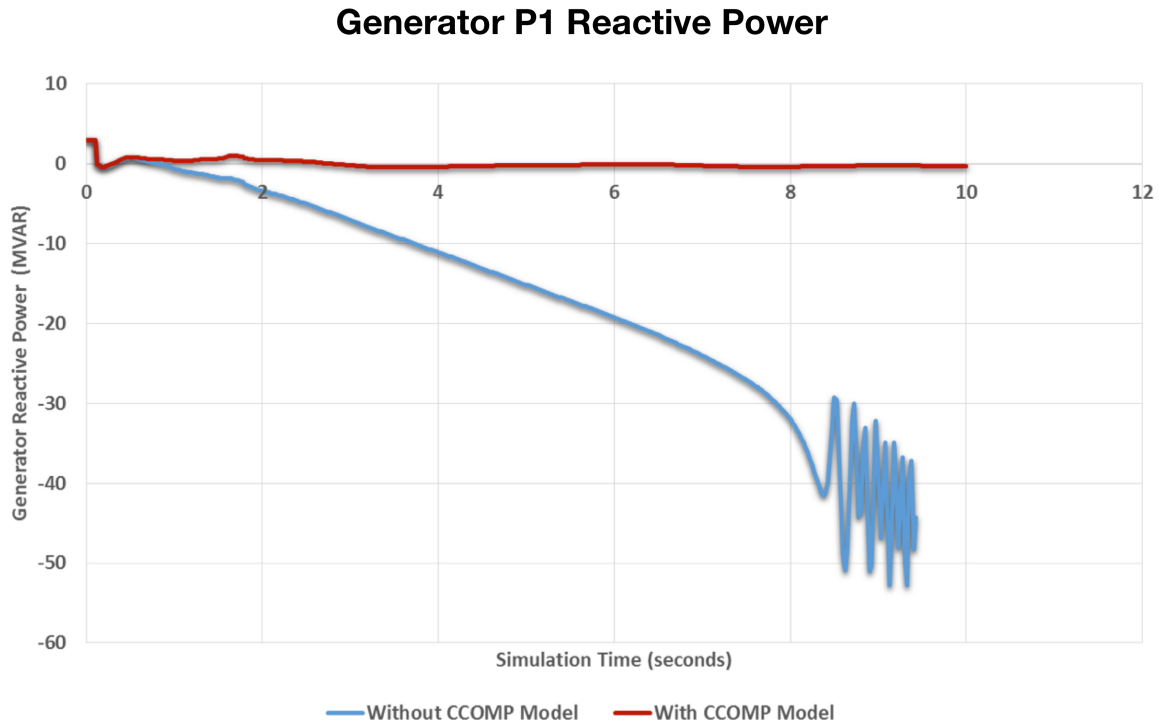


Figure 5.9: Reactive power response for generator P1 with and without CCOMP model.

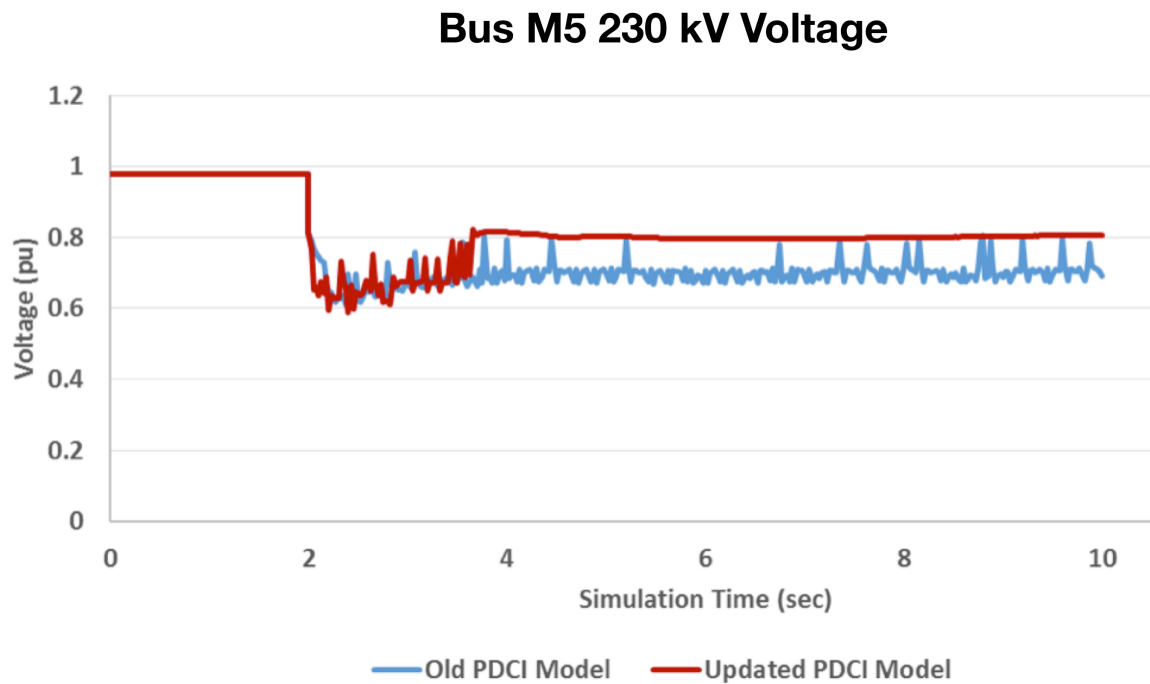


Figure 5.10: Comparison of voltage responses at bus M5 before and after updating the PDCI model.

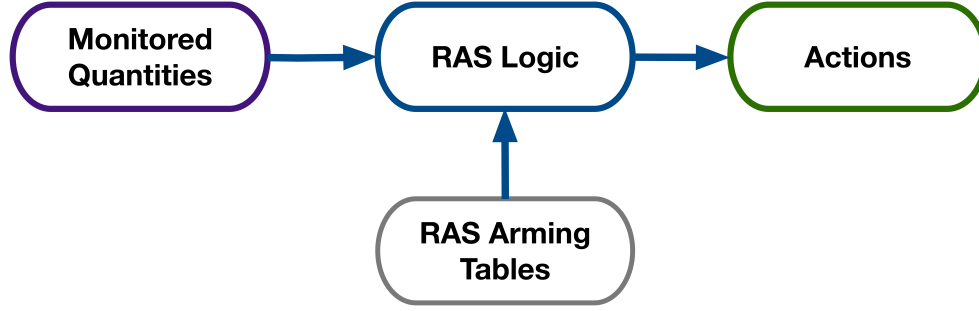


Figure 5.11: RAS basic structure.

located close to the PDCI. The response using the old model shows a sustained oscillation in the voltage while it is mitigated after some seconds using the updated model.

5.5 Implementation and Testing of RAS Models using online DSA Tools

RAS basic structure illustrated in figure 5.11, consists of four components: input signals, RAS logic, actions and in some cases arming tables. We used the following procedure for implementing and testing WECC RAS schemes for online transient stability analysis. First, based on the enabling and triggering conditions of a given RAS, the logic diagram has been designed and built using user-defined models (UDM). Once the UDM is created, its data file is included in the TSAT case (in the Dynamic Data section) to be used in computations. Then, a recent TSAT case has been selected from archive and tested to ensure its quality using a “No Disturbance” test. In this analysis, a simulation is performed with no disturbance applied to the system. TSAT will list the generators with the largest speed and angle deviations from the simulation. Selected case is considered credible if all generator angle deviations after a 10 seconds of flat run remain within five degrees. Finally, the functionality of the implemented RAS scheme is tested both off-line and online for all enabling and triggering conditions using dynamic simulations and a pre-defined set of contingencies. During this study 11 RAS schemes in WECC were implemented and tested. Below we will explain the implementation and testing procedure for one of the RAS schemes, named “Path X” RAS, in more details. The “Path X” RAS is a parameter-based RAS which is triggered based on

Table 5.2: Path X RAS enabling and triggering conditions

Enabling Conditions		Triggering Conditions	Actions
Always Enabled	Loading on any of the 230kV lines: Line 1, Line 2, Line 3, Line 4, Line 5 above 388 MVA	AND Flow from bus E to F	In 2 seconds open Line TL If the overload persists, the RAS will sequentially drop units at ABC generating station until the overload is alleviated.
			RAS will sequentially drop units at ABC generating station until the overload is alleviated.

overload on certain lines. Parameter-based RAS monitors variables for which a significant change confirms the occurrence of a critical event. Details on common RAS classifications can be found in [22]. Real names of the equipment and areas have been changed to maintain confidentiality.

5.5.1 RAS User-defined Models

Table 5.2 shows the enabling and triggering conditions for Path X RAS and summarizes the actions. This RAS is always enabled and is designed to protect certain transmission lines from overload. It is triggered by detecting an overload above 388 MVA on any of the specified 230 kV lines. The RAS action depends on the direction of the power flow from bus E to F. It will trip a line and/or drop generating units until the overload is alleviated. Defined delays for actions in the RAS design are modeled to be considered automatically. For this RAS, all the actions should take place within 10 seconds which is during transient stability analysis time frame. Figure 5.12 shows the logic diagram for this RAS mainly highlighting the required input signals and the actions. After designing the logic diagram, it is built using a graphical interface called UDM Editor. The TSAT UDM file is then added to the dynamic data of the case.

