

Chapter 1

Introduction

This chapter provides a concise overview of the low-frequency oscillations arising from the increased integration of Inverter-Based Resources (IBRs), including renewable sources like wind energy, and energy storage systems such as Battery Energy Storage System (BESS) and Virtual Synchronous Generator (VSG) in the power grid. It is the foundational introduction to the research conducted and reported in this thesis. This chapter begins by discussing the background and current state of renewable sources and IBR integration, and causing low-frequency oscillations and threatening frequency instability, followed by a comprehensive literature review that identifies existing research gaps and highlights the motivations behind this study. It then sets forth the research objectives and concludes with the organization of the thesis.

1.1 Background overview

The increased integration of renewable energy resources into the global power grid is driven by the urgent need to reduce carbon emissions and combat climate change. The rapid adoption of wind, solar, and other renewables is transforming power system dynamics and presenting challenges for stability and reliability. Among these challenges, Low-Frequency Oscillations (LFOs) have emerged as a critical issue that can undermine operational security if not adequately addressed. LFOs can cause inefficiencies, increase equipment wear, and, in severe cases, trigger blackouts. Effective mitigation strategies, including advanced control systems and robust damping techniques, are crucial to ensure the smooth integration of renewable energy while maintaining grid stability. Additionally,

the variability and intermittency of Renewable Energy Sources (RESs) require enhanced grid management and flexible energy storage solutions to balance supply and demand. Addressing these challenges is vital for achieving a sustainable, reliable, and resilient power grid in the face of increasing renewable energy penetration.

The modern power grid originated in the late 19th and early 20th centuries with centralized power generation and distribution. Initially, small-scale generators supplied local areas, but growing demand led to interconnected systems for better reliability and efficiency. Throughout the 20th century, fossil fuels dominated power generation, with coal, natural gas, and oil plants providing high inertia to stabilize the grid. Nuclear power emerged in the mid 20th century, diversifying the energy mix. Later, environmental concerns encouraged a shift to cleaner energy. While hydropower contributed significantly, advancements in wind and solar technologies in the late 20th and early 21st centuries made them viable for large-scale generation.

RESs such as wind turbines and solar photovoltaic systems usually lack the inertia provided by large Synchronous Generators (SGs) in traditional power systems. These generators stabilize the grid by absorbing and releasing energy to mitigate frequency fluctuations. However, renewable sources connected via power electronics contribute minimal inertia, which amplifies the effects of disturbances and increases the system's susceptibility to oscillations and instability. Effectively addressing this challenge is crucial for ensuring the reliable and stable integration of renewable energy into the power grid while maintaining grid stability and reliability. This lack of inertia exacerbates the impact of disturbances, making the system more susceptible to oscillations and instability. The power electronic interfaces inherent in RESs present unique dynamics and control challenges. The Inverter-Based Resources (IBRs), utilizing advanced control strategies like Virtual Synchronous Generator (VSG), can mitigate this challenge by emulating synchronous machine behaviour, enhancing damping and mitigating LFOs. Synthetic inertia provided by VSGs helps stabilize the grid by responding rapidly to frequency deviations, thereby addressing the challenges posed by reduced inertia in renewable-integrated power systems.

Integrating Energy Storage System (ESS) into power systems plays a crucial role in enhancing the damping of inter-area oscillations, which is critical for maintaining grid stability amidst increasing renewable energy integration. Traditional synchronous genera-

tors, which provide natural inertia for grid stabilization, are being replaced by renewables with minimal inertia, escalating the risk of grid instability. ESS provide rapid and precise control over active and reactive power, stabilizing grid frequency and damping oscillations, especially in areas susceptible to variability from renewables. Strategic deployment of ESS within the grid enables operators to quickly mitigate frequency deviations by injecting or absorbing power, thereby preserving system inertia and damping characteristics compromised by renewable integration. Moreover, ESS can operate independently or in conjunction with other stabilization technologies like Power System Stabilizer (PSS) and Wide-Area Damping Controller (WADC), ensuring optimal damping without compromising overall grid reliability. In addition to damping oscillations, ESS provides critical ancillary services, frequency regulation, voltage support, and load balancing, which are essential for maintaining stability in renewable-rich environments.

