

AI-Based Stochastic Electricity Market Modeling: A Contingency-Constrained Approach for the Nordic Region – AIM4Nord

Introduction

The increasing penetration of renewable energy resources and inverter-based generation has significantly transformed modern power systems, introducing high variability, uncertainty, and reduced system inertia. These challenges increase the risk of frequency instability and reduce the effectiveness of traditional deterministic electricity market models under contingency conditions. This work proposes a contingency-constrained stochastic electricity market framework integrated with AI-based scenario generation techniques to improve the resilience, security, and economic efficiency of renewable-dominated power systems. The proposed framework incorporates uncertainty management, reserve scheduling, and linearized frequency dynamic constraints, including RoCoF, frequency nadir, and quasi-steady-state frequency limits, within a two-stage stochastic MILP optimization framework under the N-1 security criterion.

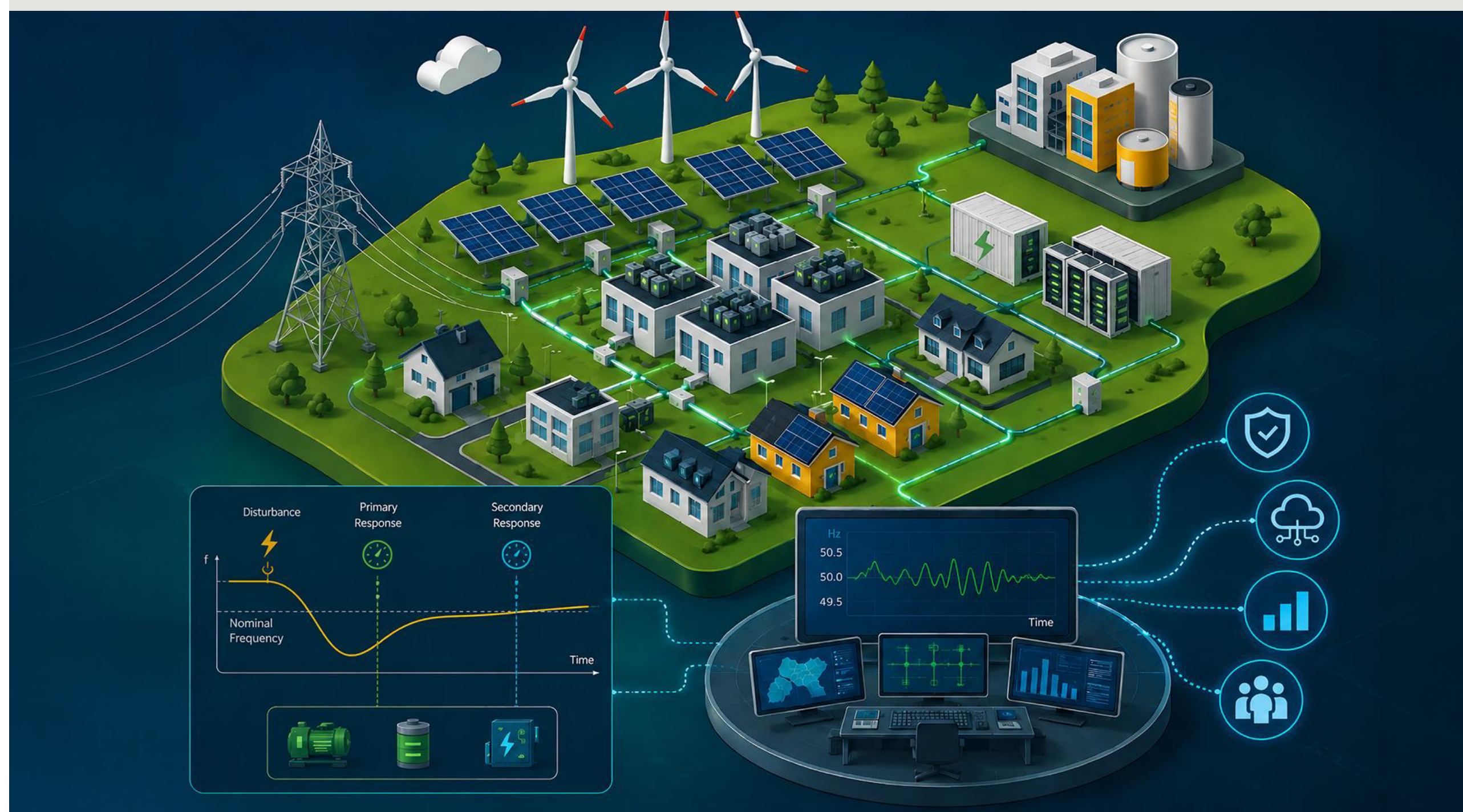
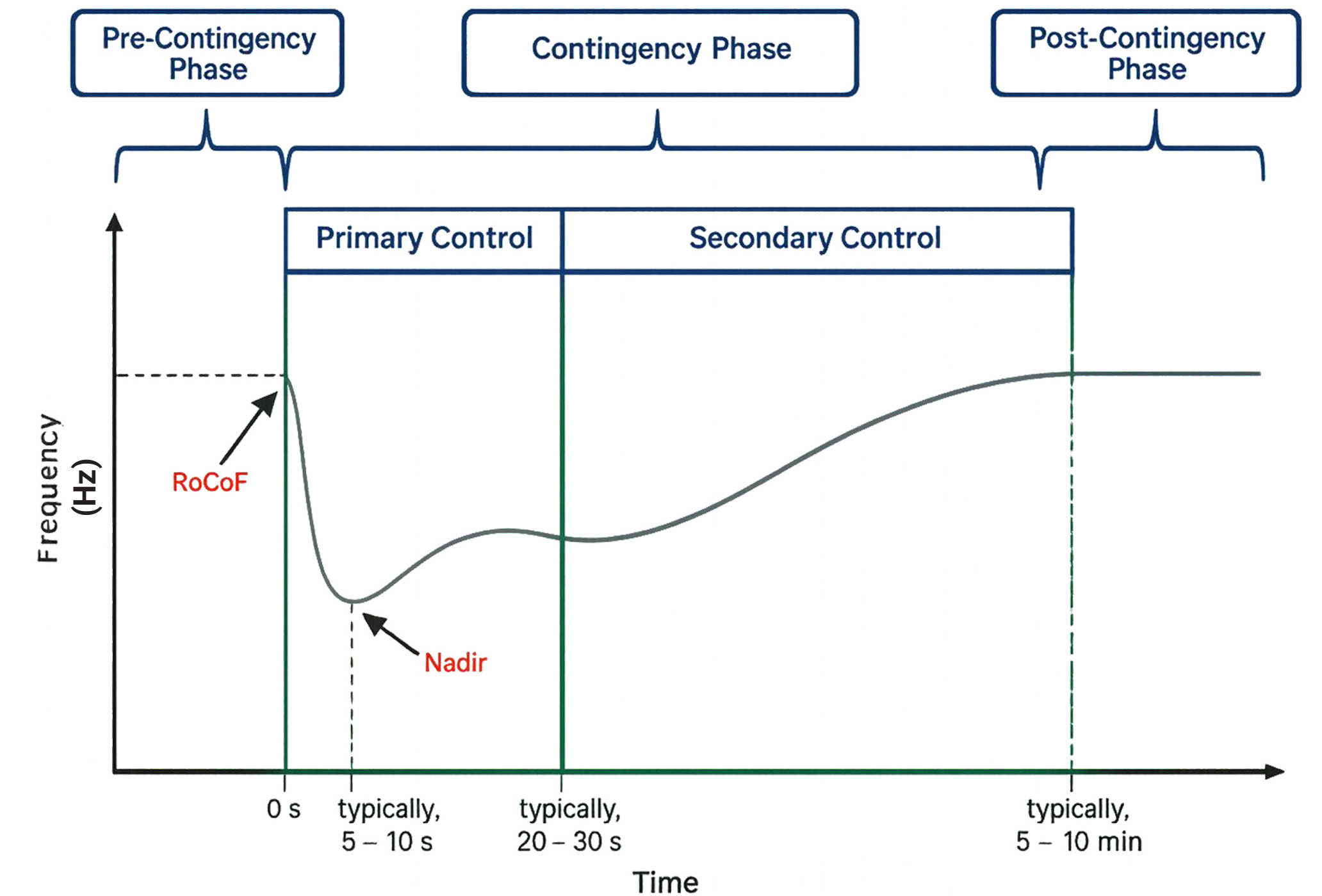
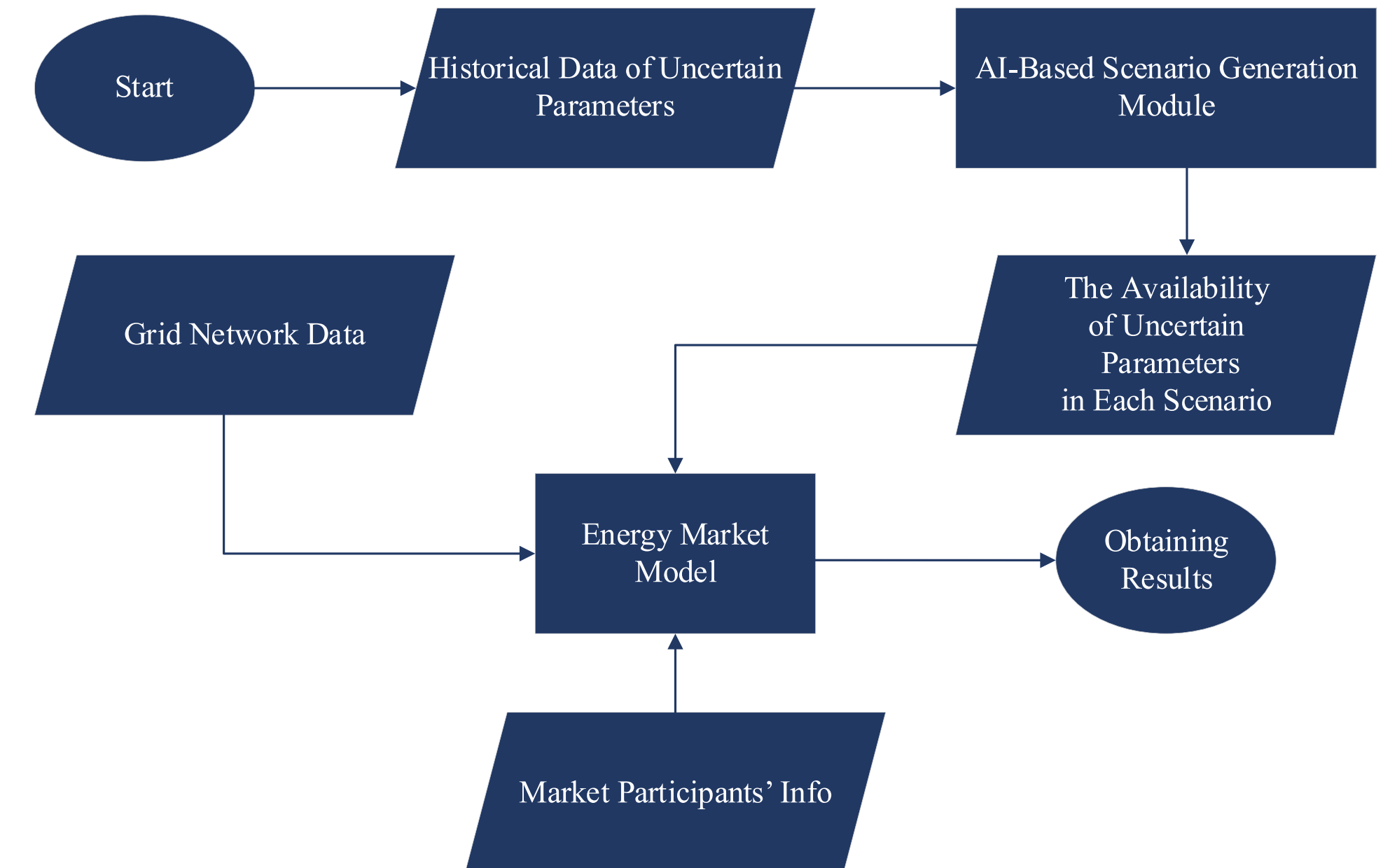


