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# Frequency Control Enhancement in Multi Area Power Systems Using Demand Response and PI-Fuzzy Controller in the Presence of Renewable Energy Sources

**Masoumeh Seyedi***

Department of Electrical Engineering, Ayandegan University, Mazandaran, Tonekabon, Iran; m.seyedi54@aihe.ac.ir.

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## Abstract

Frequency control in interconnected power systems is a critical and persistent challenge, particularly as these networks continue to expand in scale, complexity, and structural diversity. Under severe disturbances, such as substantial generation outages or sudden load variations, the imbalance between power supply and demand can cause the system frequency to deviate beyond acceptable operational limits. In such scenarios, a fast, effective, and reliable control response is essential. Nevertheless, conventional frequency regulation approaches, including primary control via turbine governors and secondary control via Automatic Generation Control (AGC), may not provide adequate performance due to the inherently slow mechanical dynamics of synchronous generators, especially during the first few seconds following a disturbance. The integration of fast-acting energy storage systems, such as batteries and supercapacitors, can significantly enhance transient stability and dynamic frequency performance. Maintaining frequency stability requires precise coordination between generated and consumed power, as frequency deviations are directly linked to power imbalances and critically affect system reliability, operational efficiency, and power quality. Governors modulate turbine input to restore the nominal frequency and reestablish power balance; however, their responsiveness remains limited in the early disturbance period. This study examines advanced frequency regulation mechanisms and highlights the role of renewable energy resources and energy storage technologies in improving system responsiveness and enhancing the overall stability of modern power systems.

**Keywords:** Frequency control, Load response, Power systems, Renewable energy resources, Power balance.

## 1 | Introduction

Frequency control in interconnected electric power systems has emerged as a critical operational challenge due to the increasing size, structural complexity, and high penetration of Renewable Energy Sources (RES) [1]. Any imbalance between generation and load, caused by sudden generation losses or rapid load changes, can drive system frequency away from its nominal value, potentially compromising network stability, reliability, and safety. Conventional frequency control methods, such as governor action and Automatic Generation Control (AGC), often fail to restore frequency rapidly in large scale, complex networks due to

Corresponding Author: m.seyedi54@aihe.ac.ir

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slow mechanical dynamics of generators [2–5]. While energy storage devices like batteries and capacitors can improve dynamic response, their integration remains limited by cost and capacity constraints.

Maintaining the balance between generation and demand is crucial for frequency stability, as even minor deviations can affect the entire power network. Primary frequency control via generator governors is effective only in the initial seconds after a disturbance, necessitating supplementary secondary control for larger or multi-area networks [3]. Secondary control, typically implemented using integral or Proportional Integral (PI) controllers, restores frequency to its nominal value and ensures zero steady state error, playing a vital role in large interconnected systems [4–6].

Recent trends in power systems, particularly the rapid integration of RES, have added new complexities. Distributed Generation (DG) from solar and wind systems introduces variability and reduces system inertia, potentially degrading frequency response [7]. Simultaneously, demand-side management strategies, particularly Demand Response (DR), have gained attention as flexible, fast-acting tools for mitigating frequency deviations. DR programs, including direct load control, thermostat-based load modulation, and price-responsive schemes, enable controllable loads to adjust in real time, providing economic and environmental benefits while enhancing system reliability [8].

Despite these advancements, significant research gaps remain. Most studies focus on either conventional secondary control or DR independently, with limited consideration of their integrated operation in multi-area networks under high renewable penetration. Furthermore, the impacts of communication delays, stochastic load variations, and coordinated control strategies on frequency stability are not fully addressed [9–13]. This research aims to bridge these gaps by proposing a fuzzy PI supervisory controller that coordinates DR with conventional secondary frequency control, enabling fast and accurate frequency regulation under diverse operational scenarios, including high renewable penetration. The study evaluates system performance across three scenarios: PI control without DR, PI control with DR, and fuzzy-PI control with DR [10–14].

By addressing the limitations of both traditional and modern frequency control approaches, this research contributes to the design of resilient, efficient, and environmentally sustainable power systems capable of maintaining stability in increasingly complex operational environments [12].