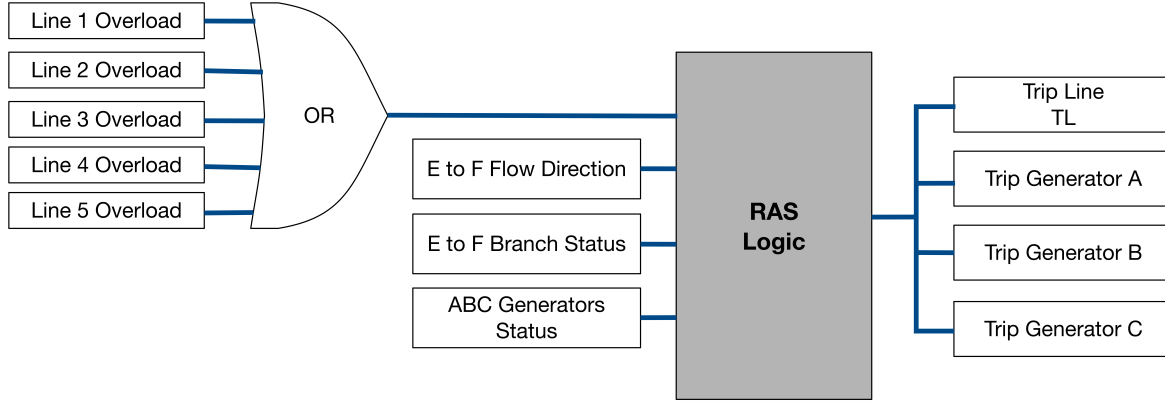


Figure 5.12: Logic diagram of Path X RAS.

5.5.2 Simulation Results

First, we simulated the no disturbance analysis to ensure the quality of the TSAT test cases. Initiation results proved the proper quality of the testing cases as all generator angle deviations after 10 seconds of flat run were within five degrees. To test the functionality of the RAS, we used a double transmission line outage at 2 seconds. This contingency caused overload on all five 230 kV lines. In the selected case the power flow was from E to F, therefore a trip signal was sent in 2 seconds to open line TL. Since the overload persisted after opening the line, RAS sequentially dropped units at ABC generating station. In this case, all the three units were dropped. Figure 5.13 shows the line loading and the RAS threshold for this simulation. More simulations were performed to test all the triggering conditions for different E to F flow patterns.

5.5.3 Impact of Modeling RAS on Transient Stability Limits and Limiting Contingencies

After adding 11 WECC RAS models to real-time transient stability analysis, we studied the impact of RAS on transient stability limits and limiting contingencies. In an off-line study, we performed transaction analysis for all of the TSAT cases archived over a day (100 TSAT cases) with and without RAS models included in the dynamic data. The selected date was not a weekend or a holiday and had a weekday demand pattern. Figure 5.14 shows the absolute value of the limit differences for one of the defined scenarios. TSAT cases before 6:33

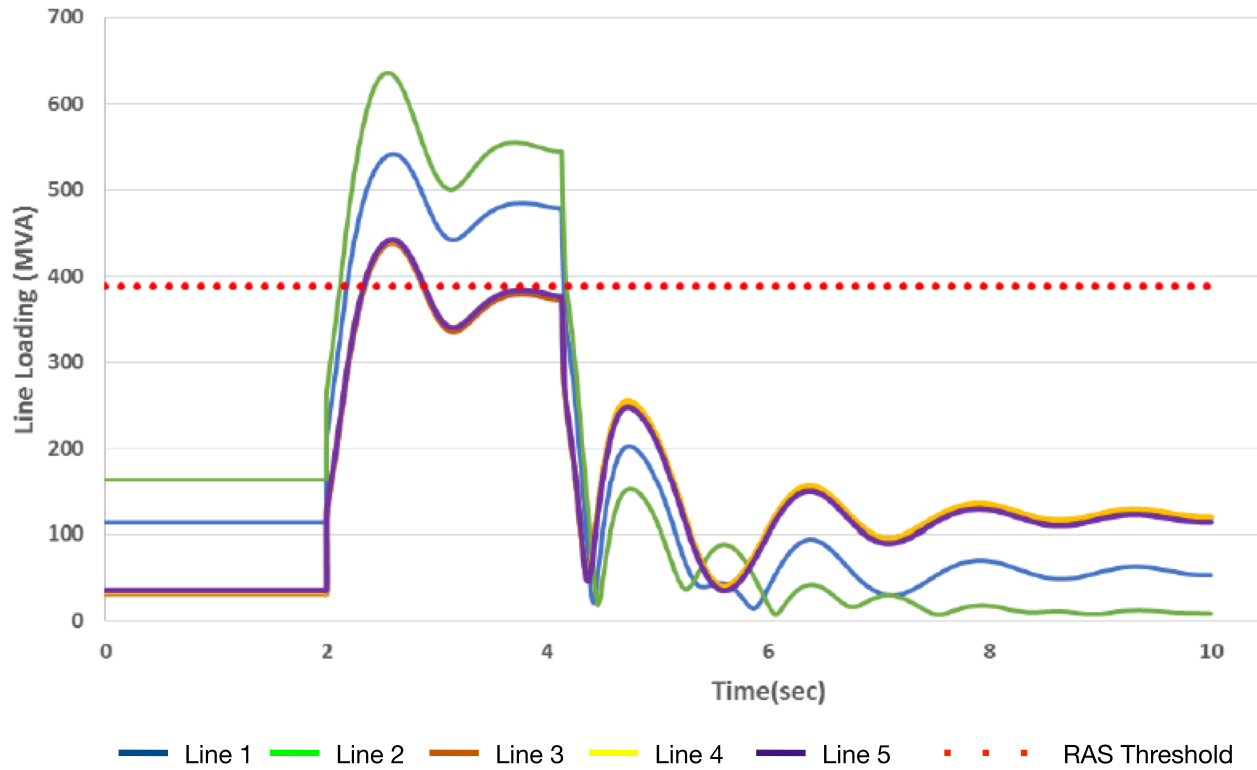


Figure 5.13: Line loading and Path X RAS threshold.

AM and after 17:18 PM did not show any difference in the limits and therefore not displayed. The one-day study showed that considering RAS models in dynamic calculations will impact the stability limits and can provide more accurate description of system constraints. In this study, adding RAS models increased the stability limits of the selected scenario in 41 percent of the test cases. The maximum limit increase was 62.5 MW. The limit decrease was detected in only seven percent of the cases, and for others, the limit remained unchanged. Some of the highest limit differences are observed during peak demand hours that the accuracy of stability limits are more critical in maintaining the reliability of the system.

We also compared limiting contingencies for this scenario with and without RAS models. Four limiting contingencies were observed in the one-day study cases. As displayed in figure 5.15, when RAS are not modeled Contingency 2 and Contingency 1 are the main limiting contingencies with the occurrence of 47 percent and 35 percent respectively.

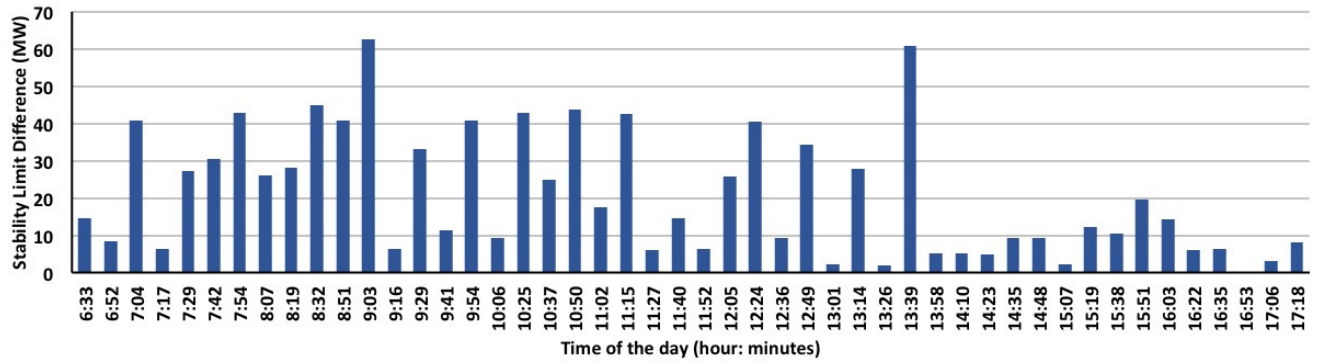
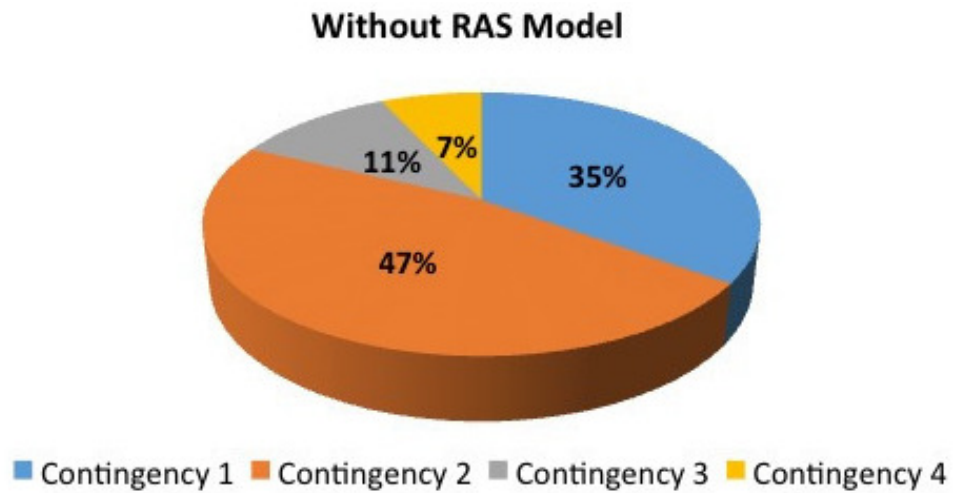
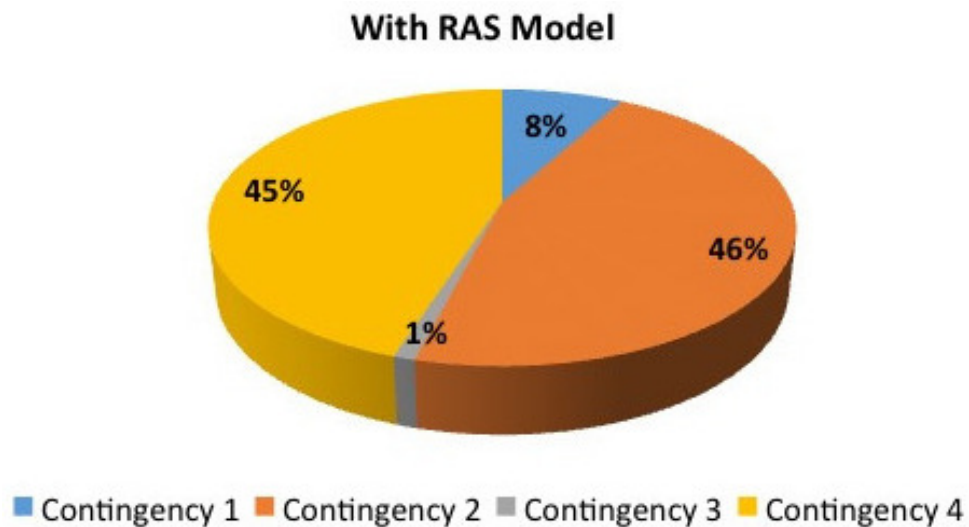


Figure 5.14: Stability limit differences with and without RAS Models.



