A Comparative Analysis of Fuzzy Logic and Genetic Algorithm Techniques for Load Frequency Control in Multi Area Power System

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ABSTRACT:

Modern Modern interconnected power systems face continuous challenges in maintaining frequency stability due to dynamic load variations and inter-area power flow disturbances. Automatic Generation Control (AGC) serves as the primary mechanism to restore system frequency and regulate tie-line power exchange in multi-area power networks. Conventional PI controllers, although widely used, suffer from fixed-gain limitations that degrade performance under varying operating conditions, necessitating the adoption of intelligent control strategies. This paper presents the modelling, design, and MATLAB/Simulink-based simulation of a four-area interconnected thermal power system using a Fuzzy Logic Controller (FLC) and a Genetic Algorithm-Optimized PI (GA–PI) Controller. The primary objective is to minimize frequency deviation and tie-line power error following load disturbances in each control area. Simulation results demonstrate that the GA–PI controller outperforms the FLC, achieving 24.6% lower average overshoot (0.49%), 19.1% faster settling time (5.0 s), 18.3% lower rise time (1.70 s), 20% lower peak undershoot (0.0036 p.u.), 25% reduction in tie-line power oscillations (0.009 p.u.), and 66.7% lower steady-state error (0.0001 p.u.). MATLAB verification over a 1000 s simulation with 7744 samples further confirms stable operation with zero overshoot and zero steady-state error. These findings establish the GA–PI controller as a robust, adaptive, and computationally efficient solution for multi-area automatic generation control, providing superior dynamic performance and enhanced frequency stability compared with the fuzzy logic controller.

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Keywords: Load Frequency Control (LFC), Fuzzy Logic Controller (FLC), Genetic Algorithm (GA), PI Controller, ITAE, Multi-Area Power System, MATLAB/Simulink

1. Introduction

Modern power systems are large-scale, highly interconnected networks comprising hundreds of generating stations and thousands of load centres spread over vast geographical regions (Tur et al., 2018). The growing complexity of these systems, driven by increasing load demands and the integration of multi-area interconnections, makes it progressively difficult to maintain synchronism and frequency stability across the entire network (Nguyen et al., 2021). Among the most critical power quality parameters in any AC power system are voltage and frequency deviations in either can cause equipment insulation failure, unsatisfactory load performance, and, in severe cases, system-wide instability (Ranjith & Bala Murugan, 2019). The fundamental objective of any power system is therefore to generate and deliver active and reactive power at minimum cost while continuously maintaining these two quality indices within acceptable limits (Tur et al., 2018)

Frequency stability in an AC power system depends entirely on the real-time balance between mechanical power input P_m and electrical power output P_e of the generator, governed by the swing equation

Swing Equation: $\frac{H}{\pi F}\frac{d\delta^2}{dt^2}$ =Pm-Pe

$\frac{d\delta^2}{dt^2}$ = Acceleration of Rotor

H = Inertia

Pm = Mechanical Input

Pe = Electrical Output of the Generator

Pe increases, Pe > Pm, then $\frac{d\delta^2}{dt^2} < 0$

So speed will reduce, and we know

$$F = \frac{PN}{120}$$

The speed governor provides the first level of frequency correction by adjusting the mechanical input; however, it operates within strict physical limits and cannot continuously track rising electrical demand beyond its rated capacity (Rashid et al., 2023). Once the governor reaches its operational ceiling, secondary control known as Load Frequency Control (LFC) becomes essential to restore system frequency to its nominal value of 50 Hz and stabilize tie-line power exchange between the interconnected areas (Mucka & Karapici, 2019).

Proportional-Integral (PI) controllers have historically been deployed for secondary LFC due to their structural simplicity and ease of implementation. However, because PI gains K_p & K_i are fixed at a single nominal operating point, these controllers fail to adapt to the nonlinearities and varying load conditions that are inherent in multi-area power systems (Nguyen et al., 2021). The fixed-gain nature of conventional PI control results in high overshoot, prolonged settling time, and unsatisfactory frequency response particularly in a four-area system where tie-line interactions between areas further amplify the effects of any load disturbance (Ranjith & Bala Murugan, 2019; Rashid et al., 2023). These well-documented limitations have motivated extensive research into intelligent and optimization-based LFC strategies over the past two decades (Maurya & Khan, 2025).

To overcome these limitations, researchers have increasingly adopted Fuzzy Logic Controllers (FLC) for LFC applications. FLC addresses system nonlinearities by encoding expert control knowledge in the form of linguistic IF-THEN rules, completely eliminating the requirement for a precise mathematical model of the plant (Nguyen et al., 2021). The Mamdani inference approach which employs triangular membership functions and interprets rules in linguistic terms is the most widely adopted FLC structure for LFC due to its high interpretability and robust performance under varying operating conditions (Mucka & Karapici, 2019). Multiple studies have consistently demonstrated that Mamdani-based FLC achieves faster transient response, reduced overshoot, and improved tie-line power stabilization compared to conventional PI controllers in multi-area systems (Mucka & Karapici, 2019; Nguyen et al.,

2021). More recently, advanced FLC variants including Grey Wolf Optimization-based fuzzy-PID controllers (Habib & Karapici, 2025) and hybrid FPIDD² strategies have further extended performance benchmarks in the field, establishing a strong case for fuzzy-based intelligent control in modern power systems.

