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Load Frequency Control of Two Area Power System Using PID and Fuzzy PID Controller

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ABSTRACT

Maintaining stable frequency and tie-line power exchange in interconnected power systems is critical for ensuring system reliability and operational efficiency. Load Frequency Control (LFC) mechanisms play a vital role in mitigating frequency deviations caused by load variations and unforeseen disturbances. This paper presents a comprehensive study on the design and performance evaluation of conventional Proportional-Integral-Derivative (PID) and Fuzzy Logic-based PID (Fuzzy-PID) controllers for a two-area interconnected thermal power system. The two control strategies are compared based on their ability to minimize frequency deviations and tie-line power fluctuations. While the traditional PID controller offers a straightforward and widely used solution, its performance deteriorates under dynamic system conditions due to fixed gain parameters. In contrast, the Fuzzy-PID controller dynamically tunes the control parameters using fuzzy logic rules, thereby improving adaptability and robustness against system non-linearities and uncertainties. Simulation studies conducted in MATLAB/Simulink reveal that the Fuzzy-PID controller achieves superior performance with reduced settling time, minimized overshoot, and lower steady-state error compared to the conventional PID controller. The results highlight the potential of intelligent control techniques for enhancing the dynamic stability of modern interconnected power systems, making them more resilient to varying operational scenarios.

Keywords: Load Frequency Control (LFC); Two-Area Power System; PID Controller; Fuzzy Logic Controller; Fuzzy-PID Controller; Frequency Deviation.

INTRODUCTION

The reliable operation of power systems is fundamentally dependent on maintaining a continuous balance between generated electrical power and the power demanded by consumers. Any imbalance between generation and demand leads to deviations in the system frequency, which, if not promptly corrected, may compromise the stability, security, and overall efficiency of the electrical network. In interconnected power systems, where multiple areas are linked through tie-lines, load frequency control (LFC) is a critical mechanism that regulates frequency fluctuations within each area and ensures appropriate power exchanges across the tie-lines.

Traditionally, the Proportional-Integral-Derivative (PID) controller has been extensively utilized for load frequency control due to its simplicity, ease of implementation, and reasonably good performance under nominal system conditions. The PID controller modifies the generator output based on the error signal, which is typically a combination of the frequency deviation and tie-line power deviation known as the Area Control Error (ACE). While PID controllers are effective under linear, time-invariant system assumptions, their fixed-parameter nature limits their ability to cope with highly dynamic and nonlinear behaviors encountered in modern power systems, especially under varying load conditions, system disturbances, or parameter uncertainties.

This paper aims to model a two-area interconnected thermal power system and design two types of controllers: a conventional PID controller and a Fuzzy- PID controller. The performance of both controllers is analyzed under standard load disturbance scenarios using MATLAB/Simulink simulations. Metrics such as settling time, peak overshoot, and steady-state error are evaluated to comprehensively assess the effectiveness of the controllers. The results clearly indicate the superiority of the Fuzzy-PID controller, particularly in its ability to enhance system stability, reduce transient oscillations, and provide robust performance under varying operational conditions.

RELATED WORK

Load Frequency Control (LFC) in interconnected two-area power systems has received significant attention in recent years, particularly focusing on enhancing stability and dynamic response under load disturbances. Traditional Proportionalm Integral Derivative (PID) controllers, although widely implemented, often struggle with optimal performance in complex interconnected grids due to their linear nature. Md Abu Kaisher et al. [1] analyzed the LFC problem using PID and Fuzzy Logic Controllers (FLC) and demonstrated that FLC provides better steady-state accuracy and transient response, indicating the limitations of conventional PID control in dynamic environments. Similarly, Vasupalli Manoj et al. [2] extended the study by incorporating Artificial Neural Networks (ANN) alongside PID and fuzzy controllers, emphasizing improvements in peak overshoot, undershoot, and settling time, highlighting that intelligent methods better accommodate the nonlinearities inherent in real-world power systems.

Enhancing upon the conventional strategies, Omar Daood et al. [3] introduced a hybrid Fuzzy-PID (F-PID) controller, revealing that the fuzzy-tuned PID controllers significantly outperform standard PID designs in maintaining frequency stability across multiple power systems. Further, Vivek Nath and D.

K. Samabriya [4] incorporated optimization techniques such as Artificial Bee Colony (ABC) algorithms to fine-tune Fuzzy-PID controllers, demonstrating lower Integral of Time Multiplied Absolute Error (ITAE) and reduced settling times compared to unoptimized controllers. These studies collectively underscore a trend toward hybridization and optimization, aiming to combine the simplicity of PID control with the adaptability of intelligent systems to meet the dynamic requirements of modern power grids.