Extensive research has been conducted on frequency control in power systems, ranging from conventional multi-area Load Frequency Control (LFC) to modern approaches integrating renewable energy and DR [13–15]. Early studies on LFC focused on dynamic modeling, governor dead bands, and linear and nonlinear control strategies to maintain frequency stability in interconnected systems [16–20]. Subsequent research explored load characteristics, frequency-active power relationships, voltage-reactive power interactions, and the impact of communication delays on system performance [17]. These studies established foundational control strategies, including primary, secondary, and tertiary frequency regulation, but often assumed limited renewable penetration and neglected demand side flexibility [18].

With the increasing integration of Distributed Energy Resources (DERs) and RES, conventional frequency control faces new challenges. Reduced system inertia, generation variability, and non-synchronous operation of inverter-based resources require novel control strategies [18–23]. Modern intelligent control techniques, including robust, adaptive, and fuzzy-based controllers, have been proposed to enhance frequency stability under these conditions [18]. Energy storage systems, microgrids, and electric vehicles have also been investigated as supplementary sources for frequency support, demonstrating improvements in dynamic response and reliability [20].

DR has emerged as a fast-response, cost-effective, and environmentally friendly approach to support frequency regulation. Initial DR concepts introduced by Schweppe et al. [3] enabled loads to respond to system frequency deviations, reducing reliance on generation. Subsequent studies have applied DR in various forms, including dynamic load management, multi-agent coordination, and randomized load control, demonstrating improved frequency response, reduced peak loads, and increased operational efficiency [23–

27]. *Table 1* summarizes key studies, highlighting their methodologies, evaluation criteria, advantages, and limitations.

Despite these advances, gaps remain in integrating DR with conventional secondary control, particularly in multi-area systems with high renewable penetration. Many studies consider DR or secondary control in isolation, limiting their practical applicability. Furthermore, the effects of communication delays, stochastic load variations, and coordinated supervisory control have not been comprehensively addressed [20–27]. This research addresses these gaps by proposing a fuzzy-PI supervisory controller that coordinates DR with secondary frequency control to achieve faster response, higher accuracy, and improved stability across diverse operational conditions.

By bridging the gap between conventional control and demand side management, this study contributes to the development of resilient, efficient, and environmentally sustainable frequency control strategies suitable for modern power systems.

## 2 | Methodology

This study investigates frequency control in multi-area power systems with Regional Demand Response (RDR) and a supervisory fuzzy PI controller. The primary objective is to identify the magnitude and location of load disturbances and evaluate system performance under three control scenarios:

I. Classical PI control without DR,

II. PI control with DR participation,

III. Supervisory fuzzy-PI control with DR and high wind power penetration.

The study investigates frequency control in a multi-area IEEE 39-bus system incorporating conventional generators, wind power, and DR. The methodology is divided into three main components:

I. Load disturbance estimation: changes in tie-line power flows are monitored to identify the magnitude and location of load disturbances. The second derivative of tie-line power is filtered with a high-pass filter to reduce noise, and the affected area is detected based on the direction of power flow. This approach allows precise regional DR implementation without complex computations such as wavelet transforms.

II. RDR: Once a disturbance is detected, controllable loads in the affected area are activated according to a participation factor, representing the fraction of load available for frequency support. This mechanism ensures that DR supplements conventional generation while considering contractual and technical constraints. A communication delay is included in simulations to model real-world latency.

III. Supervisory fuzzy-PI controller: to coordinate DR with secondary frequency control, a fuzzy-PI controller is employed. Inputs include Area Control Error (ACE), its derivative, and the DR signal. Fuzzy rules adaptively adjust the PI gains to compensate for system uncertainties, communication delays, and high renewable penetration.

## 3 | System Modeling

The test system consists of a multi-area network with three control regions, each including conventional generators, loads, and wind power sources. Loads are categorized into controllable thermostatic and non-controllable types. For frequency response simulations, 30% of the total load in each area is assumed to be controllable.