Fig. 3. Frequency Dynamic Response Under Generator Outage Conditions



PHASE 2: AI-Based Scenario Generation, AI-driven and data-driven approaches are utilized to generate realistic uncertainty scenarios using historical weather and operational data. This phase focuses on modeling renewable and load uncertainty, as well as generator outage scenarios, to improve the representation of stochastic operating conditions and support more reliable market decision-making under deep uncertainty. Finally, these two phases will be integrated, as shown in Fig. 4, where the AI-based scenario generation module provides representative uncertainty scenarios for renewable generation, load demand, and contingency events based on historical and operational data. These generated scenarios are then incorporated into the stochastic energy market model together with grid network data and market participants' information to optimize market operation and reserve scheduling under uncertain operating conditions. The integration of these phases enables a coordinated, realistic, and resilient framework for electricity market operation under deep uncertainty.

Fig. 4. Integrated AI-Based Stochastic Electricity Market Framework



Methodology

The proposed methodology integrates stochastic electricity market modeling with AI-based uncertainty characterization to improve the resilience, operational security, and economic efficiency of renewable-dominated power systems under deep uncertainty. In fact, it consists of two main phases.

PHASE 1: Energy Market Modeling, a contingency-constrained two-stage stochastic electricity market framework is developed to optimize energy dispatch and reserve scheduling under uncertainty. The model is formulated as a Mixed-Integer Linear Programming (MILP) problem and consists of Day-Ahead and Real-Time stages. In the day-ahead stage, optimal energy and reserve schedules are determined considering renewable generation variability, load uncertainty, and potential generator outages using a scenario-based stochastic framework. In the real-time stage, system dynamics are analyzed through Pre-Contingency, During-Contingency, and Post-Contingency operating phases to capture system behavior before, during, and after disturbance events. A hierarchical frequency control framework, including Primary and Secondary Frequency Control, is incorporated to maintain frequency stability under low-inertia operating conditions. The primary control layer models immediate system response using linearized droop-based frequency constraints considering system inertia, rate-of-change-of-frequency (RoCoF), frequency nadir, and steady-state frequency deviations, while the secondary control layer restores nominal frequency through reserve redistribution and coordinated power balancing.