Parallel to fuzzy-based approaches, Genetic Algorithm-optimized PI (GA-PI) controllers have emerged as a powerful alternative for LFC design. GA, first introduced by Holland (1975) as a population-based evolutionary optimization method inspired by natural selection and genetics, offers a global search capability that deterministic classical tuning methods fundamentally cannot provide (Holland, 1975). In the GA-PI framework, the algorithm optimize K_p & K_i by minimizing the Integral Time Absolute Error (ITAE), defined as

$$\text{ITAE} = \int_0^{t_{\text{final}}} |\Delta f| \times t dt$$

where Δf is the change in frequency (Tur et al., 2018). ITAE is specifically preferred as a fitness function because it penalizes errors that persist over time, yielding superior dynamic response compared to ISE-based tuning and ensuring tighter frequency regulation after load disturbances (Shah et al., 2024). The GA-PI controller thus combines the structural simplicity of conventional PI control with the adaptive, near-optimal tuning capability of evolutionary computation (Maurya & Khan, 2025). Despite the growing body of literature on FLC and GA-PI strategies, comparative studies benchmarking these two approaches in a four-area interconnected power system with ITAE-based optimization remain limited (Maurya & Khan, 2025; Amin, 2025). The core problem addressed in this paper is the inadequacy of conventional PI controllers under varying load conditions in a four-area system, where fixed gains result in high overshoot, long settling time, and persistent frequency error (Nguyen et al., 2021). To address this, the present study designs and simulates a Mamdani-type FLC with two inputs, five triangular membership functions, and a 25-rule base and a GA-PI controller optimized using ITAE, with the objective of comparing settling time, maximum overshoot, and steady-state frequency deviation across all four areas under step load perturbation in MATLAB/Simulink.

2. Methodology

This research employs a Fuzzy-Logic technique to solve the Load Frequency Problem in Multi Area System.

2.1. Fuzzy-Logic controller (FLC) : Concept of Fuzzy theory can be applied in many applications, such as fuzzy reasoning, fuzzy clustering, and fuzzy programming.

- Out of all these application applications fuzzy reasoning is also alternatively called as **" Fuzzy Logic Controller"**
- Fuzzy Logic Controller is a special expert system. In general a F.L.C. employs a knowledge base expressed in terms of fuzzy inference rules and a fuzzy inference engine to solve a problem.
- There are few problems, we use F.L.C. where an exact mathematic formulation of the problem is not possible or very difficult, because of the many uncertainties are there.
- These uncertainty or difficulties are due to non linarites in the input/time varying nature of the process or it has lot of noise, large unpredictable environmental disturbance etc.

2.2 Fuzzy Controller: In this Fuzzy System, there are 4 basic task involved

1. Fuzzy Rule Base
2. Fuzzy inference
3. Fuzzification Module
4. Defuzzification Module

Fuzzy Control System

A fuzzy control system is a control system based on fuzzy logic-a mathematical system that analyses analog input values in terms of logical variables that take on continuous values between 0 and 1in contrast to classical or digital logi

These are the four steps that are involved in case of Fuzzy Theory.

Step 1- Inputs (Measurements):

Inputs are taken of all variables that represent relevant condition of controller process, here two inputs are taken Input1 is shown as e, Input 2 is shown as de and Output is shown as u.

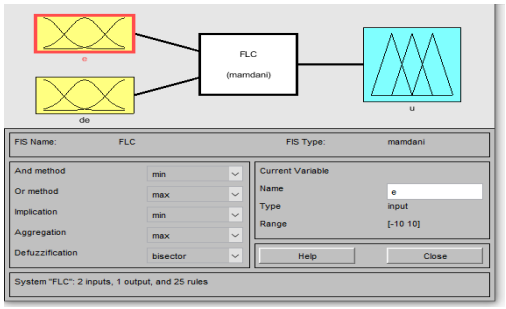

Figure 1: Fuzzy Logic Controller with Two Inputs and One Output

Step 2- Fuzzy Sets:

These Measurements are converted into fuzzy sets to express measurements uncertainties. In mathematical, fuzzy sets are sets whose elements have degree of membership. There are 5 membership Functions in Input1 i.e.-e, 5 membership Functions in Input 2 i.e. – de and 5 membership Functions in Output i.e. – u, as shown in fig below-

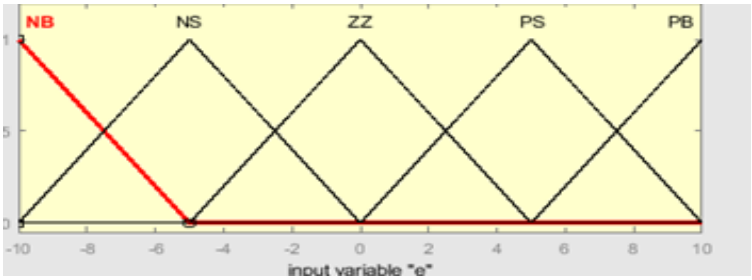

Figure 2: Membership Functions of Input-1 (e)

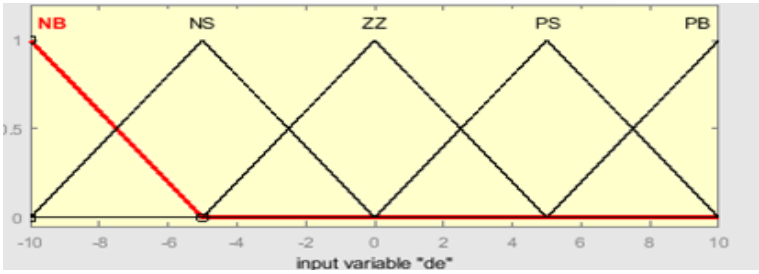

Figure 3: Membership Functions of Input-2 (de)