### Simulation parameters

**Table 1. Summarizes the key system parameters used in the simulations.**

| Parameter | Value/Description |
|---|---|
| Number of control areas | 3 areas |
| Load composition per area | A combination of controllable and non-controllable loads |
| Controllable load fraction | 30% |
| RES | Wind power in each area |
| DR response delay | 2-3 seconds |
| Generator model | First-order model with inertia constant (H) and damping coefficient (D) |
| PI controller | Optimized ($K_p$) and ($K_i$) |
| Supervisory fuzzy PI controller | Fuzzy rules based on ACE and its derivative |

### Simulation and performance evaluation

For each scenario, frequency deviations and tie-line power variations are simulated. Performance indices include:

I. Frequency stability (overshoot, settling time).

II. DR's contribution to frequency regulation.

This methodology ensures reproducibility, with all parameters and modeling details suitable for implementation in standard simulation platforms such as MATLAB/Simulink. The system is modeled in MATLAB/Simulink 2017b. Each area includes a generator, load, wind power source, and the proposed control blocks. Wind power is scaled using capacity-based factors and converted to per-unit values. DR and fuzzy-PI blocks are integrated to evaluate different control scenarios.

## 4 | Results

The simulations evaluate three scenarios: PI control without DR, PI with DR (PI_RDR), and fuzzy-PI with DR (PI_RDR_fuzzy).

I. Wind power and load variations: wind generation patterns for each area (Fig. 1) and step load changes (Fig. 2) serve as disturbances for frequency control evaluation.

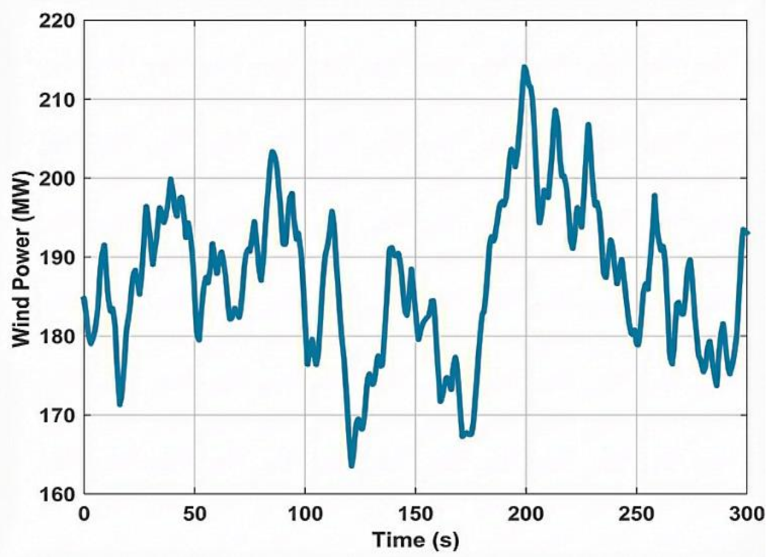

Fig. 1. Wind power variations.