(a)



(b)

Figure 5.15: Limiting contingency percentages over a one day study: (a) Without RAS model and (b) With RAS models included.

Including the RAS models changed this pattern with Contingency 2 and Contingency 4 becoming the main limiting contingencies with 46 percent and 45 percent occurrence. Therefore, the study confirms that modeling RAS in transient stability analysis will provide a more realistic representation of the critical contingencies.

5.5.4 Benefits of Modeling RAS in Transient Stability

Implementation of RAS models in transient stability analysis can benefit both real-time operations and off-line short-term and long-term planning studies. Here, we discuss two main advantages identified in our study.

Increased Accuracy

Incorporating RAS models in transient stability analysis leads to a more accurate representation of the systems behavior. As described in section 5.5.3, RAS modeling affects the stability limits and the limiting contingencies. With ever-increasing power exchange between utilities over the existing transmission network, power systems are driven closer to their limits. Therefore, efficient and reliable operation of the grid is becoming more dependent on having accurate limits.

Improved Coordination

There are around 200 existing RAS in WECC system and the numbers are continuing to grow [1]. RAS deployment represents a less costly alternative than building new infrastructure [3], but it may interact with other RAS schemes and protection systems in unintended ways and compromise the reliability of the system. Therefore, detecting coordination issues is very important specially in planning studies. Implementing RAS models in dynamic analysis can help to easily identify the coordination and design problems and prevent further complications.

5.6 Concluding Remarks

Validation of power system operation models, though not required by NERC, proved to be beneficial for increasing confidence in real-time applications and enhancing the accuracy of dynamic stability limits. Peak's recent model improvements for the real-time transient stability assessment tool described in this chapter showed that the study results using WSM and WECC base case match reasonably well against measurements for different system events. Therefore, it can be concluded that steady state and dynamic models used in Peak are trustworthy for transient stability analysis. The sensitivity of the operation models to unit baseload flags, unit status, and governor setting was also explored. These studies can provide a great insight into insufficiencies which need to be addressed for real-time operation models in power systems. Real-time stability assessment tools enhance operators situational awareness and assist them in responding effectively to degradation in the reliability of the system. With RAS numbers growing in WECC, incorporating RAS models in real-time stability analysis can present a more accurate illustration of the system stability limits. Considering the fact that power system is driven to operate closer to its limits, having accurate stability limits in real-time is essential to maximizing the usage of the transmission systems. In addition, modeling RAS can help with identifying coordination issues between these schemes and other protection systems. Therefore, adding RAS models to dynamic studies is a significant step that will benefit electric system operators and planners throughout Western Interconnection.

Chapter 6

Wide-Area Control Design with Limited Model Information

6.1 Introduction

In this chapter, we propose a wide-area control scheme using online model estimation to improve small signal stability. The proposed controller updates the control design based on a model estimated online using numerical subspace state space system identification (N4SID) algorithm. Based on previous model validation studies, we use three common cases of model inaccuracies as case studies to compare component-based and measurement-based models for control design. Our results demonstrates that inaccurate models degrade the performance of the controller while the proposed control using measurement-based model can successfully capture small signal dynamics of the system and provide a good performance. This indicates that the measurement-based models have the potential to serve as a good complement to model-based methods in designing control in power systems.

The remainder of this chapter is organized as follows. Section 6.2, introduces power system modeling approaches and describes the proposed wide-area control design using measurement-based model. Section 6.3, evaluates the proposed method through three different case studies and compares it with the wide-area control design using component-based models. Concluding remarks are presented in section 6.4.

6.2 Problem Statement

6.2.1 Power System Modeling

The power system electromechanical behavior can be described by a set of nonlinear Differential Algebraic Equations (DAEs) [66]. Power system models can be categorized as component-based and measurement-based models [39]. In component-based method, the nonlinear differential equations governing the system are linearized at a stationary operating point. Conversely for a measurement-based method, a linear model is estimated directly from system measurements. As power networks are complex large-scale systems, both computationally and geographically, building a component-based model that accurately describes the system is very challenging. The measurement-based approach requires significantly less effort. Therefore, measurement-based models can be frequently updated to capture system changes in real-time.

Following August 10, 1996 blackout in the Western Interconnection, simulation of the sequence of events using standard WECC models did not agree with the disturbance recordings [47]. This raised great concerns about model inaccuracies and its adverse effects on power system operation and planning. Since then, several model validation studies have been performed [5] in an effort to modify and improve system models. These studies revealed several cases of inaccuracies in power system models in generation, transmission and load components of the grid. In this section, we focus on three cases that caused great mismatches between model responses and observed measurements and use them as case studies to compare component-based and measurement-based models for control design. These cases are as follows:

- Case 1: Out of service equipments (e.g., power system stabilizer (PSS))
- Case 2: Excitation system models
- Case 3: Load models

6.2.2 Wide-area Control Design Using Measurement-Based Models

Let $x(t) \in \mathcal{R}^n$ denote a vector that contains the dynamic states of synchronous generators; $y(t) \in \mathcal{R}^q$ denote the system algebraic states, including bus voltage magnitudes and angles; and $u(t) \in \mathcal{R}^m$ denote the control action. The linear state-space model of the system is of the form:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y &= Cx(t)\end{aligned}\tag{6.1}$$

For model identification purpose, the model order should be selected sufficiently high to catch all the important characteristics of the system but not so high that it results in appearance of spurious modes which have no physical relevance [92]. To find the appropriate model order, we start with a low order model and increase the order until the small signal dynamics of the system are reasonably captured. Having the pre-processed data and the appropriate model order, the state-space representation of the system is then estimated using numerical subspace state space system identification (N4SID) algorithm. We use this identified model to design a linear state feedback that optimizes a standard Linear Quadratic Regulator (LQR) cost criterion [62]. Since we cannot measure the states of the estimated model, in order to implement a full-state feedback, we need an observer that provides an estimate of the states based on the measurements. The estimator is another dynamic system, identical to the state equation (6.1), but with an added correction term, based on the sensor measurements:

$$\begin{aligned}\dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) + L(y - \hat{y}) \\ \hat{y} &= C\hat{x}(t)\end{aligned}\tag{6.2}$$

The weights L can be chosen in an optimal manner, which balances the relative importance of sensor noise and process noise. The optimal compromise between sensor noise and process noise is achieved by the Kalman filter [8]. Once we have an estimate $\hat{x}$ of

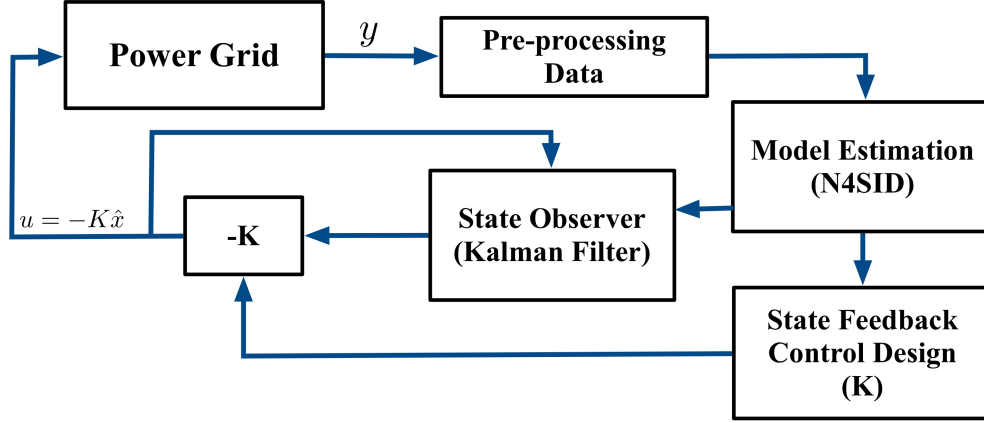


Figure 6.1: Block diagram of the proposed wide-area control design using measurement-based model.

the states, we can use this estimate in conjunction with the state feedback. The resulting feedback controller is a Linear Quadratic Gaussian (LQG) regulator which depends only on the measured output y and is defined as follows:

$$\begin{aligned}
 & \min_K \int_0^\infty (x(\tau)'Qx(\tau) + u(\tau)'Ru(\tau))d(\tau) \\
 & \text{subject to} \\
 & \text{dynamics:} \quad \dot{x}(t) = Ax(t) + Bu(t) \\
 & \text{feedback control:} \quad u(t) = -K\hat{x}(t) \\
 & \text{stability:} \quad A - BK \text{ is Hurwitz} \\
 & \text{initial condition:} \quad x(0) = x_0
 \end{aligned} \tag{6.3}$$

Figure 6.1 shows the block diagram of the proposed wide-area control design using measurement-based model. Figure 6.2 highlights the difference between using component-based models with common inaccuracies and measurement-based models for designing wide-area damping control in power systems.