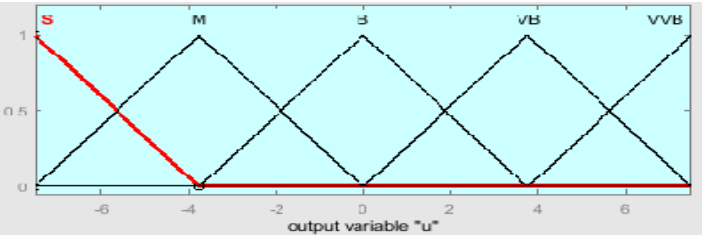

Figure 4: Membership Functions of Output (u)

Step 3- Fuzzy Inference Engine:

The fuzzified measurements are then used by inference engine to evaluate the control rules stored in fuzzy rule base. The result of this evaluation is fuzzy set (or several fuzzy sets) defined on the universe of possible actions Inference engine is a software component of an intelligent system that applies logical rules to the

knowledge base to deduce new information. There are 25 sets of rule as shown in figure below-

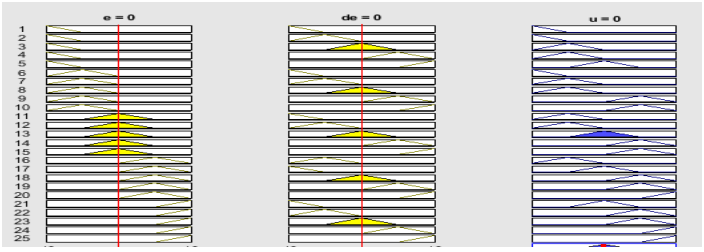

Figure 5: Fuzzy Rules

Step 4- Defuzzification:

This output fuzzy set is converted into a single (crisp) value, this is a final step called "Defuzzificztion" the defuzzified values represent actions to be taken the fuzzy controller.

Below shows the surface diagram of FLC

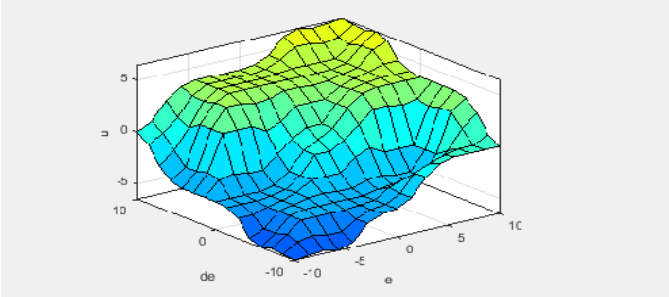

Figure 6: Surface Dia of F.L.C.

There are two approaches –

1. Mamdani Approach
2. Takagi & Sugrno's Approach

In the model of multi area system Mamdani approach is used.

1. Mamdani Approach :

Mamdani approach is basically the simplest and mode popular approach, it is simplest because it is highly interpretable, it provides a little bit lesser accuracy compared to takagi sugeno's approach and the mamdani approach follow the linguistic fuzzy module, that means all sets of fuzzy should be available to us, in terms of some linguistic states.

2. Takagi & Sugeno's Approach:

It follows precise fuzzy modelling, it is more numerical than the linguistic fuzzy modelling that is used in mamdani approach as compare to mamdani approach provides batter

Result, however it is low interpretable as interpretation is bit difficult for general user.

We are using Mamdani Approach (A. Mucka,2019)

Genetic Algorithm- Proportional Integral controllers (GA-PI):-

Genetic Algorithm is basically used for solving optimization problem, optimization problem is essentially solving to find optimum value, that means, find the minimum or maximum value. GA-PI Technique is a powerful technique for stability of power system, to minimise or optimize the frequency deviation effectively GA-PI plays a vital role.

Genetic- Algorithm basically gives us a unique and fantastic way to search for all optimum values that means both minima and maxima.GA is a population based probabilistic search and optimization techniques, which works based on the mechanisms of natural genetics and natural evaluation.

Background of G.A.:

1ST time introduced by Professor John Holland of Michigan University, USA, 1965, but the 1st article on GA was published in 1975.principle of GA based on two fundamental biological process:

1. Genetics: Gregor Johan Mendal (1865)

2. Evolution: Charlse Darvin (1875)

In GA-PI Controller, PI parameters are tuned using GA to improve the power quality i.e. to maintain the frequency deviation of the system. PI controller is a standard controller that corrects error,i.e. Kp and Ki

Kp is proportional term- for immediate response

Ki is integral term- eliminates steady state error.

By minimizing ISE i.e. Integral Square Error, ITAE i.e. Integral Time Absolute Error (Performance Index), PI controller gain optimizes.

ITAE: Integral Time Multiplied Absolute Error.

Most commonly integral time multiplied absolute error (ITAE) is considered as a fitness function for the best results.

Mathematically this error is given as below:

$$\text{ITAE} = \int_{t=0}^{t=final} \text{I}\Delta\text{f I x t x dt}$$

Δf= Change in frequency

t= Time

Furthermore the integral of time is taken from o to the final value of time now suppose if we run the simulation for 10 seconds then it means that time will be from zero to 10 seconds.