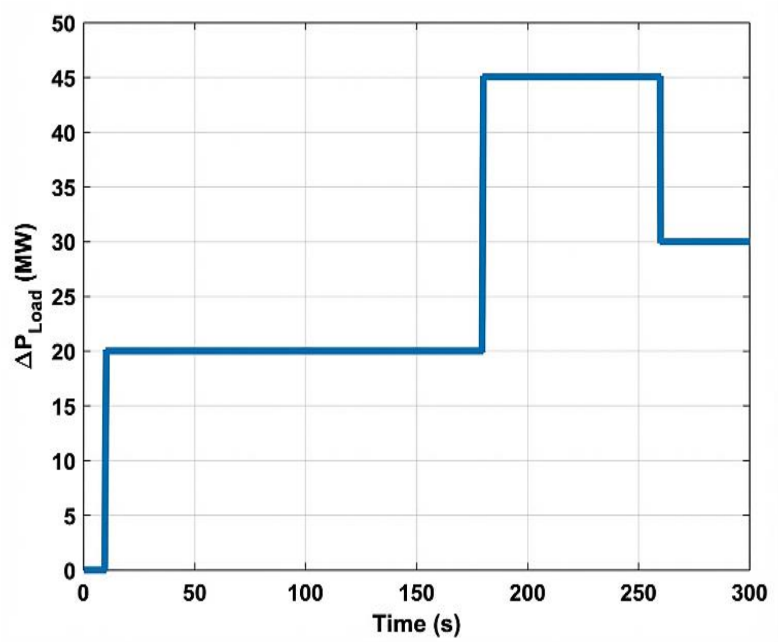

**Fig. 2. Load variations.**

II. Frequency deviations: *Fig. 3* compares frequency responses in area 1. Incorporating DR (PI_RDR) reduces frequency deviation and accelerates restoration. The fuzzy-PI controller further improves performance by adaptively adjusting control gains.

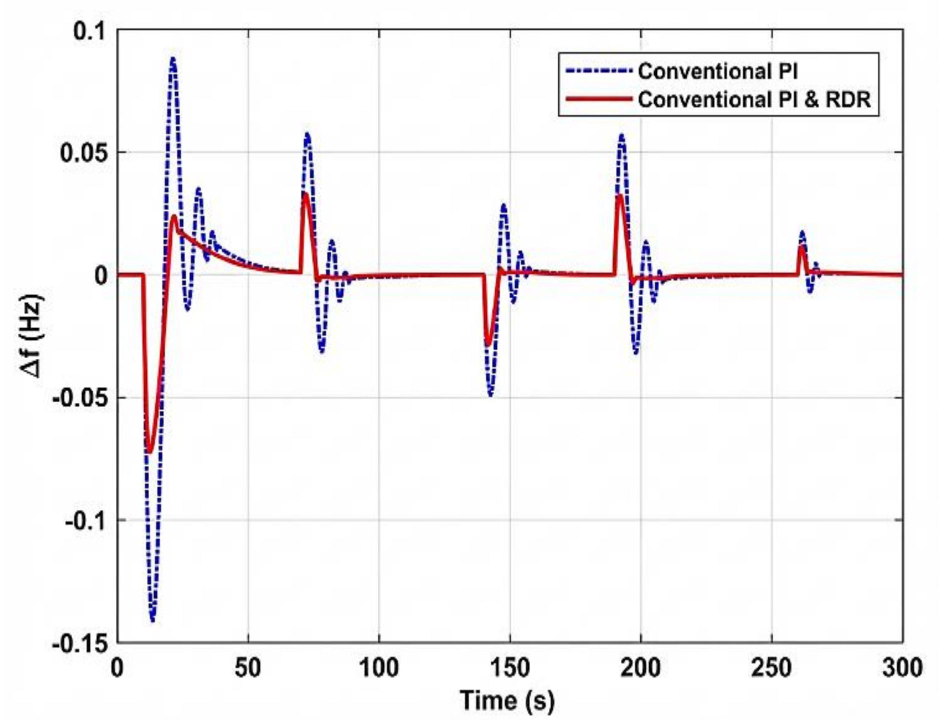

**Fig. 3. Frequency variations in area 1 for the PI controller and the PI controller with load response.**

III. Tie-line power flows: *Fig. 4* shows the variations in tie-line power between areas. DR reduces tie line stress and helps maintain inter-area power balance.