It also illustrates time sequences of the different steps of the proposed method. After the disturbance occurrence, the proper ring down measurement window of data, $[t_1 : t_2]$, is used to estimate the model of the system. The time window, $[t_2 : t_3]$, accounts for communication delay in wide-area measurements and the computation time required for model estimation

and control update. Designed control input is then applied at t_3 . Because of the inaccuracies present in the component-based model, a control designed based on a well-estimated model can provide a better performance in improving the small signal stability of the system.

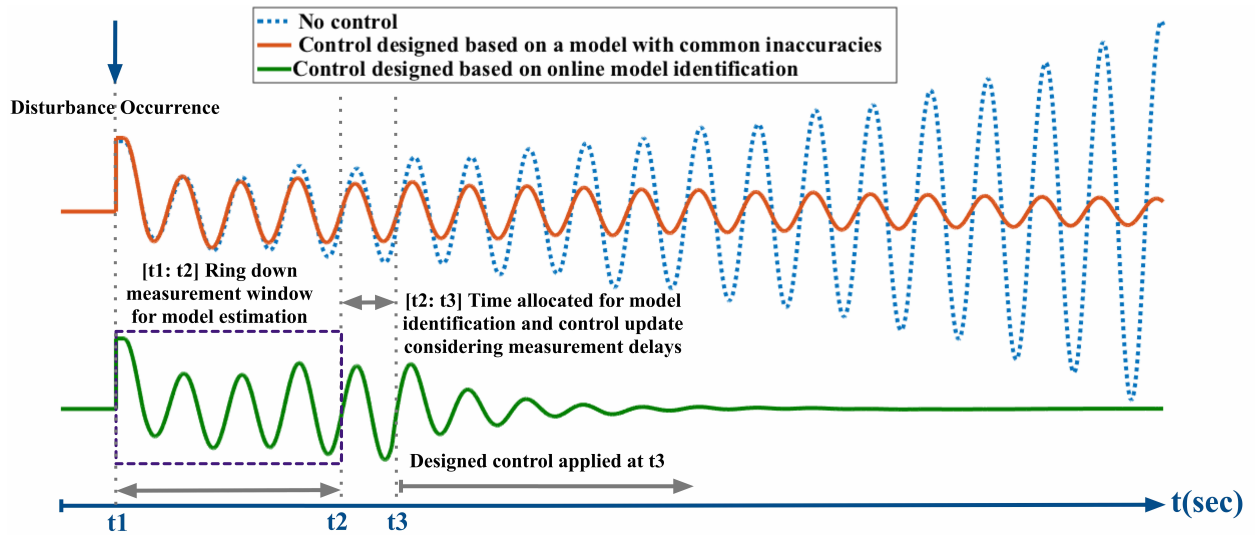


Figure 6.2: Component-based models versus measurement-based models for control design.

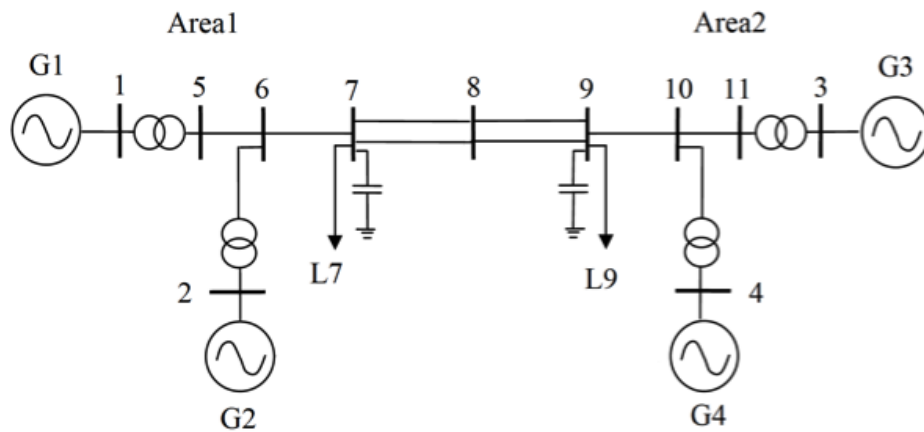


Figure 6.3: Kundurs two-area four-machine test system [48].

6.3 Evaluation of the Proposed Wide-area Control

6.3.1 Test System Overview and Simulation Considerations

To evaluate the proposed wide-area damping control, we used the Kundur's two-area system in figure 6.3. We modified this test system to create a low-damped inter-area mode while local modes can be fairly damped using PSS. The stabilizer gains of the generators were decreased to $K_{stab} = [10; 2; 10; 2]$ to allow for lightly damped modes. To increase the difference between oscillation frequencies of local and inter-area modes, generator inertias of G_2 and G_4 , were changed to $H_2 = 19.5s$ and $H_4 = 18.525s$. For simulation of the dynamic behavior, each generator is modeled using a third-order flux-decay model along with its excitation system. The disturbance scenario considered is a three phase fault at bus 8 at time $t = 1s$ cleared after $0.1s$. The nonlinear time domain simulation of the power network is carried out using MATLAB.

To estimate the system linear state-space model, voltage magnitude, voltage angle and frequency of generator terminal buses are assumed available as wide-area measurements. Practically, these measurements can be obtained from PMUs installed in the system with high sampling rates of up to 60 samples per second [80]. In our simulations, we use the same sampling rate for the measurements. These measurements are pre-processed as described in section 6.2.2. The proposed wide-area damping control is in the form of a supplementary voltage to the excitation of the generators. Therefore, in the subspace system identification algorithm, voltage magnitudes are considered as the inputs and voltage angle and frequency measurements are defined as the outputs of the model. A ring down data window of four seconds is chosen which provides a good estimate of the system. Since the proposed controller aims to provide damping for both local and inter-area modes, the model order should be set sufficiently high such that it captures these system small signal dynamics. The appropriate model order is found to be eight in this case. The model is then estimated using MATLAB system identification toolbox. Using the estimated model, the wide-area damping control is designed as described in section 6.2.2. The control signal is applied with one second delay to account for communication delay in wide-area measurements and the computation time

required for model estimation and control update. Typically, communication delay for PMU measurements in power system is between 100 *ms* and 250 *ms* [69, 44].

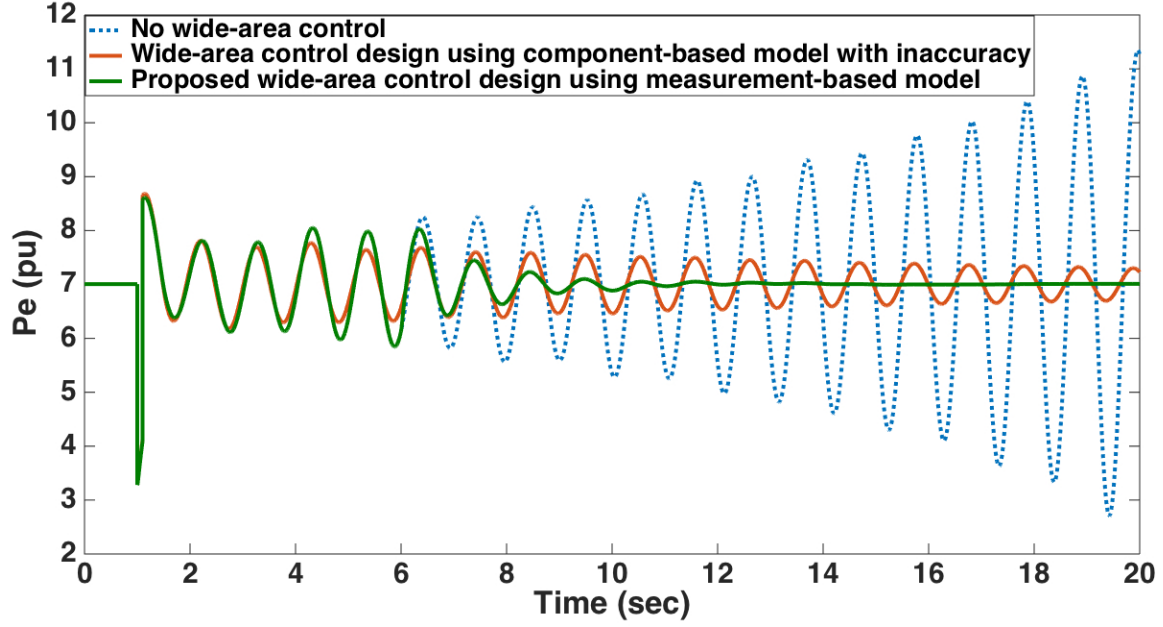
In the following subsections, for each of the cases introduced in section 6.2.1, non-linear time domain simulations were performed and compared for : 1) no wide-area control, 2) wide-area control design using component-based model with inaccuracy and 3) wide-area control design using measurement-based model. The results of small signal analysis is also provided to show the performance difference between the controllers.