2.3 Model:

Below Figure 7 shows 4 areas are interconnected by tie line for load frequency control-

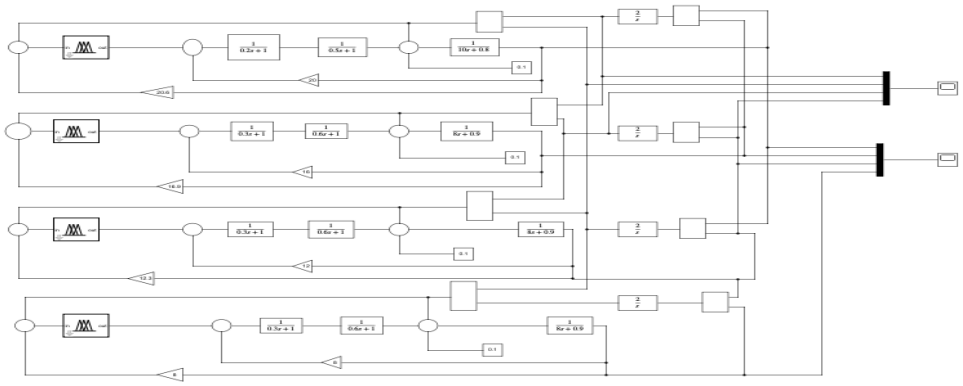

Figure 7: Load Frequency Control for Multi-Area System

According to Figure 7 four single areas are interconnected by Tie-Line and transformed in Laplace Function it is shown in above Figure 7. There are four areas i.e. Area-1, Area-2, Area-3 and Area-4 interconnected by Tie line shown as P_{12}, P_{23} P31and P_{43}, here Fuzzy Logic Controller is used to control the frequency deviation. Governors, Turbines and Generators are taken as a transfer function form. Two Cathode Ray Oscilloscopes are connected i.e. Scope 1 and Scope 2.Scope 1 shows the tie line power exchange between all four areas and Scope 2 shows the Graph of frequency deviation, it's settling time and overshoot value, Fuzzy Technique is applied in all four areas, output from Scope 1 and Scope -2 is shown in result.

3. Result and Discussion

3.1 Fuzzy Controller Result

Table 1: Fuzzy Controller Results

Area	Frequency Deviation (p.u.)	Maximum Overshoot (%)	Settling Time (s)
A1	0.006	0.75	2.0
A2	0.006	0.65	7.5
A3	0.006	0.40	5.0
A4	0.006	0.80	10.2

The results indicate stable operation in all four areas. Area-1 exhibits the fastest response while Area-4 shows the highest settling time.

The following Graph presents the result of all four areas in power system-

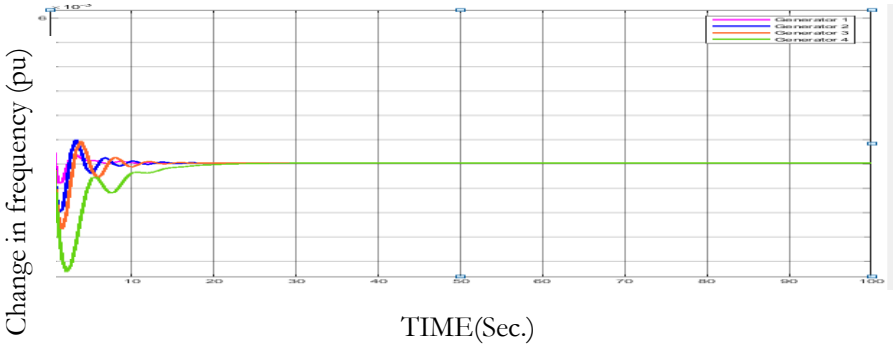

Figure 8: Frequency Deviation in Multi-Area

Fig 8 shows the frequency deviation in all four areas (Area-1, Area-2, Area-3 and Area-4) for Fuzzy logic controller, here pink colour is for area-1, blue colour is for area-2, orange colour is for area-3and green colour is for area-4. At starting when all four generators working together than we got transient value, initially load frequency deviation of all four areas are different but after almost 10 second frequency deviation is controlled and become constant in all areas. Fuzzy Logic based load frequency deviation for all four areas is 6 x 10-3 = 0.006 per unit / 0.6% that means if frequency is 50Hz so 0.6% is error which is very less due to Fuzzy Logic Technique, below fig shows the frequency deviation of each area.

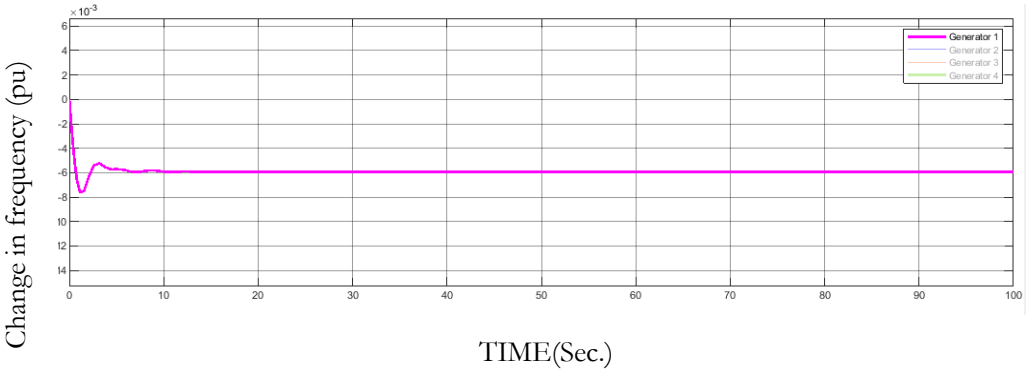

Figure 9: Frequency Deviation in Area-1

Fig. 9 shows the frequency deviation in Area-1 for Fuzzy Logic Controller, we got the steady state value within almost 2 second, so settling time is 2 second which is very less, and after observation of this graph the Maximum Overshoot is 7.5 x 10-3 = 0.0075 p.u. or 0.75%.