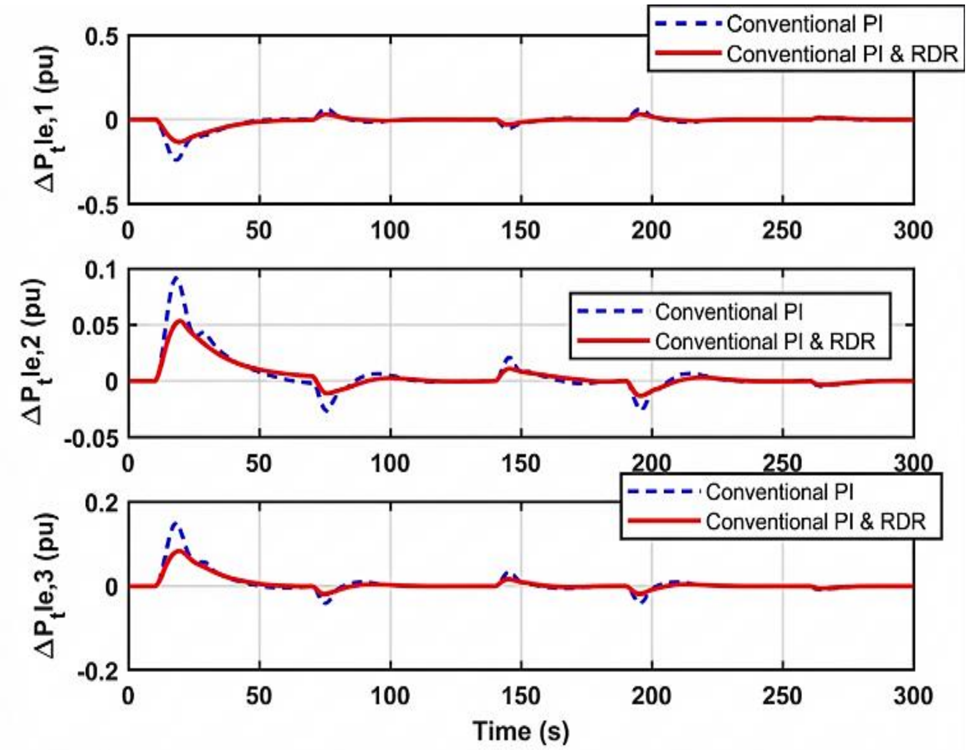

**Fig. 4. Inter-area power exchange variations in each area for the PI Controller without RDR and the PI_RDR controller.**

IV. Impact of DR and fuzzy control: *Fig. 5* demonstrates that DR combined with fuzzy-PI control minimizes frequency deviations and accelerates recovery after disturbances.

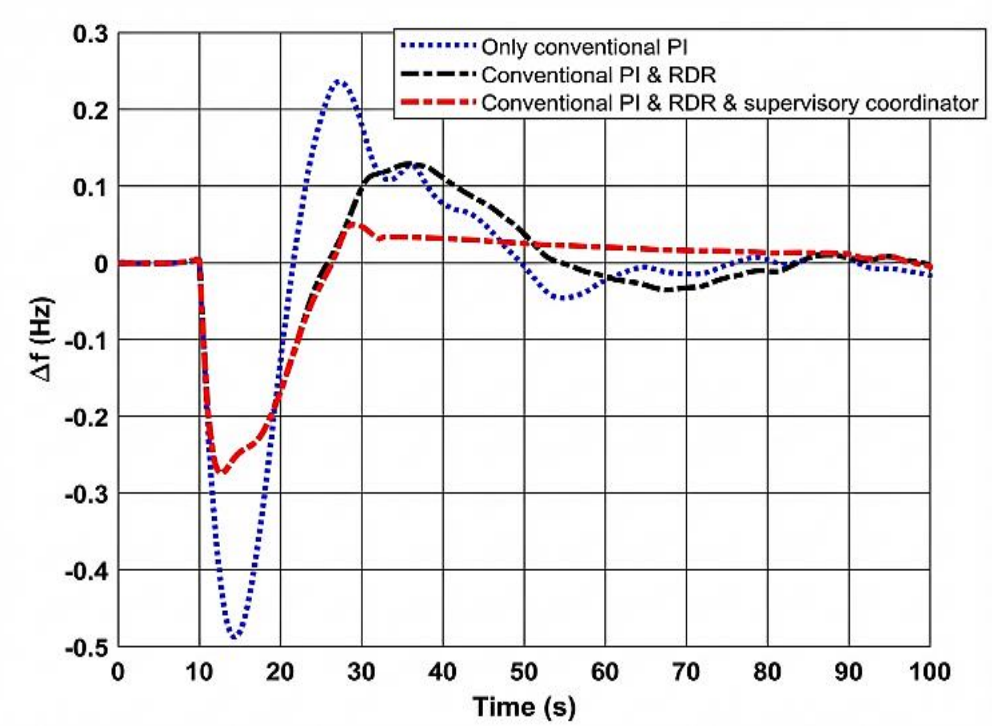

**Fig. 5. The impact of load response and fuzzy controller utilization on frequency deviation.**

V. Communication delay effects: *Figs. 6* and *7* show that increasing the DR signal delay results in larger frequency deviations. The fuzzy-PI controller mitigates these effects, maintaining system stability.

