

Preface

Power system networks are interconnected, nonlinear, and extremely complex systems susceptible to various events that might cause Low-Frequency Oscillations (LFOs), which may affect the system's stability. These LFOs, which occur at a frequency lower than 2 Hz, are frequently caused by events such as line failures, abrupt load changes, and generator output power variations. The LFOs must be damped out as quickly as possible to make the system stable and dependable because they are harmful. Consequently, reducing power oscillations through Power Oscillation Damping (POD) controller and installing Power System Stabilizers (PSSs) on Synchronous Generators (SGs) are two conventional methods for damping LFOs in multi-machine power systems. PSSs are designed to enhance system stability by providing additional damping to generator rotor oscillations through modulation of the excitation system. However, PSSs primarily utilize local signals, which limits their effectiveness in damping inter-area oscillation modes due to a lack of global observability.

To address the limitations of PSSs in damping inter-area oscillations, a robust Wide-Area Damping Controller (WADC) is introduced. WADCs use wide-area measurements, such as Phasor Measurement Unit (PMU) data, to provide a broader view of the system's dynamic behaviour. By using these wide-area signals, WADC can effectively dampen inter-area oscillations, enhancing the overall stability of the interconnected power system. This approach ensures sufficient damping across the network, mitigating the adverse effects of LFOs and maintaining system reliability.

WADC can be designed using robust control strategies, such as H_∞ , mixed sensitivity H_∞ , and H_2/H_∞ control, to effectively handle uncertainties and varying system conditions. These controllers are designed to provide sufficient damping even when system parameters change or when faced with model inaccuracies. Various actuators, including wind energy conversion systems, solar photovoltaic systems, energy storage systems, and

virtual synchronous generators, are utilized in WADC designs to mitigate system inter-area oscillations and enhance the system's dynamic performance. A brief literature survey on low-frequency oscillations under Renewable Energy Sources (RESs) and Inverter Based Resources (IBRs) integration, various control strategies to damp these oscillations, motivation behind work carried out in this thesis based on research gap, and formulated research objectives are presented in first Chapter.

The second Chapter of the thesis presents the Damping Torque Index (DTI) for determining the optimal installation location of PSS in a multi-machine power network. The selection criteria for the PSS location are based on the maximum magnitude of the DTI under normal operating conditions, ensuring that the PSS is placed where it can provide the most effective damping. The parameters of the PSS are adjusted using the phase compensation methodology to optimize its performance. Additionally, a reduced-order model-based WADC is designed and installed at the synchronous generator, where the optimal PSS is located. This approach aims to enhance the damping of LFOs in the system, thereby improving overall system stability and performance.

The increased penetration of RESs into power systems significantly impacts the damping of LFOs. RESs, such as Wind Turbine Systems (WTS), inherently differ from traditional synchronous generators in their contribution to system inertia and damping characteristics. The intermittent and variable nature of RESs often reduces system inertia, which can exacerbate LFOs and pose stability challenges. This decrease in inertia diminishes the natural damping usually provided by synchronous machines, making the power system more susceptible to oscillatory instability.

The third Chapter of the thesis investigates the impact of inter-area oscillation damping in power systems under low system inertia conditions caused by a high penetration of WTS operating in sub-synchronous, normal, and super-synchronous scenarios. This work examines the effects of replacing a synchronous generator with a WTS of the same MVA capacity on system dynamics, mainly focusing on the emergence of new critical modes of inter-area oscillations that can affect system stability. It explores the dynamic interactions between WTS and SGs and their impact on inter-area oscillations. This work proposed a reduced-order model-based double-channel WADC for WTS to address these challenges, utilizing an H_∞ control scheme. This WADC is designed to damp prominent oscillation modes effectively and mitigate the adverse effects of reduced

system inertia. The real-time feasibility of the proposed double-channel H_∞ WADC is validated using the Real-Time Digital Simulator (RTDS) platform.