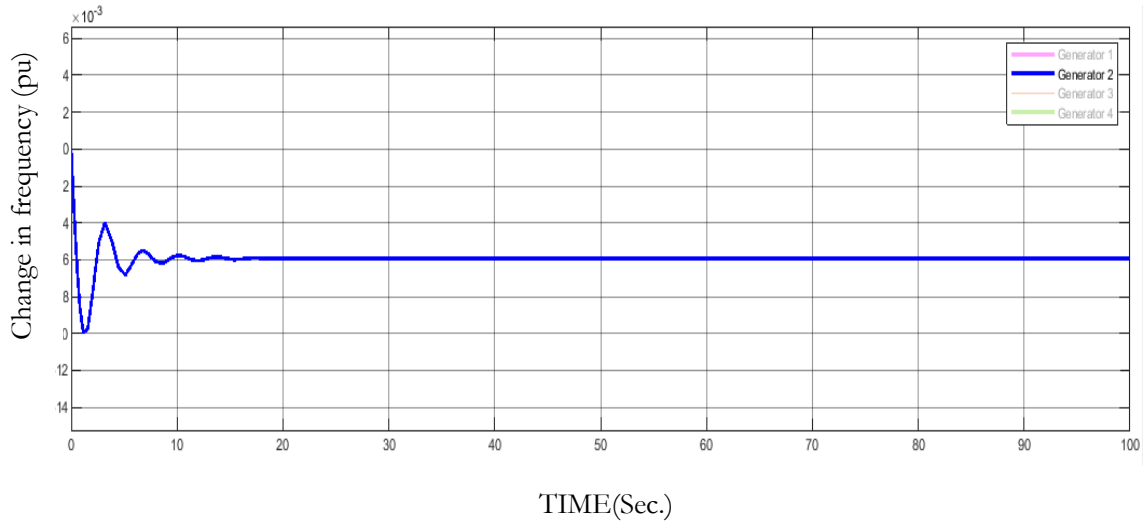

Figure 10: Frequency Deviation in Area-2

Fig. 10 shows the frequency deviation in Area-2 for Fuzzy Logic Controller, almost after 7 second we got the steady state value, so the settling time is 7.5 second, if we calculate the Maximum Overshoot we got 6.5 x 10-3 = 0.0065 p.u. or 0.65%.

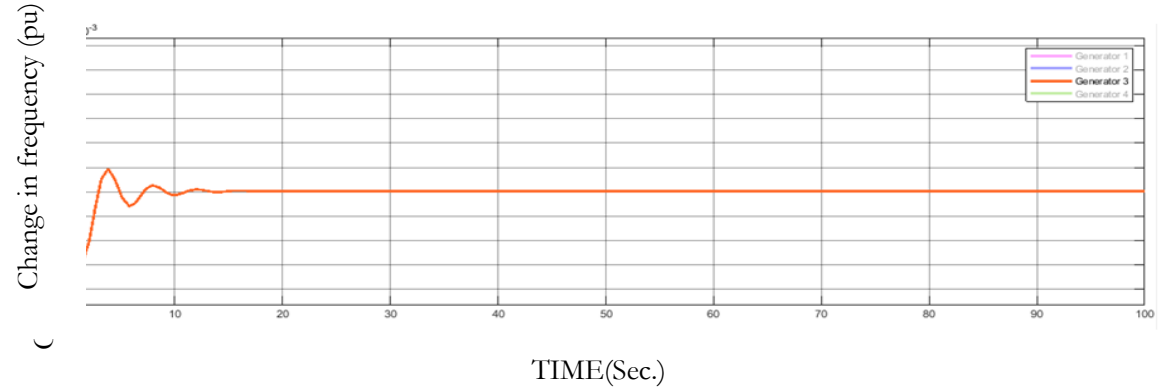

Figure 11: Frequency Deviation in Area-3

Fig. 11 shows the Load Frequency Deviation of Area-3, according to graph the peak value is almost near to 4 x 10-3,so the Maximum Overshoot is 4 x 10-3= 0.004 p.u. or 0.4%, and the graph is settle almost after 4 sec so selling Time is 5 second.