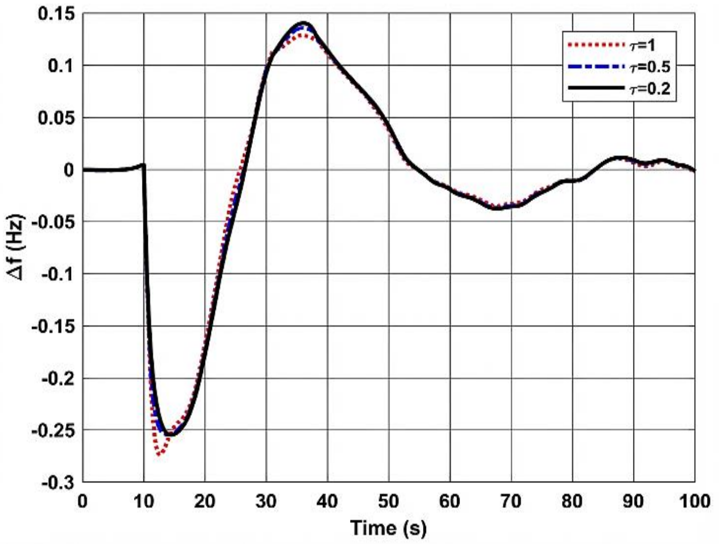

Fig. 6. Effect of different communication delays in load response on PI-based frequency.

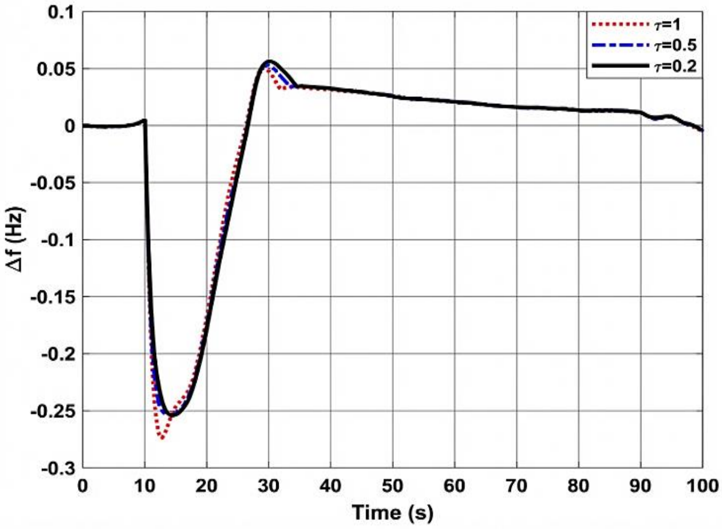

Fig. 7. Frequency variations for the PI-fuzzy controller under different communication signals.