Several researchers have also explored the role of evolutionary optimization algorithms in further refining controller performance. Rinku Doley and Saradindu Ghosh [5] compared PID and fuzzy controllers for both single-area and two-area systems, showing significant improvements in dynamic response and robustness using fuzzy control. Complementarily, Nimai Charan Patel et al. [6] utilized the Ant Lion Optimizer (ALO) to tune fuzzy based Proportional-Integral (FPI) controllers, outperforming both traditional PID and Particle Swarm Optimization (PSO) tuned counterparts in a hydro-thermal two-area model. These advancements point toward a growing consensus that intelligent control methods, particularly when coupled with metaheuristic optimization, provide a resilient solution for maintaining frequency regulation in increasingly complex and variable energy systems.

Ali Bagheri and Reza Sedaghati [7] contributed further to this discourse by detailing the Fuzzy-PID design, emphasizing the faster damping of frequency fluctuations and enhanced stability under varying load demands. Their results validate the hypothesis that embedding fuzzy logic into PID frameworks allows controllers to dynamically adjust to system nonlinearities, an advantage over fixed-gain PID controllers. A novel dimension was added by Kamel Sabahi and Mehdi Tavan [8] who addressed input delays by proposing a Type-2 Fuzzy PID (T2FPID) controller, employing Lyapunov-Krasovskii functionals to ensure system stability despite time-delay effects, a crucial factor for practical grid implementations.

Finally, Basavarajappa S. R. and M. S. Nagaraj [9] compared PID, Fuzzy Logic Controller (FLC), and Optimal Controllers (OC) for LFC applications. Their findings revealed that fuzzy-tuned PID controllers significantly minimize frequency deviations and improve system damping characteristics compared to traditional PID, affirming the trend toward fuzzy hybridization. The comprehensive body of work across these studies suggests a clear evolution from linear, rule-based control towards flexible, intelligent, and optimized frameworks that are better suited for the dynamic challenges of interconnected, renewableintegrated power grids.

MODELING OF TWO-AREA POWER SYSTEM

In an interconnected power system, multiple control areas are linked through tie-lines, allowing power exchange. Each area includes a governor, turbine, generator load, and control block. The aim of Load Frequency Control (LFC) is to maintain nominal system frequency and scheduled tie-line power flow under load disturbances. Each component is modeled by a first-order transfer function.

System Components

Governor Model The governor adjusts turbine input based on frequency deviation

$$G_g(s) = \frac{1}{1+T_g s} \tag{1}$$

where T_g is the governor time constant.

Turbine Model The turbine dynamics are modeled as:

$$G_t(s) = \frac{1}{1+T_t s} \tag{2}$$

where T_t is the turbine time constant.

Generator-Load Model The generator-load block is expressed as:

$$G_p\,(s) = \frac{1}{1+T_p s} \tag{3}$$

where K_p and T_p are the system gain and time constant, respectively.
Tie-Line Model The tie-line power deviation is defined as:

$$\Delta p_{tie}(s) = \frac{2\pi T_{12}}{s}[\Delta f_1(s) - \Delta f_2(s)] \quad (4)$$

where T_{12} is the synchronizing coefficient.

Area Control Error (ACE)

The Area Control Error combines frequency and tie-line deviations:

$$ACE_1 = B_1\Delta f_1 + \Delta P_{\text{tie}},\ \ ACE_2 = B_2\Delta f_2 + \Delta P_{\text{tie}} \quad (5)$$

Closed-Loop Area Model

Combining the governor, turbine, and generator-load dynamics:

$$G_{area}(s) = G_g(s).G_t(s).G_p(s). = \frac{k_p}{(1+t_g s)(1+T_t s)(1+T_p s)} \quad (6)$$

IMPLEMENTATION OF PID AND FUZZY PID CONTROLLERS

PID Controller Design and Implementation

The Proportional-Integral-Derivative (PID) controller is one of the most widely adopted techniques for Load Frequency Control (LFC) due to its simplicity and ease of tuning. The control objective is to minimize the Area Control Error (ACE), which is a weighted combination of frequency deviation and tie-line power deviation for each area.

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \quad (7)$$

where

- u(t) is the controller output (control signal to the governor),
- e(t) is the Area Control Error (ACE),
- K_p is the proportional gain,
- K_i is the integral gain,
- K_d is the derivative gain.