6.3.2 Case 1: Out of Service Power System Stabilizer

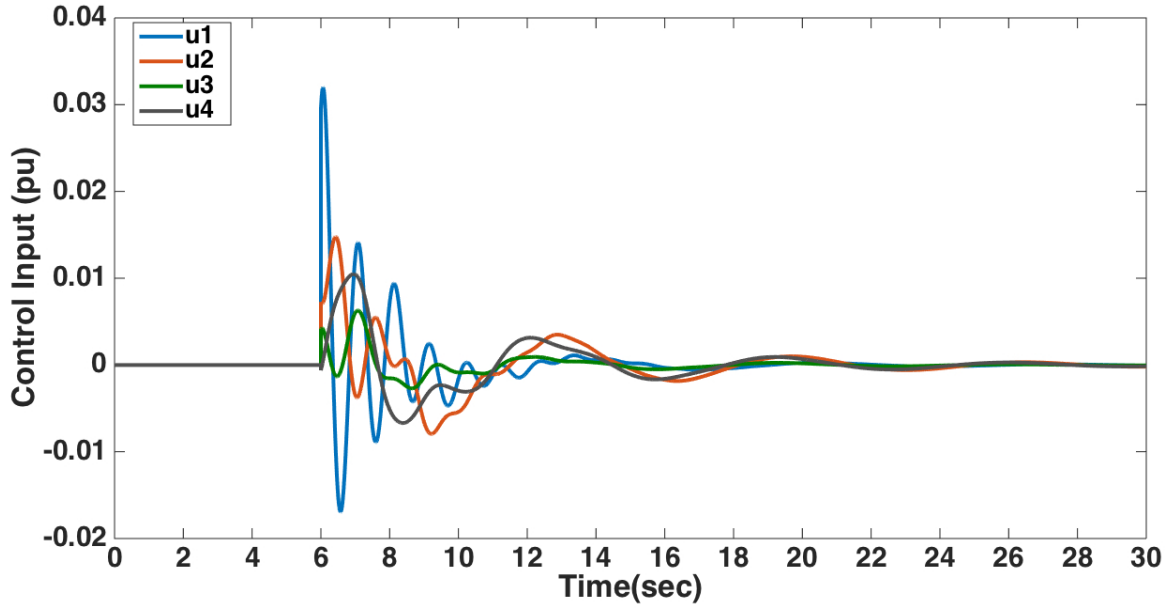
One of the main causes of model inaccuracies are components of the system that were included in the model but are out of service. A very common case in power system are the power system stabilizers. To explore this case we assumed that the PSS on G_1 that is included in the component-based model has been turned off. Figure 6.4 (a) shows the electric power output, P_{e1} , of G_1 . With PSS on G_1 out of service, system with no wide-area control becomes unstable. Since this PSS is the main source of damping for the local mode in Area 1, the wide-area control design using component-based model considers this mode fairly damped and fails to provide sufficient damping. However, the proposed wide-area control successfully captures the characteristics of the local and inter-area modes using online model identification and provides adequate damping for these modes. Table 6.1 summarizes the small signal analysis results for case 1.

Table 6.1: Local and inter-area modes for different control designs in case study 1.

Type of Wide-area Control		No Control	Component-based Model	Measurement-based Model
Local Modes	Eigenvalue	$0.08 \pm 6.03i$	$-0.058 \pm 6.04i$	$-0.721 \pm 5.87i$
	Frequency (Hz)	0.9603	0.9628	0.9413
	Percentage Damping	-1.4782	0.9674	12.1906
	Eigenvalue	$0.002 \pm 6.22i$	$-0.488 \pm 6.08i$	$-0.81 \pm 6.03i$
	Frequency (Hz)	0.9915	0.9720	0.9690
	Percentage Damping	-1.2476	7.999	13.4096
Inter-area Modes	Eigenvalue	$0.001 \pm 2.65i$	$-0.23 \pm 2.64i$	$-0.26 \pm 2.63i$
	Frequency (Hz)	0.4232	0.4220	0.4215
	Percentage Damping	-0.0543	8.713	10.129



(a) Comparison of electric power output at G_1 for case study 1.



(b) Proposed wide-area control input for all four generators.

Figure 6.4: Nonlinear time domain simulation results.

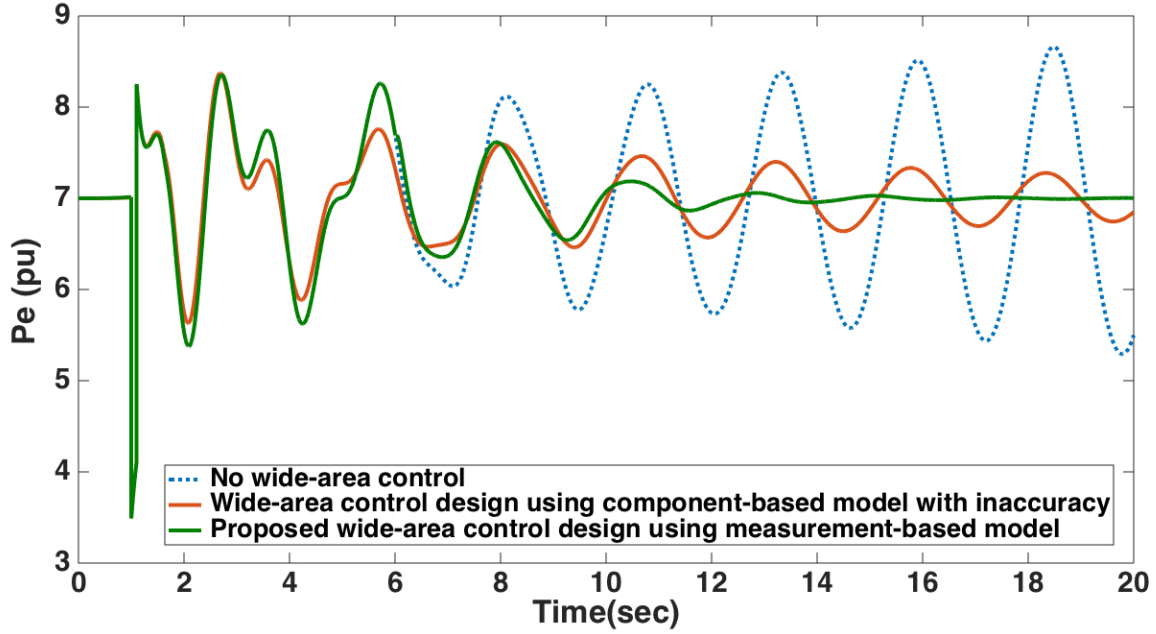


Figure 6.5: Comparison of electric power output at G_4 for case study 2.

Figure 6.4 (b) shows the proposed wide-area control signal for all four generators. As shown in the figure the control is applied at $t = 6s$, five seconds after the disturbance happens.

6.3.3 Case 2: Excitation System Models

Another common cause of mismatches between system models and disturbance recordings are inappropriate excitation models. In validation studies following 1996 blackout in WECC, excitation system models were reported as the most improved [47]. To study the effect of excitation models, we assume that a DC exciter in the system at G_2 is improperly modeled as a static exciter. Figure 6.5 shows the electric power output, P_{e4} , at G_4 . The DC exciter at G_2 hinders the performance of the PSS at G_1 as described in [46]. Thus, the inter-area mode of the two-area system becomes unstable, without the wide-area control. Wide-area control designed using component-based model, assumes a static exciter model, and therefore did not provide sufficient damping for the inter-area mode. The proposed wide-area control captures the effect of the DC exciter on system modes and damps the inter-area mode. 6.2, compares the inter-area mode damping for component-based and measurement-based method.

Table 6.2: Inter-area modes for different control designs in case study 2.

Type of Wide-area Control		No Control	Component-based Model	Measurement-based Model
Inter-area Modes	Eigenvalue	$0.039 \pm 2.455i$	$-0.068 \pm 2.451i$	$-0.322 \pm 2.532i$
	Frequency (Hz)	0.39	0.39	0.40
	Percentage Damping	-1.620	2.774	12.643

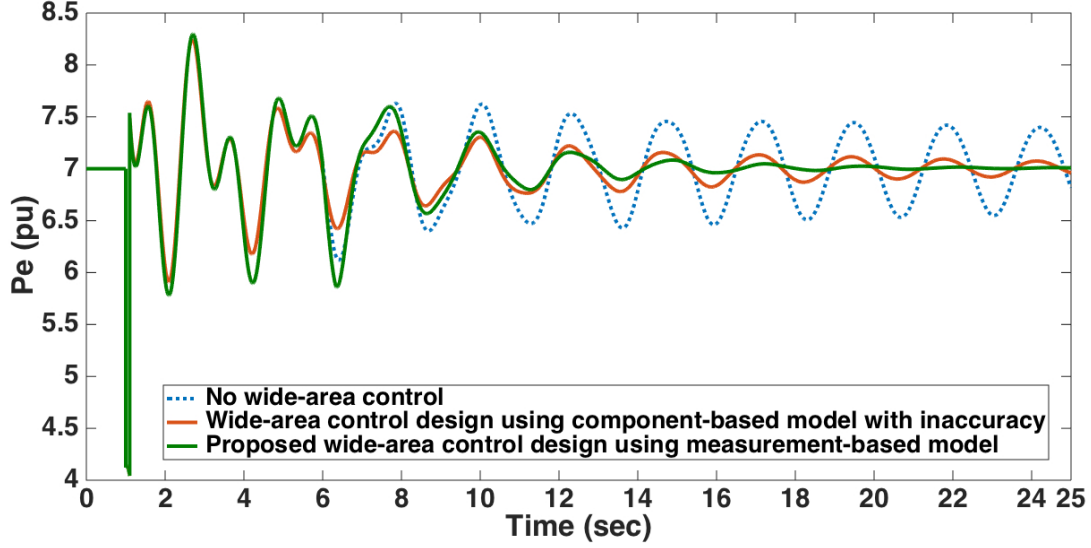


Figure 6.6: Comparison of electric power output at G_2 for case study 3.

6.3.4 Case 3: Loads

Load models have a significant influence on the accuracy of system models. In WECC model validation studies after all modifications were made, the simulated system still showed more damping than the actual system [47]. Proper load models were the key modeling improvement. To explore the effect of load models in wide-area damping control design, we assumed that the system loads are represented as constant impedance in the component-based model but the actual system loads are a combination of different types of load. We used the ZIP load model coefficients $Z_p = 0.15$, $I_p = 0.25$, $P_p = 0.6$ to represent the actual loads. Figure 6.6 shows the electric power output, P_{e2} , of G_2 . Presence of constant current and constant power loads in the system causes the inter-area mode to become unstable without wide-area control. Wide-area control design using the component-based model stabilizes the

Table 6.3: Inter-area modes for different control designs in case study 3.