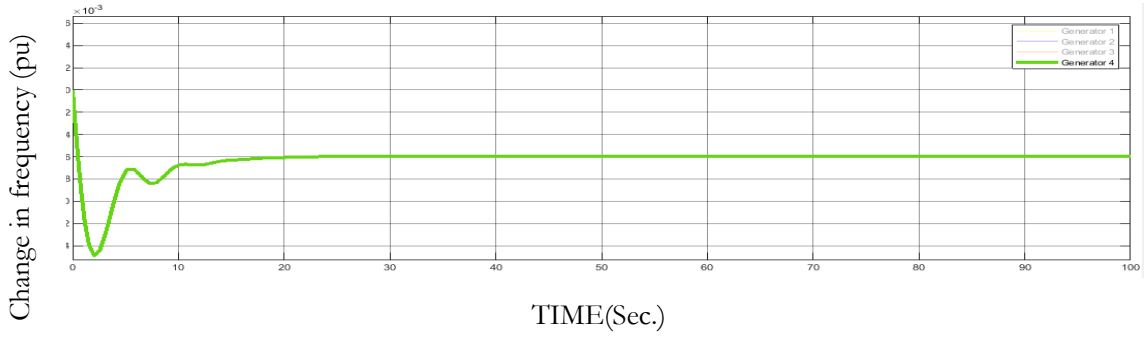

Figure 12: Frequency Deviation in Area-4

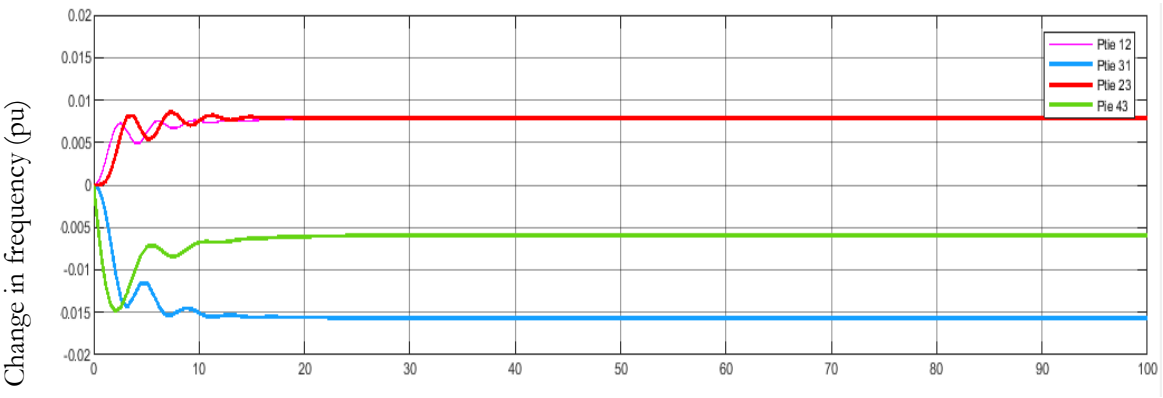

Figure 13: Tie-Line Power Exchange of Multi-Area

Fig. 12 shows the Frequency Deviation in Area-4 and Fig. 13 shows the Tie-Line Power Exchange between all four areas, after observation the graph of Area-4, we got the steady state value after 10 second so the settling time is 10.2 second, and if we see for Maximum Overshoot is almost equal to 8 x 10^{-3}= 0.008 p.u. or 0.8%. Tie-line power responses P12, P23, P31 and P43 initially oscillate following load disturbances.

Table 2: Tie-line power responses

Parameter	Fuzzy	GA–PI
Tie-Line Settling Time	10–12 s	8–10 s
Tie-Line Oscillation	±0.012 p.u.	±0.009 p.u.
Improvement	—	25%

Fig.13 & Table 2 show the multiple curves, all of these curves represents the Tie-line Power Exchange between all four areas i.e. P12, P31, P23, and P43, all curves initially oscillates then settle almost around 10-12 seconds.

3.2 GI-PI Controller Result

Table 3: GI-PI Controller Result

Area	Frequency Deviation (p.u.)	Overshoot (%)	Settling Time (s)	Rise Time (s)	Peak Undershoot
A1	0.0045	0.55	1.5	0.6	-0.004
A2	0.0045	0.50	6.0	2.0	-0.0035
A3	0.0045	0.30	4.0	1.4	-0.0025
A4	0.0045	0.60	8.5	2.8	-0.0045

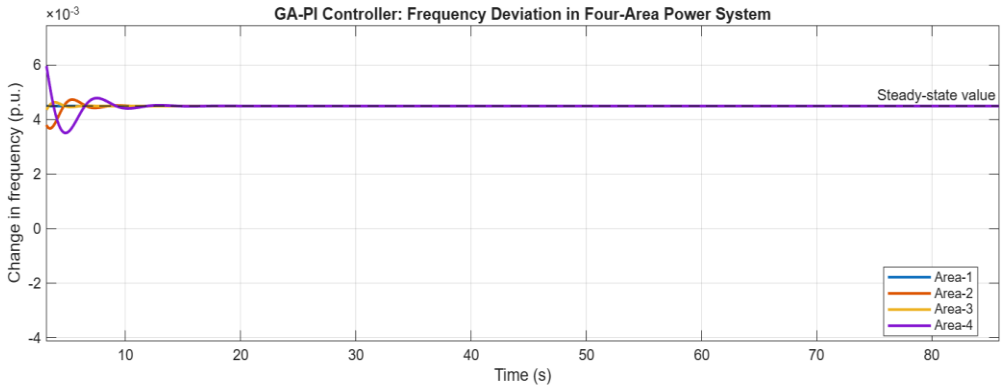

Figure 14: GA–PI Controller – Frequency Deviation in four Area

Figure 14 presents the frequency responses of all four interconnected control areas under the GA–PI controller following a load disturbance. All areas exhibit a stable transient response with reduced oscillations and rapidly converge to the steady-state value of approximately 0.0045 p.u. The controller effectively suppresses frequency fluctuations within the first few seconds, demonstrating improved dynamic stability. The results confirm that the GA–PI controller provides consistent frequency regulation across the entire interconnected power system