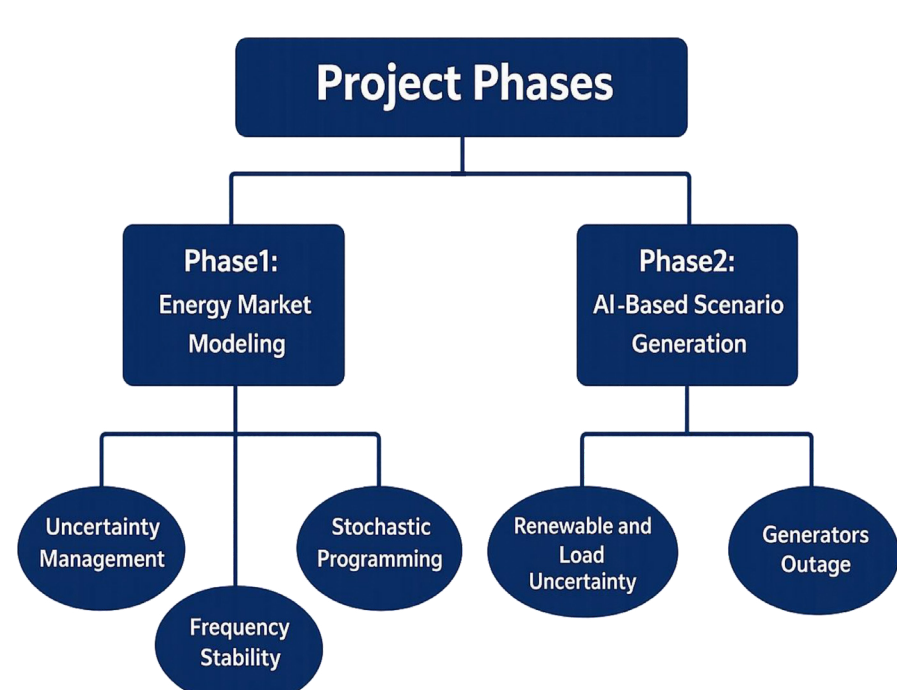


Fig. 1. Project Phases

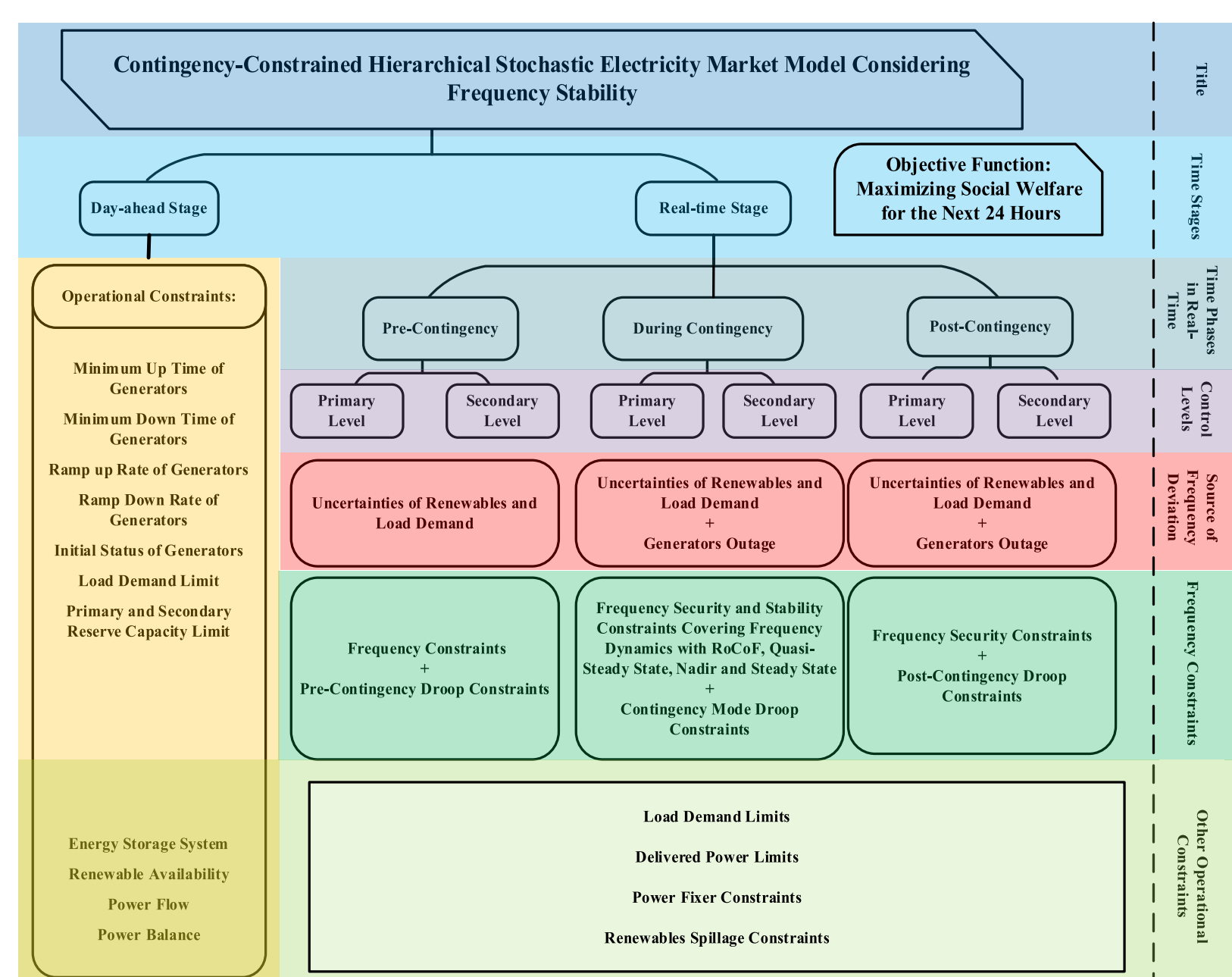


Fig. 2. Electricity Market Model Details

Results and Conclusion

The proposed stochastic MILP-based framework is evaluated on the isolated 16-bus CIGRE benchmark system under different operational scenarios, considering renewable uncertainty and generator outage contingencies under the N-1 security criterion. In the first case, the objective function value is \$8971 when frequency dynamic constraints, including RoCoF, frequency nadir, and quasi-steady-state frequency limits, are not considered. By incorporating linearized RoCoF and quasi-steady-state frequency constraints, the objective function decreases by approximately 1.6% under a one-hour outage event due to additional reserve and operational security requirements. In the final case, all frequency dynamic constraints, including RoCoF, frequency nadir, and quasi-steady-state frequency constraints, are incorporated into the proposed framework. The results show that the objective function is reduced by approximately 2.7% compared to the base case under a one-hour outage scenario. Although the operational cost increases due to enhanced security requirements, the proposed framework successfully guarantees system frequency stability and secure operation throughout the operating horizon, even after the loss of one generating unit. Overall, the results demonstrate that integrating stochastic market modeling with frequency security constraints significantly improves the resilience and operational security of low-inertia renewable-dominated power systems while maintaining acceptable economic performance under uncertain operating conditions.

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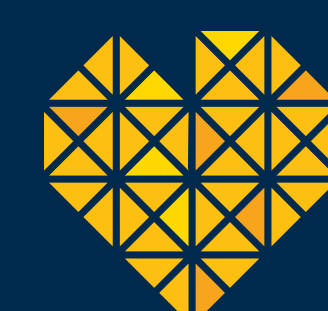
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