In the context of LFC, the PID controller processes the ACE and generates an appropriate command to adjust the governor set-point, which in turn influences the generator's output power and helps restore frequency to its nominal value.

The Turning of the PID gains is a critical task. In this study, the Ziegler-Nichols tuning method was initially applied to determine approximate gains, followed by fine adjustments based on trial-and-error to optimize system performance. tuning objectives include minimizing the frequency overshoot, achieving faster settling times, and reducing steady-state error.

The PID controller for each area is implemented in MATLAB/Simulink using standard PID blocks connected to the respective ACE signals. Anti-windup mechanisms are incorporated to prevent integral saturation during large transient disturbances.

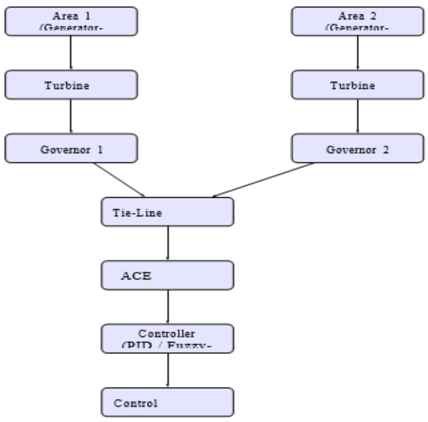

Figure 1: Flowchart of Two-Area Load Frequency Control System

Fuzzy PID Controller Design and Implementation

The Fuzzy PID controller is designed to enhance the traditional PID controller by dynamically adjusting its gains based on system conditions, particularly the error and its rate of change. This adaptive feature enables superior performance in the presence of system nonlinearities, parameter variations, and unmodeled dynamics.

The Fuzzy PID controller structure integrates a Fuzzy Inference System (FIS) with the PID mechanism. The implementation follows these steps:

Input Variables Two inputs are defined for the FIS:
– Error (e): the instantaneous ACE.
– Change in Error (∆e): the rate of change of ACE.
Each input is fuzzified into seven linguistic variables: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB).
Triangular membership functions are used for simplicity and efficiency.
Output Variables Three outputs are generated by the FIS corresponding to the adjustments in:
– Proportional gain adjustment (ΔK_p),
– Integral gain adjustment (ΔK^i),
– Derivative gain adjustment (ΔK_d).
The outputs are also divided into seven fuzzy sets similar to the input variables.
Rule Base A total of 49 fuzzy rules (7×7) are defined based on expert knowledge and control heuristics. A typical rule is:
IF Error is NB AND Change in Error is NB, THEN ΔK_p is PB, ΔK_i is PS,ΔK_d is NS.
These rules are designed to increase the proportional action when the error is large and to modulate integral and derivative actions accordingly to improve transient response and avoid instability
Inference Mechanism The Mamdani-type fuzzy inference mechanism is adopted. The minimum operator is used for the AND operation, and the maximum operator is used for aggregation
Defuzzification The centroid method is used to defuzzify the fuzzy outputs into crisp values that adjust the PID parameters dynamically during operation.
The updated PID control law thus becomes:

$$u(t) = (k_g + \Delta k_p)e(t) + (k_i + \Delta k_i \int_0^t e(\tau)d\tau + (k_d + \Delta k_d)\frac{de(t)}{dt} \qquad (8)$$