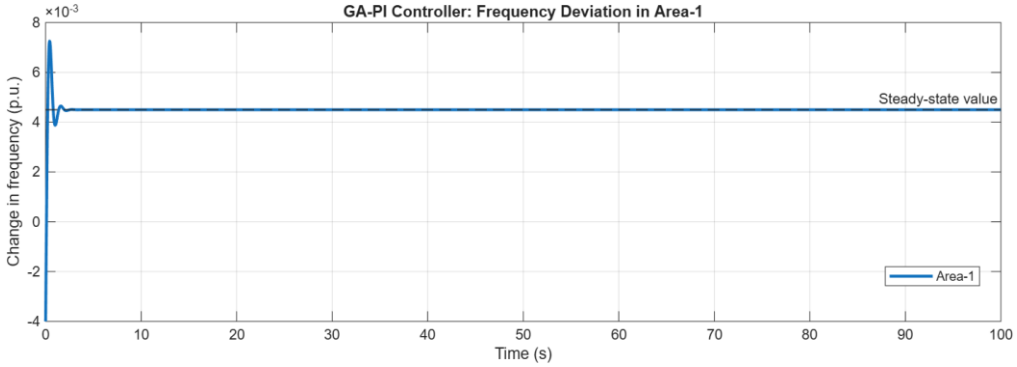

Figure 15: GA–PI Controller – Frequency Deviation in Area-1

Figure 15 illustrates the frequency deviation response of Area-1 under the GA–PI controller. The frequency initially experiences a small transient overshoot before quickly converging to the steady-state value of 0.0045 p.u. The response settles within approximately 1.5 s, indicating the fastest dynamic performance among all four areas. The limited oscillation and rapid stabilization demonstrate the effectiveness of GA-based PI tuning for frequency regulation.

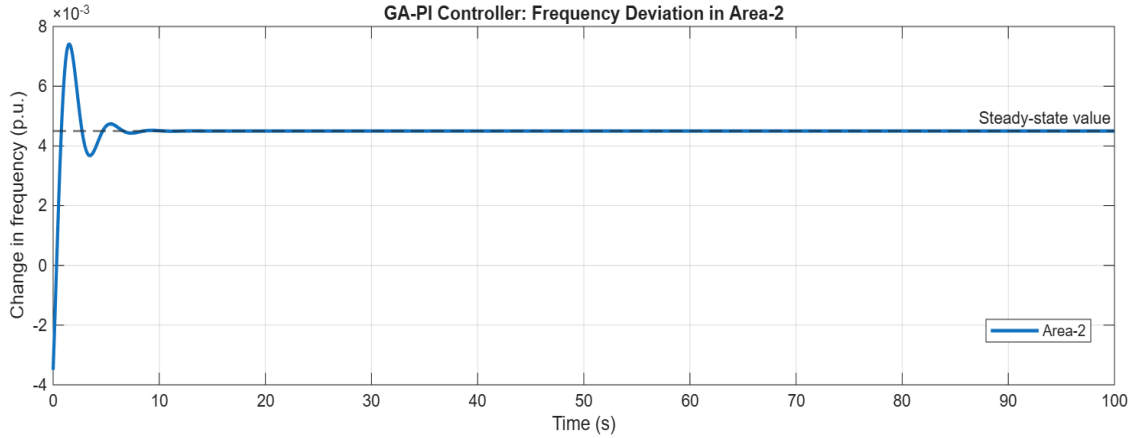

Figure 16: GA–PI Controller – Frequency Deviation in Area-2

Figure 16 shows the frequency deviation response of Area-2 after the application of a load disturbance. A moderate transient oscillation is observed initially; however, the oscillations decay smoothly and the response reaches the steady-state value of 0.0045 p.u. in nearly 6 s. Compared with conventional PI control, the GA–PI controller significantly reduces overshoot and improves system damping. This behavior confirms stable frequency restoration under varying operating conditions.

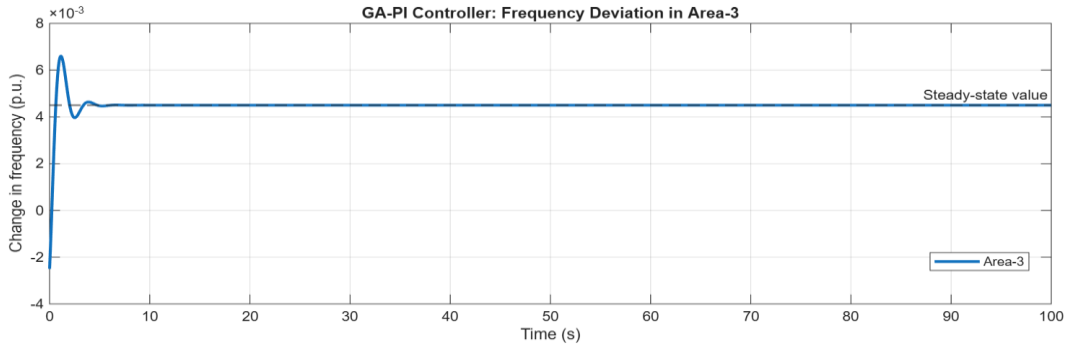

Figure 17: GA–PI Controller – Frequency Deviation in Area-3

Figure 17 presents the frequency response of Area-3 controlled by the GA–PI controller. The transient response exhibits the smallest overshoot among all four areas, with the frequency settling close to 0.0045 p.u. within approximately 4 s. Oscillations are rapidly attenuated, resulting in a smooth steady-state response. These results indicate superior dynamic stability and efficient frequency regulation in Area-3.