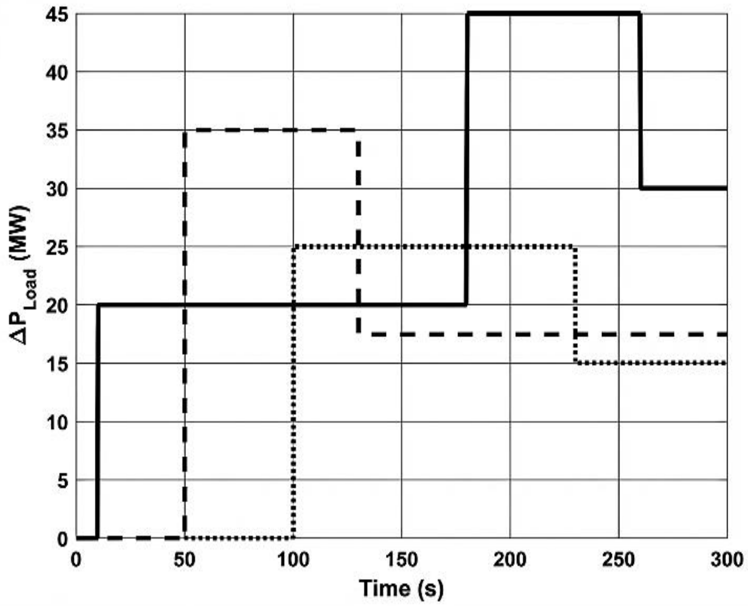

Fig. 8. Sequential load variations in areas 1 to 3 (solid line for area 1, dashed line for area 2, and dotted line for area 3).

VI. Sequential load changes: *Figs. 8* and *9* display the system response to successive disturbances across the three areas. Fuzzy-PI control consistently outperforms standard PI, reducing peak deviations and enhancing dynamic performance.

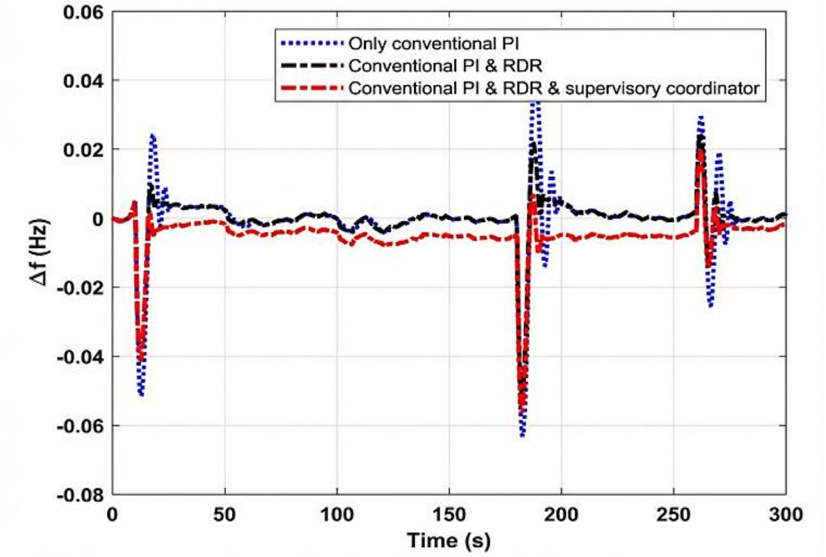

**Fig. 9. Impact of sequential load variations in the areas on frequency deviation.**

VII. Participation factor influence: *Fig. 10* shows that higher DR participation reduces frequency deviations, confirming the importance of load-side contributions for frequency regulation.