LFOs, typically ranging from 0.1 to 2 Hz, are electromechanical oscillations arising from dynamic interactions among generators, loads, and other components in the power network. This oscillation mode is categorized as local and inter-area oscillation mode. The local oscillation modes in power systems occur when SGs in a single geographic area oscillate against each other at frequencies of 1–2 Hz. Conversely, inter-area oscillation modes manifest when SGs in one area oscillate against those in another. These oscillations pose risks such as power swings, mechanical stress on equipment, and potential system-wide blackouts. The traditional method uses Power System Stabilizer (PSS), which enhances damping by adjusting the excitation of SG to mitigate system LFOs. While effective for local oscillations, PSS may face limitations in grids heavily integrated with renewable energy sources due to the latter’s variability and reduced inertia. This can pose challenges, particularly in damping inter-area oscillations spanning multiple generators across extensive geographical areas.

To address these challenges, this thesis explores integrating robust Wide-Area Damping Controller (WADC) with conventional PSS. Unlike traditional PSS, which operates based on localized generator measurements, WADC utilizes wide-area data from Phasor Measurement Units (PMUs) distributed across the grid. These PMUs provide real-time electrical system information, enabling WADC to implement coordinated control actions that effectively damp inter-area oscillations prevalent in large interconnected systems with significant renewable generation. The combination of WADC and traditional PSS offers a

promising approach to strengthening overall stability and resilience in modern power networks. By using wide-area measurements and advanced control strategies, this integrated approach aims to mitigate challenges posed by LFOs, supporting reliable grid operation amidst increasing renewable energy integration and dynamic operational conditions.

This thesis explores robust control strategies, including H_∞ , fixed structure H_∞ , mixed sensitivity H_∞ , and H_2/H_∞ control, to enhance system damping performance under different operating scenarios. By integrating these strategies with traditional PSS and advanced WADC, the research addresses the challenge of maintaining stability and reliability amidst increasing renewable energy penetration, ensuring stable operation in modern power systems.

1.2 Literature Survey

This thesis focuses on identifying the optimal location for installing PSS in SG into multi-machine power systems and enhancing system inter-area oscillation damping in low inertia conditions caused by high penetration of the Wind Turbine System (WTS). It proposes a dual-channel WADC designed for WTS applications using the H_∞ control method. Additionally, this thesis investigates the optimal placement of Battery Energy Storage System (BESS) in the power system and determines the effective locations and feedback signals for the WADC. It highlights the dynamic interactions between BESS control modes and SGs and how BESS control loop parameters influence damping for system LFO. Furthermore, the thesis explores how IBRs, controlled via Virtual Synchronous Generator (VSG), impact power system LFOs, which are integrated into the system of low-inertia buses. It analyzes the impact of dynamic interaction between the power network and active and reactive power loops of IBR with varying parameters on damping system LFO modes. The Supplementary Damping Controller (SDC) scheme that links to the active and reactive control loops of IBRs is proposed to mitigate IBRs power oscillations and improve overall system stability. The subsequent sections provide a comprehensive overview of current research, addressing existing issues and challenges related to these topics.

1.2.1 Effects of low-frequency oscillations on power system performance

A major problem in modern power systems is transferring large amounts of power across long transmission lines from one region to another due to rising power demand. In order to improve the transient stability of the power system, nonlinear components such as fast automatic voltage regulators are frequently being integrated. On the other hand, incorporating such devices gives rise to developing LFOs at frequencies below 2 Hz [1], which are sustained in the system. When SGs oscillate against one another at a frequency of 1–2 Hz in a single geographical area, local oscillation modes are triggered in a power system. On the other hand, inter-area oscillation modes are observed when a set of SGs in one area swings against a group of SGs in another area in the frequency range of 0.1 to 1 Hz.

The LFOs must be damped out as quickly as possible to make the system stable and dependable because they are harmful. Consequently, reducing power flow through long transmission networks and installing PSSs on SGs are two conventional methods for damping LFOs in multi-machine power systems [2]. However, due to the lack of global observability in local signals, PSSs are ineffective for damping inter-area oscillation modes [3]. To resolve this issue, a WADC is introduced that offers enough damping to reduce inter-area oscillations in the interconnected power system. Flexible AC Transmission Systems (FACTS) controllers were used earlier for damping power oscillations. However, additional controls were needed to offer more damping [4]. A variety of actuators, including wind energy conversion systems [5], solar photovoltaic systems [6], and energy storage systems [7], are employed for damping controller design to mitigate system inter-area oscillation.