The application of Energy Storage Systems (ESSs) in power systems is pivotal for enhancing the damping of inter-area oscillations, which is essential for maintaining grid stability amidst the increasing integration of renewable energy sources. ESS provides rapid and precise control over active and reactive power, helping to stabilize grid frequency and dampen oscillations, particularly in regions prone to variability due to renewables. The strategic deployment of ESS in the grid allows operators to quickly mitigate frequency deviations by injecting or absorbing power, thus preserving system inertia and damping characteristics that might be compromised by integrating renewable energy sources.

Furthermore, ESS can operate independently or in conjunction with other stabilization technologies, such as PSS and WADC, to ensure optimal damping without compromising overall grid reliability. In addition to damping oscillations, ESS provides critical ancillary services, including frequency regulation, voltage support, and load balancing, which are essential for maintaining stability in environments with high renewable energy penetration. These capabilities make ESS a crucial component in modern power systems, enhancing flexibility and resilience in managing the dynamic challenges posed by renewable energy integration.

Mitigating inter-area LFOs is crucial for maintaining power system stability. These oscillations are closely tied to power oscillations, and adequate power modulation through the Battery Energy Storage System (BESS) can help preserve stability. The fourth Chapter of this thesis proposes a strategy for selecting the optimal location for BESS placement based on the maximum of all minimal residue indices under varying system loading conditions. This method determines the best location for the BESS, the appropriate feedback signal, and the suitable damping control loop (i.e., active or reactive power control) for implementing 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. The robust damping performance of the designed controller is validated on the RTDS under different contingencies, including varying system operating scenarios, uncertainties associated with fixed and variable communication delays in the feedback signal, nonlinearities in the damping control loop, and the integration of renewable sources such as solar photovoltaic (PV) systems.

The fifth Chapter of this thesis examines the impact of multiple BESSs on inter-area oscillations in the power system under varying loading conditions 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. Further, WADC based on an H_∞ mixed sensitivity scheme is proposed for BESS. This controller, designed using the Linear Matrix Inequality (LMI) framework, aims to mitigate prominent inter-area oscillations. The sensitivity to variations in BESS control parameters is used to determine optimal location for supplementary damping controller. The RTDS platform is used to assess the real-time effectiveness of the proposed WADC, with simulation results demonstrating that the controller significantly reduces several inter-area oscillation modes.

In RES-based generation, IBR is used to supply power to the grid. However, the increasing integration of RES-based generation in modern power systems reduces grid inertia and damping performance because IBR lacks inherent rotating inertia. This issue is especially significant when RES are integrated into the grid through IBR, given their high voltage levels and large power capacities. Conventional grid-following controls for IBR do not provide inertia support, which can lead to stability problems and pronounced oscillations from minor disturbances, potentially compromising frequency stability. The Virtual Synchronous Generator (VSG) control technique addresses this issue by emulating the inertia of synchronous generators, thereby improving grid stability and reducing these challenges.

The sixth Chapter of this thesis presents the impact of IBRs controlled through the VSG technique on power system LFOs. It investigates how dynamic interactions between the power network and the active and reactive power loops of IBRs, with varying parameters such as inertia constant (H), damping coefficient (D_p), and voltage gain coefficient (k_q), influence LFO damping. Further, the Supplementary Damping Controller (SDC) scheme for IBRs is proposed to enhance system LFOs damping and mitigate the power oscillations of IBRs. This SDC comprises a multi-stage mixed H_2/H_∞ decentralized damping controller linked with the IBR's active control loop and the PSS linked with the reactive control loop of the IBR. The robustness of the proposed SDC is validated using RTDS simulations under various operating conditions, including load changes, network topology adjustments, and the integration of renewable sources. The simulation results

demonstrate that the proposed SDC effectively mitigates both system LFOs and power oscillations in IBRs. Finally, the seventh Chapter concludes the thesis by summarizing key findings and suggesting directions for future research.