Type of Wide-area Control		No Control	Component-based Model	Measurement-based Model
Inter-area Modes	Eigenvalue	$0.0005 \pm 2.041i$	$-0.111 \pm 2.035i$	$-0.317 \pm 2.115i$
	Frequency (Hz)	0.32	0.32	0.34
	Percentage Damping	-0.024	5.461	14.837

inter-area mode but still the control design based on measurement-based model provides a better damping due to a more accurate model. Table 6.3 compares the damping of the inter-area mode for these cases.

6.4 Concluding Remarks

This chapter discusses the use of measurement-based models for designing control for future power grid. A new wide-area control framework with online model identification was proposed to improve the small signal stability of the system. As explored through simulation of different case studies, common inaccuracies present in component-based models can degrade the control performance and even lead to instability. On the other hand, measurement-based models have the potential to capture system dynamic characteristics in real-time and provide a good platform for implementing corrective control actions.

Chapter 7

Conclusions and Future Directions

7.1 Concluding Remarks

In this dissertation, we addressed two key challenges regarding the design and implementation of wide-area control schemes for damping inter-area oscillations. First is the high communication cost associated with optimal centralized control approaches. Second is the difficulty of obtaining accurate system-wide dynamic models for initiating and updating the control design. Achieving this goal requires methodologies which span different areas of power system stability, control systems, and dynamic modeling. We introduced wide-area damping control strategies that not only ensure the small signal stability with the desired performance but also consider communication and model information constraints in the design.

A distributed excitation control is designed and implemented on a large, idealized power network to mitigate the electromechanical disturbance propagations. The performance of the proposed controller is then compared to centralized and decentralized schemes. To make the method suitable for systems with arbitrary structures and information patterns, a distributed linear quadratic optimal control framework is then developed using group sparse regularization function. The proposed control aims to optimize a standard cost criterion while penalizing the number of communication links. The group sparse regularization approach is used to induce the desired sparsity pattern and encode prior information about the underlying system into the control design. This new approach is described in a general form and can be applied to different applications other than improving small signal stability.

The proposed method not only provides flexibility to explore different communication structures but also creates a platform for finding the information exchange pattern that best fits the system constraints and satisfies the required performance criteria.

To further minimize the number of communication links, a control and communication co-design framework is used to find the most critical links in a distributed control structure. It has been shown that the proposed method is consistent with the conventional geometric controllability and observability approaches in the search for the effective measurement-control loops.

To improve the performance of wide-area control schemes in the face of limited model information or model inaccuracies, a new framework is proposed using online model estimation techniques. The proposed controller updates the control design based on a model estimated online using the numerical subspace state-space system identification (N4SID) algorithm. Three common cases of dynamic model inaccuracies, selected based on previous model validation studies, are used to compare component-based and measurement-based models for control design. It is demonstrated that inaccurate models degrade the performance of the controller while the proposed control using measurement-based model can successfully capture small signal dynamics of the system and provide satisfactory performance. The performances of the proposed wide-area damping control architectures are validated through nonlinear simulations on different test systems.

7.2 Future Directions

This dissertation initiates the use of distributed control design for improving small signal stability in power systems. Although the results of the proposed methods in the studied test cases are promising, these approaches can be extended to overcome some of the design and analysis limitations arising in real-world systems that have not been discussed in this work. Below we list some of the interesting research directions that can be followed.

- **Changes in small signal stability in future power systems:** A crucial step in designing wide-area damping control schemes is to understand how different factors influence the small signal stability. Expansion of renewables, replacement of sizable

generation with inertia-less sources and changes in load profiles and dynamics, are just a few examples of emerging transitions that can affect the existing oscillation modes or introduce new modes in future power systems. Thus, there is a need for studies to consider future scenarios and evolving system conditions, so that worst damping conditions can be predicted and avoided from becoming a security concern.

- **Controller performance vs. communication costs:** The distributed control design methods proposed in this dissertation create a flexible framework to induce the desired structure for information exchange and find critical communication links. However, as demonstrated in this research, not all information has the same value in improving the controller performance. Therefore, an analysis can be done to establish new metrics to quantify the benefit of adding a communication link based on its role in improving the control response.
- **Adaptive control solutions:** This research mainly provides novel methods for wide-area control design to be used in planning studies while allowing for minor model updates in real-time. Therefore, for the controller to be able to better react to the unpredictable sequence of events in real-time operation, adaptive control solutions can be studied.

Bibliography

- [1] (April 2013). Special protection systems (SPS) and remedial action schemes (RAS): Assessment of definition, regional practices, and application of related standards. Technical report, North American Electric Reliability Corporation (NERC). [64](#), [82](#)
- [2] Aboul-Ela, M., Sallam, A., McCalley, J., and Fouad, A. (1996). Damping controller design for power system oscillations using global signals. *Power Systems, IEEE Transactions on*, 11(2):767–773. [9](#)
- [3] Ahmadi, H., Khanabadi, M., and Ghasemi, H. (2013). Transmission system reconfiguration for congestion management ensuring transient and voltage stability. In *Environment and Electrical Engineering (EEEIC), 2013 13th International Conference on*, pages 22–26. [82](#)
- [4] Ali, M., Buisson, J., and Phulpin, Y. (2010). Improved control strategy to mitigate electromechanical wave propagation using pss. In *MELECON 2010-2010 15th IEEE Mediterranean Electrotechnical Conference*, pages 35–40. IEEE. [14](#)
- [5] Allen, E., Kosterev, D., and Pourbeik, P. (2010). Validation of power system models. In *Power and Energy Society General Meeting, 2010 IEEE*, pages 1–7. [12](#), [63](#), [85](#)
- [6] Anh, N. T., Vanfretti, L., Driesen, J., and Hertem, D. V. (2015). A quantitative method to determine ict delay requirements for wide-area power system damping controllers. In *2015 IEEE Power Energy Society General Meeting*, pages 1–1. [3](#)
- [7] Asadinejad, A., Tomsovic, K., and Varzaneh, M. G. (2015). Examination of incentive based demand response in western connection reduced model. In *North American Power Symposium (NAPS), 2015*, pages 1–6. IEEE. [12](#)
- [8] Aström, K. J. and Murray, R. M. (2010). *Feedback systems: an introduction for scientists and engineers*. Princeton university press. [86](#)
- [9] Bamieh, B., Paganini, F., and Dahleh, M. (2002). Distributed control of spatially invariant systems. *Automatic Control, IEEE Transactions on*, 47(7):1091–1107. [11](#)

- [10] Borrelli, F. and Keviczky, T. (2008). Distributed lqr design for identical dynamically decoupled systems. *Automatic Control, IEEE Transactions on*, 53(8):1901–1912. [11](#), [15](#), [17](#), [21](#), [22](#)
- [11] Chakraborty, A. (2012). Wide-area damping control of power systems using dynamic clustering and tcsc-based redesigns. *Smart Grid, IEEE Transactions on*, 3(3):1503–1514. [10](#)
- [12] Chakraborty, A. and Chow, J. (2013). Measurement-based methods for model reduction of power systems using synchrophasors. In *Power System Coherency and Model Reduction*, pages 159–197. Springer. [34](#)
- [13] Chakraborty, A., Chow, J., and Salazar, A. (2011). A measurement-based framework for dynamic equivalencing of large power systems using wide-area phasor measurements. *Smart Grid, IEEE Transactions on*, 2(1):68–81. [34](#)
- [14] Chaudhuri, N. R., Domahidi, A., Majumder, R., Chaudhuri, B., Korba, P., Ray, S., and Uhlen, K. (2010). Wide-area power oscillation damping control in nordic equivalent system. *IET Generation, Transmission Distribution*, 4(10):1139–1150. [3](#)
- [15] Chow, J. H. (1982). *Time-scale modeling of dynamic networks with applications to power systems*. Springer Berlin etc. [34](#)
- [16] Cresap, R. and Hauer, J. (1981). Emergence of a new swing mode in the western power system. *Power Apparatus and Systems, IEEE Transactions on*, PAS-100(4):2037–2045. [14](#)
- [17] Dagle, J. (2009). North american synchrophasor initiative - an update of progress. In *2009 42nd Hawaii International Conference on System Sciences*, pages 1–5. [40](#)
- [18] Dagle, J. E. (2010). The north american synchrophasor initiative (naspi). In *IEEE PES General Meeting*, pages 1–3. [10](#)
- [19] D’Andrea, R. and Dullerud, G. (2003). Distributed control design for spatially interconnected systems. *Automatic Control, IEEE Transactions on*, 48(9):1478–1495. [11](#)