1.2.2 Influence of renewable energy sources on power system LFO damping

The integration of RESs into power systems significantly impacts the damping of LFO. RES, such as Wind Turbine System (WTS) and Solar Photovoltaics, inherently differ from traditional synchronous generators in their contribution to system inertia and damping characteristics. The intermittent and variable nature of RES often leads to reduced system

inertia, which can exacerbate LFOs and pose stability challenges. This reduction in inertia decreases the natural damping provided by synchronous machines, making the power system more susceptible to oscillatory instability.

Substantial integration of renewable sources, mainly through a Doubly-Fed Induction Generator (DFIG) for wind power generation, would potentially change the dynamic performance of modern power systems. Integrating a grid-connected DFIG-based WTS causes dynamic interactions and changes in the load flow circumstances of power systems. The LFOs in the power system are affected by the dynamic interactions between the WTS and the SGs [8]. This interaction introduces new oscillation modes specific to the behaviour of the WTS. The several factors affecting power system stability, such as wind farm integration, wind penetration levels, and SG replacements with equivalent wind farm capacity, are discussed in [9]. However, the high penetration of DFIG-based wind farms in the power system may have a negative effect on the damping of critical oscillation modes [10]. This is primarily due to the replacement of SG and the less synchronized coupling. Additionally, the dynamic interaction among WTS converter controls and the reduction of system inertia can exacerbate this impact on the power system. These circumstances result in intricate power oscillations in the system and must be mitigated as soon as conceivable to preserve the stability and dependability of the system. The typical PSS may not be capable of controlling the power oscillations in these conditions [11].

The influence of Superconducting Magnetic Energy Storage (SMES) and DFIG-based wind farms on power system inter-area oscillations are investigated in [12]. It also examines SMES operating in virtual synchronous generator control mode for mitigating these oscillations in erratic wind conditions. The WTS-based wind farm, with a supplementary Power Oscillation Damping (POD) controller, has recently been used to mitigate LFO modes in the power system [13]. The coordinated auxiliary damping control of WTS along with PSS to mitigate power systems LFOs is presented in [14]. The coordinated PSS and POD provide a more substantial damping effect in inter-area mode than separate control of PSS or POD controller. Further, the design of PSS and Static Synchronous Compensator (STATCOM)-based POD controllers are discussed in [15]. These controllers work in coordination to suppress LFOs while maintaining voltage stability in a wind-PV-thermal-bundled power network. The controller's parameters are optimized using a combination of genetic and particle swarm optimization methods. Moreover, in

[16], a second-order sliding mode control scheme is presented for WTS to improve their fault-ride-through capability when facing unbalanced grid faults.

1.2.3 Effect of energy storage systems on LFO damping in power systems

The integration of Energy Storage Systems (ESSs) is pivotal for enhancing LFO damping in power systems. Unlike traditional generation sources, ESS provides rapid and precise control over active power injections, supporting system stability. Strategically placing ESS at critical grid points, especially near areas prone to oscillations or high variability in renewable generation, effectively mitigates LFOs. ESS primarily improves damping by quickly adjusting power in response to grid frequency fluctuations, thereby regulating system inertia and damping characteristics often compromised by renewable integration. ESS operates autonomously or in coordination with PSS and WADC, ensuring optimal damping contribution without compromising grid reliability.

Recent technological advancements have increased ESS capabilities, which, when properly integrated, could lead to better dynamics. Among the numerous well-liked ESSs are the energy capacitor system, Battery Energy Storage System (BESS), and flywheel energy storage system. ESS can assist with real-time regulation of active and reactive power by enhancing the stability and security of the power system. Applying energy storage-based technology to enhance transient stability and LFO damping in multi-machine systems is fascinating. The application of BESS in power systems for frequency stability and oscillation damping is discussed in [17, 18]. ESS is more effective and efficient than FACTS and PSSs for reducing the power oscillation between two interconnected power systems [19]. Also, ESS is a better choice for increasing power system stability than a renewable generation source with a POD controller [20].

ESS can enhance the power system's dynamic stability by using its quick, active power-providing capability. In [21], using an energy storage device with optimal feedback control schemes is suggested to improve power dynamic performance, encompassing enhanced power flow through inter-area lines and effective frequency regulation during varying loading conditions. This has been accomplished using a variety of advanced control techniques, including Sliding Mode Control [22], finite-time control [23], and model

predictive control [24]. Also, the mixed-Particle Swarm Optimization (PSO) technique described in [25] is used to optimize the location and damping controller parameters for BESSs to improve the power system LFO mode damping.