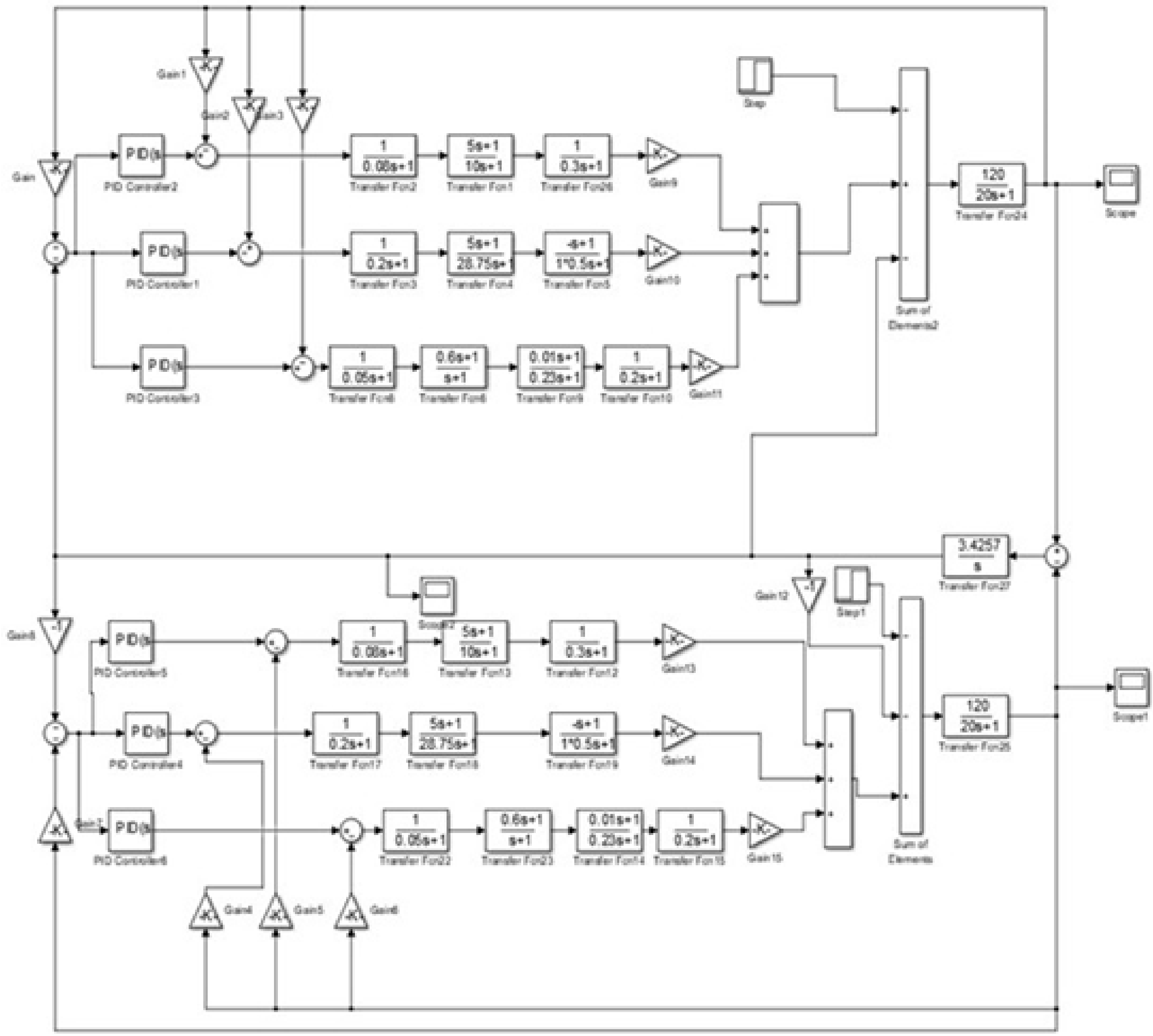

Figure 2: MATLAB/Simulink Diagram for Two area Power System.

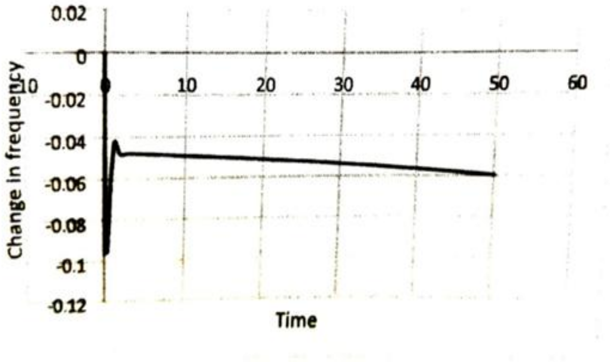

Figure 3: Area 1 without Controller

RESULTS AND DISCUSSION

The simulation model of the two-area interconnected thermal power system, developed in MATLAB/Simulink, is depicted in Figure 2. The model incorporates all major components, including the governor, turbine, generator-load models, and tie-line dynamics for both areas. The Area Control Error (ACE) computation, control blocks (PID and Fuzzy PID), and disturbance injection mechanisms are

