# A Physics-Informed Graph Reinforcement Learning Framework for Robust Coordinated Control of Sub-Synchronous Oscillations in Weak Grids with Multi-Machine Inverter-Based Resources


**Abstract**

The increasing penetration of inverter-based resources (IBRs) and converter-interfaced renewable energy systems has fundamentally transformed the dynamic characteristics of modern power systems, leading to heightened vulnerability to sub-synchronous oscillations (SSOs) and sub-synchronous resonance (SSR) phenomena under weak-grid conditions. These oscillations arise from complex interactions among converter control loops, network impedance characteristics, electromechanical dynamics, and grid-forming/grid-following control mechanisms, potentially resulting in poorly damped modes, instability propagation, and large-scale disturbances. Conventional mitigation approaches, including supplementary damping controllers, adaptive filtering techniques, FACTS-based compensation, and optimization-driven tuning methods, often exhibit limitations related to model dependency, fixed parameter settings, restricted operating ranges, and inadequate coordination among geographically distributed IBRs under uncertain operating conditions.

To address these challenges, this paper proposes a **Physics-Informed Graph Reinforcement Learning (PI-GRL)** framework for adaptive and coordinated mitigation of SSOs in multi-machine IBR-dominated weak power systems. The proposed framework is validated on a modified IEEE 39-bus system comprising synchronous generators, DFIG/PMSG-based wind farms, and hybrid grid-forming/grid-following converters. High-resolution phasor measurement unit (PMU) data, including voltage, current, and power measurements, are utilized to support data-driven monitoring and control.

The PI-GRL framework integrates a **Physics-Informed Graph Neural Network (PI-GNN)** with **multi-agent reinforcement learning (MARL)** and an **H∞ robust control** layer. The PI-GNN embeds power-flow constraints, swing dynamics, converter control relationships, and network topology into a graph representation, enabling accurate identification of critical oscillatory modes and system-wide stability characteristics. Based on these graph features, distributed MARL agents coordinate damping control actions through adaptive adjustment of converter control parameters, virtual impedance settings, and current injection references. To

enhance practical applicability, the framework adopts decentralized agent coordination and lightweight inference mechanisms, allowing real-time deployment with low online computational burden, while the H∞ robust control layer provides additional stability and robustness against parameter uncertainty, measurement noise, and external disturbances.

The proposed approach is evaluated under diverse operating scenarios, including low short-circuit ratio conditions (SCR < 2), varying series-compensation levels (30–70%), renewable penetration exceeding 70%, stochastic wind-speed and load variations, three-phase faults, post-fault recovery processes, and mixed grid-forming/grid-following interactions. Performance assessment is conducted using eigenvalue analysis, damping-ratio evaluation, participation-factor analysis, impedance-based stability assessment, and electromagnetic transient simulations.

Simulation results indicate that the proposed PI-GRL framework significantly enhances oscillatory stability, improving critical-mode damping ratios from approximately 0.03–0.06 to 0.18–0.32, corresponding to average improvements of 250–400%. Oscillation settling times are reduced by 55–70%, while peak oscillation amplitudes decrease by 60–80% relative to conventional damping-control approaches. Comparative studies against GA/PSO-optimized controllers, battery-energy-storage-based damping methods, adaptive multi-modal damping controllers, and reinforcement-learning-based supplementary damping controllers demonstrate 30–50% faster oscillation suppression, 25–45% greater damping enhancement, and improved robustness across the evaluated operating conditions.

Furthermore, the framework effectively captures and mitigates coupled oscillatory mechanisms, including induction-generator effects, torsional interactions, and converter-control-induced oscillations. The reported generalization capability is demonstrated across operating conditions and disturbances not explicitly encountered during individual training episodes but within the range of system configurations and operating scenarios considered during training and validation. Overall, the proposed PI-GRL framework provides a scalable and robust solution for coordinated SSO mitigation and stability enhancement in renewable-dominated weak-grid environments.