1.2.4 Effect of IBR controlled through VSG technique on power system LFO damping

In RES-based generation, Inverter-Based Resources (IBR) is utilized to feed power into the grid. However, the increased penetration of RES-based generation in modern power systems reduces grid inertia and damping performance due to the absence of inherent rotating inertia in IBR-based RES [26]. This effect may be particularly pronounced when RES is integrated into power grids via IBR, given their high voltage level and substantial power capacity.

The conventional control strategy for grid-connected IBRs is grid-following control, where the IBR synchronizes with the power grid to facilitate electricity generation. However, this approach does not offer inertia support to the grid, potentially leading to stability issues. As a result, power systems with a high share of RES might experience significant oscillations, even from minor disturbances, which could compromise frequency stability and risk cascading failures [27, 28].

One promising approach to address this issue is to have IBR mimic the rotor behaviour of synchronous generators through a control strategy known as Virtual Synchronous Generator (VSG) [29]. The VSG can provide the inertia support typically offered by traditional generators, enhancing grid stability. However, poorly designed VSG might suffer from considerable power oscillations during transients, similar to those seen with conventional SG.

The effect of system LFO mode damping with multiple grid-connected VSG is discussed in [30]. Recent studies suggest[31] that new LFO modes may emerge from interactions between SGs and RESs, introducing additional risks to system stability. Further, the dynamic interaction between Grid Forming Converter (GFC) and power systems is explored in [32], with GFCs controlled via the VSG technique with varying parameters in the active control loop. This control mode interaction could significantly impact system stability. Existing studies have discussed the dynamic interaction between a single IBR

controlled through the VSG technique and the power system. However, the impact of LFO damping from control mode interactions among IBRs and power systems has not been explored well. Therefore, this work explores the dynamic interactions between IBRs controlled through the VSG technique and power systems, focusing on how variations in the active and reactive power control loop parameters of these IBRs affect system stability in terms of LFO damping.

The VSG control for IBR can exhibit some of the same disadvantages as traditional SG, notably power oscillations caused by large inertia [33]. This issue can be even more pronounced in systems with parallel VSG configurations, as reported in [34, 35]. Power oscillations can have more severe consequences in a VSG than in a traditional SG because power semiconductor devices have lower overcurrent capability, and the power-electronic-based grids they inhabit have much lower natural damping. A power reference feedforward-based damping control scheme is suggested in [36] to reduce active power oscillations in VSG. In addition, other control schemes, including frequency feedback [37], power feedback [38], and a combined power and frequency feedback [34] damping control scheme, are recommended to control active power oscillations in VSG systems when loading conditions change.

Most previous studies on VSGs have primarily focused on their application in microgrid systems. However, LFOs remain a significant concern for large power systems, particularly during bulk power transfers through weak tie-lines in the power grids. Various control approaches have been proposed to suppress power oscillations in the system. For example, adjusting damping/droop coefficients and inertia constants in VSG control has been explored to enhance system LFO damping performance [39]. However, the effectiveness of these adjustments can be limited, with some studies suggesting that changes like larger damping coefficients or smaller inertia constants can even lead to degraded system dynamic performance [40].

In addition to existing methods, several new techniques have been proposed to enhance system damping by incorporating additional control signals into the reactive power/voltage loop or active power loop of the VSG [40, 41]. The SDC design scheme is suggested in [42] for multiple VSG excitation loops to mitigate system LFOs. Additionally, tuning the droop coefficient parameters of the active power loop (D_p) and reactive power loop (D_q) in VSGs is suggested in [43]. This method focuses on enhancing VSG's

ability to control active and reactive power in response to frequency and voltage changes, respectively, thereby improving system damping in inter-area modes.

1.2.5 Wide-area damping controller for power system

The previous literature proposed several methods for mitigating the power system's LFOs, which employ the local signal to design the damping controller. Due to their poor observability, local signals are less effective in damping inter-area oscillation modes. In these situations, wide-area/global signals are selected for designing the WADC, which is utilized to mitigate LFO modes [44]. Wide-area control signals are now feasible to be measured via PMU devices as a result of recent advancements in wide-area measurement system technology. However, the local/wide-area signals are a natural consequence of real-world communication limitations, including packet failure and time delay. In practical scenarios, the time delay in WADCs can vary considerably, ranging from 6 ms to 1s, depending on the specific characteristics of the communication channel [45]. The performance of the WADC may be impacted by these constraints, making it essential to design the WADCs that are resistant to them. As a result, the WADC design process must consider the communication time delay in feedback signals.