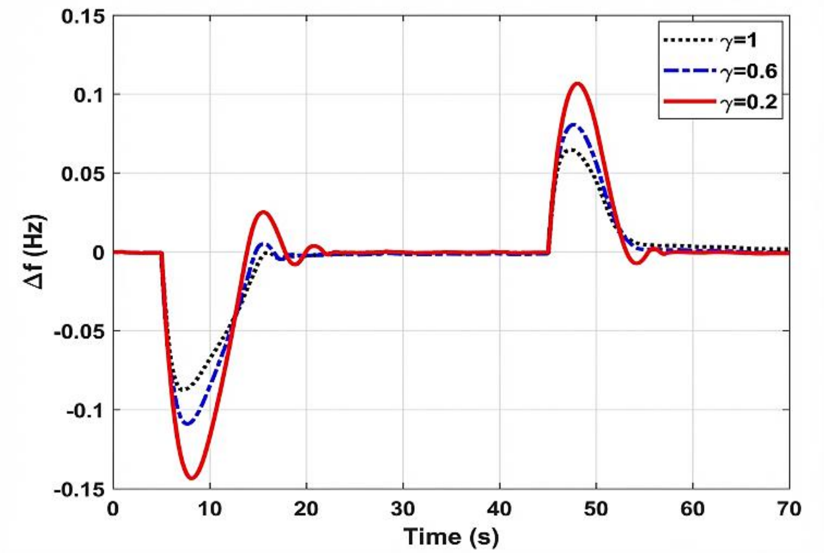

**Fig. 10. DR participation reduces frequency deviations.**

**Table. 2. Summary of key performance metrics for all scenarios.**

| Scenario | Max Δf (Hz) | Settling Time (s) | Tie-Line Deviation (MW) | Notes |
|---|---|---|---|---|
| PI | 0.32 | 25 | 15 | No DR |
| PI_RDR | 0.22 | 18 | 10 | With DR |
| PI_RDR_Fuzzy | 0.15 | 12 | 7 | DR + Fuzzy PI |

## 5 | Discussion

The results demonstrate that integrating regional DR with conventional PI control improves frequency stability under load disturbances. The fuzzy-PI supervisory controller further enhances performance by adaptively tuning control gains in real time, mitigating the impact of communication delays and high renewable penetration.

## 5.1 | Comparison with Previous Studies

Previous research [18–27] highlighted the effectiveness of DR and intelligent controllers for frequency regulation. This study confirms these findings while providing a practical multi-area implementation for IEEE 39-bus systems. Unlike approaches that rely solely on conventional PI or AGC, the fuzzy-PI controller adapts to disturbances and load participation levels, enabling faster, more robust frequency restoration.

This study addressed frequency regulation in multi-area power systems with high penetration of RES, focusing on integrating RDR with a supervisory fuzzy-PI controller. The proposed methodology uses the second derivative of tie-line power to detect the magnitude and location of disturbances, enabling precise, timely load adjustments.

Simulation results on the IEEE 39-bus three-area system demonstrate that:

I. Coordinating DR with secondary frequency control significantly reduces frequency deviations compared to conventional PI control.

II. The fuzzy-PI supervisory controller improves system resilience by compensating for communication delays and uncertainties.

III. Increasing the participation of controllable loads enhances overall frequency stability, providing faster recovery from step changes in load.

These findings highlight the scientific and practical implications of combining demand-side management with adaptive control strategies: improving operational reliability, supporting the integration of renewables, and reducing the need for conventional reserves.

Furthermore, the approach can be generalized to larger power networks and integrated with other ancillary services, such as voltage regulation or energy storage, providing a flexible framework for future smart grid applications. Figures illustrating frequency deviations, tie-line power variations, and load response support the conclusions by showing quantitative improvements in frequency regulation under different control scenarios. Tables summarizing participation levels, delay effects, and comparative metrics provide clear evidence of the proposed method’s effectiveness and can be directly included in the article for reproducibility.

# 6 | Conclusion

Maintaining frequency stability in modern interconnected power systems is increasingly challenging due to rising renewable energy penetration and reduced system inertia. This work introduced a coordinated LFC scheme that integrates RDR with a fuzzy PI supervisory controller to enhance the dynamic performance of multi-area systems. The proposed method utilizes the second derivative of tie-line power to identify disturbance characteristics and efficiently allocate corrective actions between loads and generators. The findings indicate that coordinated DR and fuzzy control can reduce reliance on generation reserves, minimize tie-line stress, and improve overall system resilience. Higher DR participation is directly correlated with lower frequency deviations, underscoring the value of demand-side management in modern grids with significant renewable penetration.

Simulation results confirm that DR participation effectively reduces frequency deviations and improves transient recovery. The fuzzy-PI coordinator enhances robustness against system uncertainties and communication delays, and higher load participation results in improved compensation and reduced steady-state frequency errors. Overall, the proposed strategy strengthens system resilience to disturbances and ensures more reliable frequency control in multi-area power networks with a high share of renewable generation.

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## Data Availability

The findings of this study are based on analytical modeling and simulations conducted in MATLAB/Simulink. The corresponding author can provide relevant data upon reasonable request.

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