- [20] Deng, J., Li, C., and Zhang, X. P. (2015). Coordinated design of multiple robust facts damping controllers: A bmi-based sequential approach with multi-model systems. *IEEE Transactions on Power Systems*, 30(6):3150–3159. [2](#), [3](#)
- [21] Donaldson, D. L. and Piper, D. M. (2015). Advances in remedial action scheme modeling for power system analysis. In *Power and Energy Engineering Conference (APPEEC), 2015 IEEE PES Asia-Pacific*, pages 1–5. [64](#)
- [22] Dong, Z., Zhang, P., Ma, J., Zhao, J., Ali, M., Meng, K., and Yin, X. (2010). *Emerging Techniques in Power System Analysis*. Springer Berlin Heidelberg. [64](#), [78](#)
- [23] Donoho, D. L. (2006). Compressed sensing. *IEEE Trans. Inform. Theory*, 52:1289–1306. [36](#)
- [24] Dorfler, F., Jovanovic, M., Chertkov, M., and Bullo, F. (2014). Sparsity-promoting optimal wide-area control of power networks. *Power Systems, IEEE Transactions on*, 29(5):2281–2291. [3](#), [31](#), [37](#), [39](#)
- [25] Dotta, D., e Silva, A., and Decker, I. (2009). Wide-area measurements-based two-level control design considering signal transmission delay. *Power Systems, IEEE Transactions on*, 24(1):208–216. [10](#)
- [26] Dullerud, G. and D’Andrea, R. (2004). Distributed control of heterogeneous systems. *Automatic Control, IEEE Transactions on*, 49(12):2113–2128. [11](#)
- [27] Eriksson, R. and Soder, L. (2011). Wide-area measurement system-based subspace identification for obtaining linear models to centrally coordinate controllable devices. *IEEE Transactions on Power Delivery*, 26(2):988–997. [13](#), [34](#)
- [28] Fardad, M., Lin, F., and Jovanovic, M. (2011). Sparsity-promoting optimal control for a class of distributed systems. In *American Control Conference (ACC), 2011*, pages 2050–2055. [11](#), [36](#)
- [29] Fatehi, F., Smith, J. R., and Pierre, D. A. (1996). Robust power system controller design based on measured models. *IEEE Transactions on Power Systems*, 11(2):774–780. [13](#)

- [30] Force, W. R. E. M. T. (2014). Cross-current compensation model. [75](#)
- [31] Hamdan, H. and Hamdan, A. (1987). On the coupling measures between modes and state variables and subsynchronous resonance. *Electric power systems research*, 13(3):165–171. [57](#)
- [32] Hauer, J. (2002). Preliminary examination of the alberta trip on august 4, 2000. *Working Note for the WECC Modeling and Validation Work Group*. [8](#)
- [33] Hauer, J., Lee, H., Burns, J., and Baker, R. (2003). Preliminary analysis of western system oscillation event on june 4, 2003: Bpa and canada. *Working Note for the WECC Disturbance Monitoring Work Group*. [8](#)
- [34] Heniche, A. and Karnwa, I. (2002). Control loops selection to damp inter-area oscillations of electrical networks. *Power Systems, IEEE Transactions on*, 17(2):378–384. [56](#), [61](#)
- [35] Hill, D., Liu, T., and Verbic, G. (2012). Smart grids as distributed learning control. In *Power and Energy Society General Meeting, 2012 IEEE*, pages 1–8. IEEE. [15](#)
- [36] Huang, L. (2003). *Electromechanical Wave Propagation in Large Electric Power Systems*. PhD thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. [xii](#), [15](#), [23](#), [24](#)
- [37] Huang, L., Parashar, M., Phadke, A., and Thorp, J. (2002). Impact of electromechanical wave propagation on power system protection and control. In *Proceedings 2001 CIGRE conference*. [14](#)
- [38] Huang, Z., Zhou, N., Tuffner, F., Chen, Y., Trudnowski, D., Mittelstadt, W., Hauer, J., and Dagle, J. (2010a). Improving small signal stability through operating point adjustment. In *Power and Energy Society General Meeting, 2010 IEEE*, pages 1–8. [8](#)
- [39] Huang, Z., Zhou, N., Tuffner, F. K., Chen, Y., Trudnowski, D. J., Diao, R., Fuller, J. C., Mittelstadt, W. A., Hauer, J. F., and Dagle, J. E. (2010b). *MANGO: Modal*

Analysis for Grid Operation: a Method for Damping Improvement Through Operating Point Adjustment. Pacific Northwest National Laboratory. [12](#), [85](#)

- [40] Jenatton, R., Mairal, J., Obozinski, G., and Bach, F. (2011). Proximal methods for hierarchical sparse coding. *J. Mach. Learn. Res.*, 12:2297–2334. [37](#), [39](#)
- [41] Juan, S.-G., John, P., Charles, C., Prabha, K., and Einar, L. (2007). *Power System Stability and Control*, chapter 9 Small Signal Stability and Power System Oscillations. CRC Press. [8](#)
- [42] Kamwa, I., Grondin, R., and Hebert, Y. (2001). Wide-area measurement based stabilizing control of large power systems-a decentralized/hierarchical approach. *Power Systems, IEEE Transactions on*, 16(1):136–153. [10](#)
- [43] Kamwa, I., Trudel, G., and Gerin-Lajoie, L. (1995). Low-order black-box models for control system design in large power systems. In *Proceedings of Power Industry Computer Applications Conference*, pages 190–198. [13](#)
- [44] Khosravani, S., Naziri, I., Afshar, A., and Karrari, M. (2011). Fault tolerant control of large power systems subject to sensor failure. In *Power Engineering, Energy and Electrical Drives (POWERENG), 2011 International Conference on*, pages 1–7. [91](#)
- [45] Kincic, S., Davies, D., Kosterev, D., Zhang, H., Thomas, B., Vaiman, M., Weber, J., and Ramanathan, R. (2016). Bridging the gap in between operation and planning in WECC. In *2016 IEEE Power Energy Society General Meeting*. [64](#), [67](#)
- [46] Klein, M., Rogers, G. J., Moorty, S., and Kundur, P. (1992). Analytical investigation of factors influencing power system stabilizers performance. *IEEE Transactions on Energy Conversion*, 7(3):382–390. [94](#)
- [47] Kosterev, D. N., Taylor, C. W., and Mittelstadt, W. A. (1999). Model validation for the August 10, 1996 WSCC system outage. *IEEE Transactions on Power Systems*, 14(3):967–979. [8](#), [9](#), [12](#), [85](#), [94](#), [95](#)

- [48] Kundur, P., Balu, N. J., and Lauby, M. G. (1994). *Power system stability and control*, volume 7. McGraw-hill New York. [xii](#), [xiv](#), [9](#), [41](#), [89](#)
- [49] Kundur, P., Klein, M., Rogers, G., and Zywno, M. (1989). Application of power system stabilizers for enhancement of overall system stability. *Power Systems, IEEE Transactions on*, 4(2):614–626. [9](#)
- [50] Kundur, P., Lee, D., and Zein El-Din, H. (1981). Power system stabilizers for thermal units: Analytical techniques and on-site validation. *Power Apparatus and Systems, IEEE Transactions on*, PAS-100(1):81–95. [8](#)
- [51] Kundur, P., Paserba, J., Ajarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., et al. (2004). Definition and classification of power system stability ieee/cigre joint task force on stability terms and definitions. *IEEE transactions on Power Systems*, 19(3):1387–1401. [8](#)
- [52] Kunjumammed, L. P., Singh, R., and Pal, B. C. (2012). Robust signal selection for damping of inter-area oscillations. *IET Generation, Transmission Distribution*, 6(5):404–416. [3](#)
- [53] Langbort, C., Chandra, R., and D’Andrea, R. (2004). Distributed control design for systems interconnected over an arbitrary graph. *Automatic Control, IEEE Transactions on*, 49(9):1502–1519. [3](#), [15](#)
- [54] Lesieutre, B., Scholtz, E., and Verghese, G. C. (2002). Impedance matching controllers to extinguish electromechanical waves in power networks. In *Control Applications, 2002. Proceedings of the 2002 International Conference on*, volume 1, pages 25–30 vol.1. [14](#)
- [55] Lesieutre, B. C. and Verghese, E. (2002). A zero-reflection controller for electromechanical disturbances in power networks. In *Power Systems Computation Conference (PSCC), Sevilla*, pages 24–28. [14](#)
- [56] Li, Y., Rehtanz, C., Ruberg, S., Luo, L., and Cao, Y. (2012a). Assessment and choice of input signals for multiple hvdc and facts wide-area damping controllers. *IEEE Transactions on Power Systems*, 27(4):1969–1977. [3](#)

- [57] Li, Y., Rehtanz, C., Ruberg, S., Luo, L., and Cao, Y. (2012b). Wide-area robust coordination approach of hvdc and facts controllers for damping multiple interarea oscillations. *IEEE Transactions on Power Delivery*, 27(3):1096–1105. [3](#)
- [58] Lin, F. (December 2012). *Structure identification and optimal design of large-scale networks of dynamical systems*. PhD thesis, The University of Minnesota. [35](#)
- [59] Lin, F., Fardad, M., and Jovanovic, M. (2013). Design of optimal sparse feedback gains via the alternating direction method of multipliers. *Automatic Control, IEEE Transactions on*, 58(9):2426–2431. [36](#), [37](#), [38](#)
- [60] Lu, C., Li, L., He, J., Wu, X., and Li, P. (2007). Optimal coordinate design of multiple hvdc modulation controllers based on mimo system identification. In *2007 IEEE Power Engineering Society General Meeting*, pages 1–6. [13](#)
- [61] Lu, C., Zhang, X., Wang, X., and Han, Y. (2015). Mathematical expectation modeling of wide-area controlled power systems with stochastic time delay. In *2015 IEEE Power Energy Society General Meeting*, pages 1–1. [3](#)
- [62] Mahmoudi, M., Dong, J., Tomsovic, K., and Djouadi, S. (2015). Application of distributed control to mitigate disturbance propagations in large power networks. In *North American Power Symposium (NAPS), 2015*, pages 1–6. [11](#), [86](#)
- [63] Mahmoudi, M., Kincic, S., Zhang, H., and Tomsovic, K. (2017). Implementation and testing of remedial action schemes for real-time transient stability studies. In *2017 IEEE Power Energy Society General Meeting*, pages 1–5. [68](#)
- [64] Mahmoudi, M. and Tomsovic, K. (2016a). *Distributed Control Design for Damping Inter-area Oscillations in Cyber-Physical Power Networks*, chapter Cyber-Physical-Social Systems and Constructs in Electric Power Engineering, pages 15–38. The Institution of Engineering and Technology (IET). [63](#), [64](#)
- [65] Mahmoudi, M. and Tomsovic, K. (2016b). A distributed control design methodology for damping critical modes in power systems. In *2016 IEEE Power and Energy Conference at Illinois (PECI)*, pages 1–6. [64](#)