The Pad'e approximation is a common modelling technique to consider continuous time delay. First and second-order Pad'e approximations are used in [46] and [47], respectively, to represent the time delay model. Further, the Adaptive Time-Delay Compensator (ATDC) technique is given in [48] to mitigate the effects of time delays. Inter-area oscillations damping through aggregated loads modulation without consideration of time delay is proposed [49]. The design approach described in [45] considers a fixed time delay while designing WADCs. In contrast, the design approach presented in [50] incorporates the consideration of a time delay with a small margin of 50 ms when designing WADC. As a result, the extensive range of communication time delay variations experienced by these WADCs could potentially undermine their capacity to deliver effective damping performance consistently.

Several methods are present in the literature to design WADC to mitigate the power system inter-area oscillations. A wide-area power system stabilizer is proposed in [51], with controller parameters designed using the phase compensation method. Further, a wide-area power system stabilizer has been designed for the voltage control loop of VSGs

to mitigate system LFOs under various operating conditions [52], and PSS parameters are optimized using the PSO technique. The STATCOM-based WADC is proposed in [53] with the ATDC designed to mitigate communication time delays' effects, and parameters are tuned using the PSO technique. The model predictive control based WADC is proposed in [54] to mitigate power system LFOs utilizing a self-triggered control strategy. Although these control techniques were initially designed for rudimentary systems with a focus on mitigating a single inter-area mode, their application and validation on extensive power networks comprising multiple inter-area oscillation modes have not been extensively validated.

As previously indicated, the issue can be resolved using the modal linear quadratic regulator control technique based on WADC presented in [55] to simultaneously reduce multiple inter-area power system oscillations. For solar photovoltaic systems, the time-delayed feedback control approach based on WADC is suggested in [56] to improve the damping of power system LFOs modes. Moreover, the fixed order robust H_∞ control scheme based WADC is described in [57], and the control scheme is synthesized using a non-smooth optimization method. The H_∞ control scheme-based WADC considering random delay and packet drops is suggested in [58]. The networked predictive control scheme-based wide-area POD controller is suggested in [59] for DFIG-based wind farms. Its purpose is to mitigate inter-area oscillations in multi-machine power systems. Interacting multiple model approach based WADC design for WTS incorporated power network to diminish various LFO modes is suggested [60]. The design scheme of a WADC is presented in [61], considering the uncertainty of power system operating conditions, communication time delays, and ensuring resilience against permanent communication channel failures. The WADC design in [62] is based on a multiple-controller switching technique to reduce different inter-area oscillations in the power system and alleviate strong attacks. Further, the WADC system discussed in [63] is designed for integration into large-scale wind generation power systems. The parameters of the WADC system are optimized using a multi-objective grey wolf algorithm, demonstrating its adaptability and efficiency in enhancing power system stability and performance.

1.3 Research Gap and Motivation

Power system networks are interconnected, nonlinear, and extremely complex systems susceptible to various events that might cause LFOs, which may affect the system's stability. These oscillations are detrimental and must be damped out as soon as possible to maintain system stability and reliability. Based on the literature review, the research gap and motivation behind this work are summarized below:

1. In much of the literature, PSS locations in power systems are typically predefined, while some studies use the Participation Factor (PF) method and sensitivity analysis to determine PSS locations. However, these methods often focus solely on state variables, neglecting input and output performance. They are insufficient for accurately estimating the contribution of damping torque from the power system damping controller to each SG in the LFO mode of interest.
2. The increasing integration of WTS results in low inertia in power grids that pose stability challenges. Not much effort has been made to study the impact of WTS on inter-area oscillations and control interactions with synchronous generators under low system inertia conditions.
3. The application of BESS in multi-machine power systems for frequency stability and oscillation damping, lack a detailed analysis on the optimal placement of BESS. Proper placement is crucial for enhancing inter-area oscillation damping, ensuring effective power flow management, system stabilization, and synchronization with other control mechanisms. Additionally, selecting effective damping control loops for BESS, such as active or reactive power control, for installing supplementary damping controllers has not been studied much.
4. Dynamic control mode interactions between BESS and SG under varying system loading scenarios and the design of damping controllers for BESS in wide-area scenarios with uncertainties need further investigation.
5. Existing studies have discussed the dynamic interaction between a single IBR controlled through the VSG technique and the power system. However, there is a lack of exploration regarding how variations in the parameters of the active and

reactive power control loops of multiple IBRs impact system stability in terms of LFO damping.