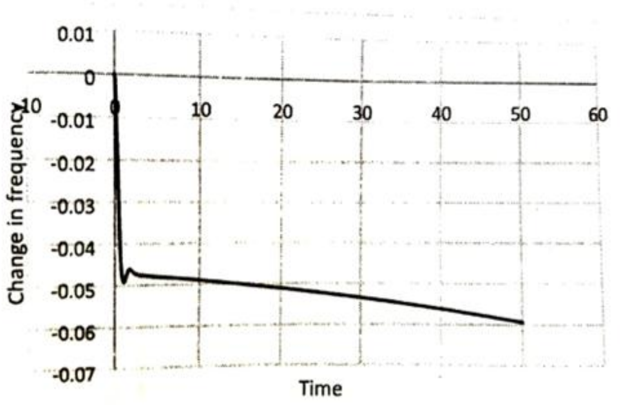

Figure 4: Area 2 without Controller

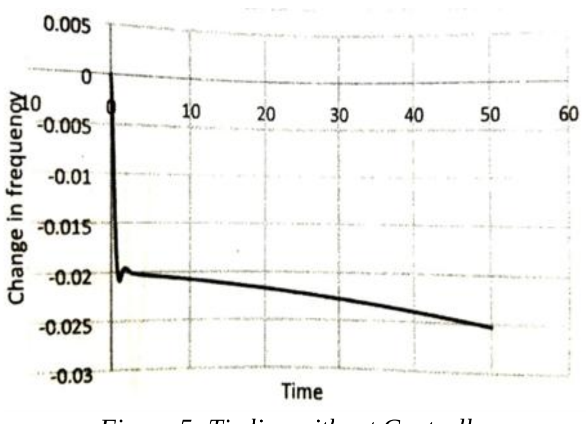

Figure 5: Tie line without Controller

Systematically integrated, facilitating a comprehensive performance evaluation under identical operational conditions.

Figures 3, 4, and 5 illustrate the frequency deviations in Area 1, Area 2, and the tie-line respectively, in the absence of any controller. It is evident that when a step load disturbance occurs, both areas experience significant frequency fluctuations, and the tie-line power exhibits pronounced oscillations. The system demonstrates poor damping characteristics, with large overshoots and prolonged settling times. This behavior underlines the critical necessity of effective Load Frequency Control (LFC) to ensure system stability and minimize adverse dynamic responses.

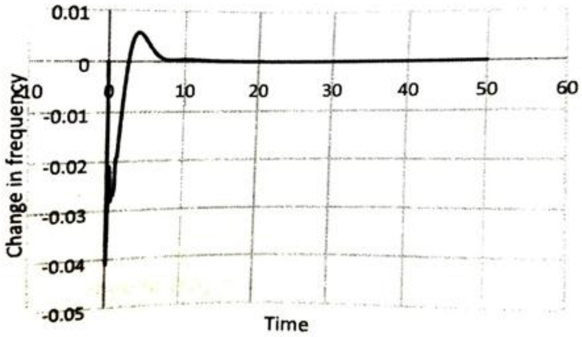

Figure 6: Area 1 with PID

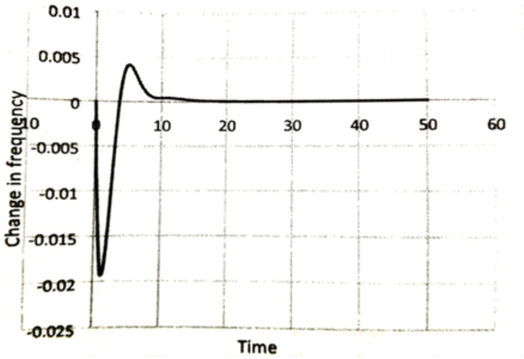

Figure 7: Area 2 with PID

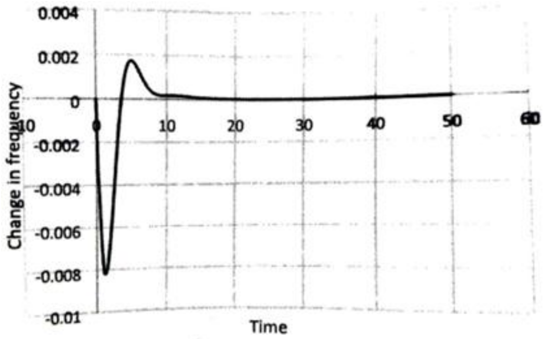

Figure 8: Tie line with PID

The performance of the conventional PID controller is presented in Figure 6, 7, and 8. Upon activation of the PID controller, notable improvements in the system dynamics are observed. The frequency deviations in both areas are significantly reduced, and the tie-line power oscillations are better controlled. The PID controller successfully mitigates the overshoot and reduces the settling time compared to the uncontrolled system. However, minor oscillations persist, and the controller's performance is somewhat sensitive to parameter settings, emphasizing the limitations of fixed-gain designs in handling dynamic system variations effectively.