- [66] Mahmoudi, M. and Tomsovic, K. (2016c). A distributed control design methodology for damping critical modes in power systems. In *Power and Energy Conference at Illinois (PECI), 2016 IEEE*, pages 1–6. IEEE. [85](#)
- [67] Mahmoudi, M. and Tomsovic, K. (2016d). Measurement-based models for wide-area control design in the future power grid. In *Innovative Smart Grid Technologies Conference (ISGT), 2016 IEEE Power Energy Society*, pages 1–5. [63](#), [64](#)
- [68] Munz, U., Pfister, M., and Wolfrum, P. (2014). Sensor and actuator placement for linear systems based on h_2 and h_∞ optimization. *Automatic Control, IEEE Transactions on*, 59(11):2984–2989. [36](#)
- [69] Naduvathuparambil, B., Valenti, M., Feliachi, A., et al. (2002). Communication delays in wide-area measurement systems. In *Southeastern Symposium on System Theory*, volume 34, pages 118–122. Citeseer. [91](#)
- [70] Nguyen-Duc, H., Dessaint, L. A., Okou, A. F., and Kamwa, I. (2010). Selection of input/output signals for wide area control loops. In *IEEE PES General Meeting*, pages 1–7. [3](#)
- [71] Ni, H., Heydt, G., and Mili, L. (2002). Power system stability agents using robust wide area control. *Power Systems, IEEE Transactions on*, 17(4):1123–1131. [10](#)
- [72] Okamoto, H., Kurita, A., Sanchez-Gasca, J. J., Clark, K., Miller, N. W., and Chow, J. H. (1996). Identification of equivalent linear power system models from electromagnetic transient time domain simulations using prony’s method. In *Proceedings of 35th IEEE Conference on Decision and Control*, volume 4, pages 3857–3863 vol.4. [13](#)
- [73] Pal, B. and Chaudhuri, B. (2006). *Robust control in power systems*. Springer Science & Business Media. [9](#)
- [74] Parashar, M., Thorp, J. S., and Seyler, C. E. (2004). Continuum modeling of electromechanical dynamics in large-scale power systems. *Circuits and Systems I: Regular Papers, IEEE Transactions on*, 51(9):1848–1858. [14](#), [25](#)

- [75] Parikh, N. and Boyd, S. (2013). Proximal algorithms. *Foundations and Trends in optimization*, 1(3):123–231. [39](#)
- [76] Peng, L., Xiaochen, W., Chao, L., Jinghai, S., Jiong, H., Jingbo, H., Yong, Z., and Xu, A. (2009). Implementation of csg’s wide-area damping control system: Overview and experience. In *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, pages 1–9. [2](#), [10](#)
- [77] Pourbeik, P. (2010). Approaches to validation of power system models for system planning studies. In *Power and Energy Society General Meeting, 2010 IEEE*, pages 1–10. [12](#)
- [78] Preece, R., Milanovic, J. V., Almutairi, A. M., and Marjanovic, O. (2013). Damping of inter-area oscillations in mixed ac/dc networks using wams based supplementary controller. *IEEE Transactions on Power Systems*, 28(2):1160–1169. [2](#)
- [79] Raoufat, M. E., Tomsovic, K., and Djouadi, S. M. (2016). Virtual actuators for wide-area damping control of power systems. *IEEE Transactions on Power Systems*, 31(6):4703–4711. [64](#)
- [80] Ree, J. D. L., Centeno, V., Thorp, J. S., and Phadke, A. G. (2010). Synchronized phasor measurement applications in power systems. *IEEE Transactions on Smart Grid*, 1(1):20–27. [90](#)
- [81] Sauer, P. W. and Pai, M. (1998). *Power system dynamics and stability*, volume 4. Prentice Hall Upper Saddle River, NJ. [20](#), [33](#)
- [82] Semlyen, A. (1974). Analysis of disturbance propagation in power systems based on a homogeneous dynamic model. *Power Apparatus and Systems, IEEE Transactions on*, (2):676–684. [14](#)
- [83] Taalimi, A. and Qi, H. (2015). Robust multi-object tracking using confident detections and safe tracklets. In *2015 IEEE International Conference on Image Processing (ICIP)*, pages 1638–1642. [39](#)

- [84] Taalimi, A., Qi, H., and Khorsandi, R. (2015). Online multi-modal task-driven dictionary learning and robust joint sparse representation for visual tracking. In *Advanced Video and Signal Based Surveillance (AVSS), 2015 12th IEEE International Conference on*, pages 1–6. 36
- [85] Taalimi, A., Rahimpour, A., Capdevila, C., Zhang, Z., and Qi, H. (2016a). Robust coupling in space of sparse codes for multi-view recognition. In *2016 IEEE International Conference on Image Processing (ICIP)*, pages 3897–3901. 36
- [86] Taalimi, A., Rahimpour, A., Liu, L., and Qi, H. (2017). Multi-view task-driven recognition in visual sensor networks. In *2017 IEEE International Conference on Image Processing (ICIP)*. 39
- [87] Taalimi, A., Shams, H., Rahimpour, A., Khorsandi, R., Wang, W., Guo, R., and Qi, H. (2016b). Multimodal weighted dictionary learning. In *2016 13th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*, pages 173–179. 39
- [88] Thomas, B., Kincic, S., Davies, D., Zhang, H., and Sanchez-Gasca, J. (2016). A new framework to facilitate the use of node-breaker operations model for system model validation in WECC. In *2016 IEEE Power Energy Society General Meeting*, pages 1–5. 64
- [89] Tomsovic, K., Bakken, D. E., Venkatasubramanian, V., and Bose, A. (2005). Designing the next generation of real-time control, communication, and computations for large power systems. *Proceedings of the IEEE*, 93(5):965–979. 15
- [90] Trudnowski, D., Kosterev, D., and Undrill, J. (2013). Pdc damping control analysis for the western north american power system. In *2013 IEEE Power Energy Society General Meeting*, pages 1–5. 2
- [91] Trudnowski, D., Pierre, J., Zhou, N., Hauer, J., and Parashar, M. (2008). Performance of three mode-meter block-processing algorithms for automated dynamic stability assessment. In *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, pages 1–1. 13

- [92] Van Overschee, P. and De Moor, B. (2012). *Subspace identification for linear systems: Theory, Implementation, Applications*. Springer Science & Business Media. 86
- [93] Wang, S.-H. and Davison, E. (1973). On the stabilization of decentralized control systems. *IEEE Transactions on Automatic Control*, 18(5):473–478. 11
- [94] Wang, Z., Chung, C., Wong, K., and Tse, C. (2008). Robust power system stabiliser design under multi-operating conditions using differential evolution. *Generation, Transmission Distribution, IET*, 2(5):690–700. 9
- [95] Wu, H., Tsakalis, K. S., and Heydt, G. T. (2004). Evaluation of time delay effects to wide-area power system stabilizer design. *IEEE Transactions on Power Systems*, 19(4):1935–1941. 3
- [96] Yao, W. and Jiang, L. (2014). Wide-area damping controller of facts devices for inter-area oscillations considering communication time delays. In *2014 IEEE PES General Meeting / Conference Exposition*, pages 1–1. 2
- [97] Yao, W., Jiang, L., Wen, J., Wu, Q., and Cheng, S. (2015). Wide-area damping controller for power system interarea oscillations: A networked predictive control approach. *IEEE Transactions on Control Systems Technology*, 23(1):27–36. 2
- [98] Yousefian, R. and Kamalasadan, S. (2014). Design and real-time implementation of optimal power system wide area system-centric controller based on temporal difference learning. In *Industry Applications Society Annual Meeting*, pages 1–7. IEEE. 11
- [99] Yousefian, R., Sahami, A., and Kamalasadan, S. (2015). Hybrid energy function based real-time optimal wide-area transient stability controller for power system stability. In *Industry Applications Society Annual Meeting*, pages 1–8. IEEE. 11
- [100] Zhang, H. and Wang, B. (2012). Implementation of a full western bulk system operational model for reliability monitoring. In *2012 IEEE Power and Energy Society General Meeting*, pages 1–7. 67

- [101] Zhang, J., Chung, C. Y., Lu, C., Men, K., and Tu, L. (2015). A novel adaptive wide area pss based on output-only modal analysis. In *2015 IEEE Power Energy Society General Meeting*, pages 1–1. [2](#)
- [102] Zhang, J., Chung, C. Y., Zhang, S., and Han, Y. (2013). Practical wide area damping controller design based on ambient signal analysis. *IEEE Transactions on Power Systems*, 28(2):1687–1696. [2](#)
- [103] Zhang, X., Lu, C., Liu, S., and Wang, X. (2016). A review on wide-area damping control to restrain inter-area low frequency oscillation for large-scale power systems with increasing renewable generation. *Renewable and Sustainable Energy Reviews*, 57:45–58. [2](#), [10](#)
- [104] Zhang, Y. and Bose, A. (2008). Design of wide-area damping controllers for interarea oscillations. *Power Systems, IEEE Transactions on*, 23(3):1136–1143. [2](#), [3](#), [10](#), [11](#), [56](#)
- [105] Zhao, Y., Lu, C., Liu, Y., and Han, Y. (2012). Residue and identification based wide-area damping controller design in large-scale power system. In *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, pages 1–7. [3](#)
- [106] Zhou, K. and Doyle, J. (1998). *Essentials of Robust Control*. Prentice Hall. [38](#)
- [107] Zhou, N., Pierre, J., and Hauer, J. (2008). Initial results in power system identification from injected probing signals using a subspace method. In *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, pages 1–1. [13](#)

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