1.4 Research Objectives

The following are the research objectives of this thesis:

1. To propose the optimal placement of PSS in multi-machine power networks using the Damping Torque Index (DTI) to enhance damping performance against LFOs. PSS parameters are adjusted via phase compensation methodology. Furthermore, a reduced-order model-based WADC is designed and installed at the SG, where the optimal PSS is installed in the system to improve LFO damping performance.
2. To investigate how power system inter-area oscillation damping is affected by low system inertia due to high penetration of WTS operating in sub-synchronous, normal, and super-synchronous scenarios. It examines the dynamic interactions introduced by WTS and their control mode interactions with SGs under low inertia conditions, focusing on their impact on inter-area oscillations. Furthermore, a reduced-order model-based double-channel (i.e., active and reactive control loops) WADC is proposed for WTS to damp system inter-area oscillation.
3. To identify the appropriate location for installing BESS in the power system based on the maximum of all minimal residue indices using modal analysis under varying system loading conditions. This strategy is employed to choose the best location for the BESS, the appropriate feedback signal, and the suitable damping control loop (i.e., active or reactive power control) for placing a supplementary damping controller. A reduced-order model-based fixed-structure H_∞ scheme-based WADC is proposed to enhance the damping performance for system LFOs.
4. To study the impact of dynamic interaction between the BESS control modes and synchronous generators, along with BESS control parameters, on the damping of prominent inter-area oscillations under different loading conditions. To propose a robust WADC for a BESS-integrated power network to damp low-frequency oscillations.

5. To investigate the dynamic interaction between power networks and the active and reactive power loops of IBRs controlled via the VSG technique and to propose a Supplementary Damping Controller (SDC) to damp low-frequency oscillations in the network and power oscillations in IBRs.

1.5 Organisation of the Thesis

The thesis has been structured into seven chapters as follows:

- **Chapter 1:** This chapter introduces the thesis with a brief overview, followed by a comprehensive literature survey to identify research gaps and formulate the research problem. Subsequently, this chapter provides an overview of the thesis structure and its organization.
- **Chapter 2:** The linearized model of a multi-machine power system, including PSS, is proposed. The damping torque analysis method is proposed to determine the appropriate location for PSS in the power system. This chapter also compares the damping performance of PSS with locations identified using the participation factor method and sensitivity analysis methods. The reduced-order model-based WADC is also proposed, including feedback signal selection based on the GMO method. Finally, the damping performance of the designed PSS and WADC is validated on the IEEE 9-bus and IEEE 14-bus systems.
- **Chapter 3:** This chapter presents a detailed modelling of WTS and proposes an H_∞ control scheme-based double-channel WADC for WTS. It discusses the damping performance of WTS-integrated power systems under low inertia conditions in LFO modes. It examines the dynamic impact of control modes in system inter-area modes under change in inertia condition. Additionally, the robustness of the proposed control scheme's damping performance is validated under various system operating conditions.
- **Chapter 4:** A new selection strategy for determining the optimal location for the BESS, the appropriate feedback signal, and the suitable damping control loop for placing a supplementary damping controller is presented. Additionally, a fixed-structure H_∞ scheme-based WADC for BESS is proposed. The robustness of its

damping performance is validated under various system loading conditions and uncertainties, including variable communication delays in the feedback loop, nonlinearities in the damping control loop, and the integration of renewable sources such as solar PV systems.

- **Chapter 5:** The effect of multiple BESS on damping system inter-area oscillation modes is discussed, along with the impact of dynamic interactions between BESS control loops and the power system under varying loading conditions. Furthermore, an H_2/H_∞ mixed sensitivity scheme-based WADC is proposed for BESS to improve system damping performance. The robustness of this controller is validated under different system operating conditions.
- **Chapter 6:** The effect of IBRs controlled via the VSG technique on system damping performance in LFO modes are discussed. The impact of dynamic interactions between IBRs and power systems, considering changes in active and reactive control parameters through the VSG technique, on system damping performance is also examined. Additionally, the influence of the most dominant state variable of IBRs on system inter-area oscillation modes is analyzed. An SDC scheme for IBRs controlled through the VSG technique is proposed to enhance system inter-area oscillation damping and mitigate power oscillations of IBRs.
- **Chapter 7:** This chapter concludes by summarizing the main findings of this thesis and suggests future research directions.