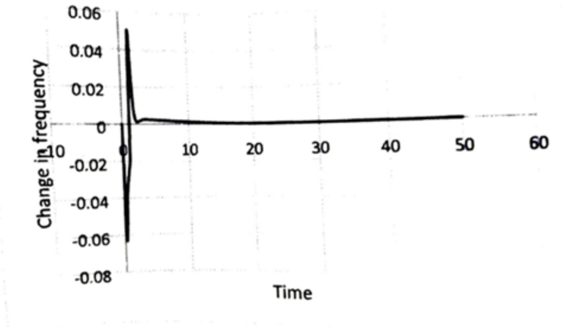

Figure 9: Area 1 with Fuzzy PID

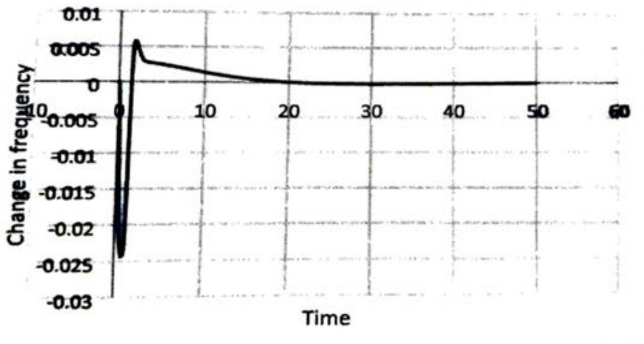

Figure 10: Area 2 with Fuzzy PID

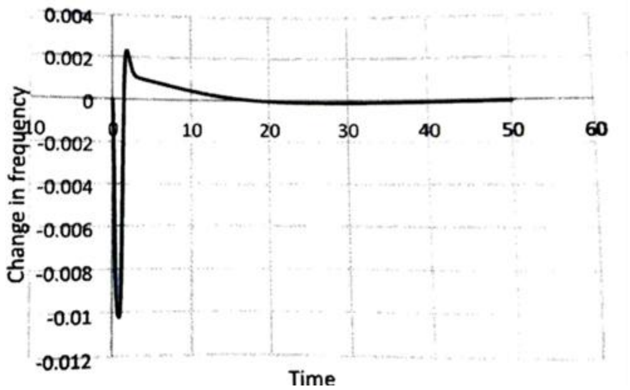

Figure 11: Tie line with Fuzzy PID

Figures 9, 10, and 11 present the results obtained using the Fuzzy PID controller. Compared to the conventional PID controller, the Fuzzy PID approach exhibits superior dynamic response characteristics. The frequency deviations in Area 1 and Area 2 are minimized further, with the system reaching steady-state conditions much faster. Moreover, the tie-line power oscillations are significantly damped, displaying minimal overshoot and rapid convergence. This improved performance can be attributed to the adaptive tuning of PID gains in real-time based on error and change in error information, which enables the controller to respond more robustly to load disturbances and system uncertainties.

Table 1. Performance Comparison of Controllers for Two-Area Power System

Controllers	Without Controller			PID			Fuzzy-PID		
Parameters	Area1	Area2	Tie line	Area1	Area2	Tie line	Area1	Area2	Tie line
Settling Time	-	-	-	17	20	18	15.8	19.7	20
Undershoot	0.09	0.05	0.022	0.06	0.02	0.01	0.04	0.019	0.08

In summary, the results clearly indicate that the Fuzzy PID controller outperforms the traditional PID controller in all evaluated aspects—namely, in reducing. peak overshoot, shortening settling time, and minimizing steady-state error. The adaptive nature of the Fuzzy PID controller allows it to better accommodate the nonlinearities and parameter variations inherent in large interconnected power systems. These findings suggest that intelligent control techniques, such as fuzzy logic-based designs, hold significant promise for enhancing the dynamic stability and robustness of modern power systems under variable operating conditions.

CONCLUSION

This study presented a comparative analysis of Load Frequency Control (LFC) in a two-area interconnected thermal power system using conventional PID and Fuzzy PID controllers. Simulation results clearly demonstrated that while the PID controller improved system response compared to the uncontrolled case, the Fuzzy PID controller provided significantly enhanced performance by achieving faster settling times, reduced overshoot, and minimized steady-state errors. The adaptive nature of the Fuzzy PID controller allowed it to dynamically adjust control actions in response to changing system conditions, thus offering superior robustness and stability. These findings highlight the potential of intelligent control approaches, such as Fuzzy Logic-based techniques, in addressing the growing challenges of frequency regulation and tie-line power management in modern interconnected power systems.

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