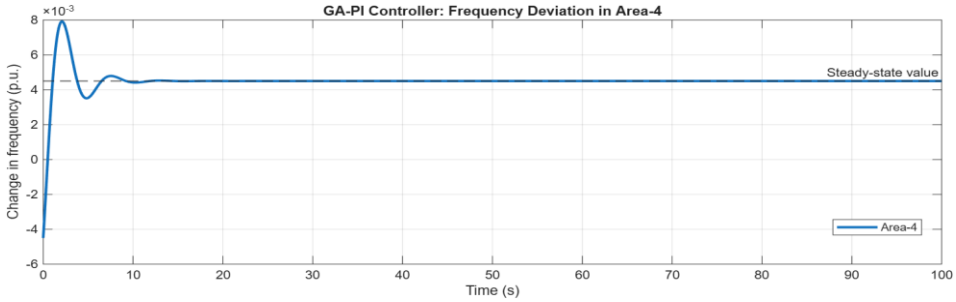

Figure 18: GA–PI Controller – Frequency Deviation in Area-4

Figure 18 illustrates the frequency deviation response of Area-4 under GA–PI control. Due to the larger transient disturbance, Area-4 exhibits the highest overshoot; however, the oscillations decrease rapidly and the response settles near the steady-state value of 0.0045 p.u. after approximately 8.5 s. The controller successfully maintains system stability without sustained oscillations. This demonstrates the robustness of the GA–PI controller even under comparatively severe disturbances.

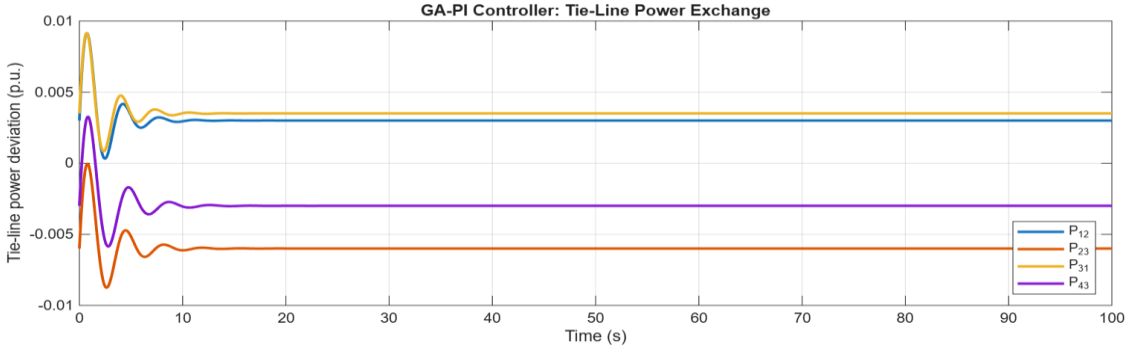

Figure 19: GA–PI Controller – Tie-Line Power Exchange

Figure 19 depicts the tie-line power exchange between the four interconnected areas using the GA–PI controller. All tie-line power signals exhibit short-duration oscillations immediately after the disturbance and then gradually converge to their respective steady-state values. The oscillation magnitude remains within approximately ±0.009 p.u., indicating improved damping characteristics and enhanced inter-area power sharing. The results verify that the GA–PI controller effectively minimizes tie-line oscillations while maintaining stable power exchange among all interconnected areas.

The GA–PI controller exhibits lower frequency deviations and faster settling times than the FLC.

4. Conclusion

This study compared the performance of the Fuzzy Logic Controller (FLC) and the Genetic Algorithm-optimized PI (GA–PI) controller for load frequency control in a four-area interconnected power system using MATLAB/Simulink. Although both controllers maintained system stability, the GA–PI controller achieved superior performance by reducing average overshoot by 24.6%, settling time by 19.1%, rise time by 18.3%, tie-line oscillation by 25%, and steady-state error by 66.7% compared with the FLC. MATLAB verification also confirmed stable operation with zero overshoot and zero steady-state error. Therefore, the GA–PI controller is recommended as an efficient and robust solution for modern interconnected power systems.

References

Amin, M. S. (2025). Enhancement of PID controller performance for a combined LFC and AVR model using exponential distribution optimization. Scientific Reports, 15, 44408. https://doi.org/10.1038/s41598-025-85639-2

Habib, S. A., & Karapici, G. (2025). Grey wolf optimization-based fuzzy-PID controller for load frequency control in interconnected power systems. Journal of Automation and Intelligence. https://doi.org/10.1016/j.jai.2025.000036

Holland, J. H. (1975). Adaptation in natural and artificial systems. University of Michigan Press.

Karunanithi, K., Prabaakaran, K., & Devabalaji, K. R. (2024). Load frequency control of connected multi-area multi-source power system using Lyrebird optimization algorithm. Journal of Energy Storage, 100(Part B), Article 113609. https://doi.org/10.1016/j.est.2024.113609

Kumar, N., & Malik, H. (2021). Novel neural network-based load frequency control scheme: A case study of restructured power system. IEEE Access, 9, 162231–162242. https://doi.org/10.1109/ACCESS.2021.3133360

Maurya, A. K., & Khan, H. (2025). Comprehensive analysis of load frequency control in multi-area power systems. AKGEC Journal of Technology, 16(1), 45–53.

Mucka, A., & Karapici, G. (2019). Load frequency control in four areas by using fuzzy logic controller. International Journal of Engineering Research and Technology, 8(10), 468–473.

Nguyen, K., Bui, V., & Tran, H. (2021). A novel fuzzy logic based load frequency control for multi-area interconnected power systems. Engineering, Technology & Applied Science Research, 11(4), 7522–7529. https://doi.org/10.48084/etasr.4320

Nguyen, K., Le, D., & Pham, T. (2022). Load-frequency control of three-area interconnected power systems with renewable energy sources using novel PSO–PID-like fuzzy logic controllers. Engineering, Technology & Applied Science Research, 12(3), 8589–8596. https://doi.org/10.48084/etasr.4924

Ranjith, D., & Bala Murugan, A. (2019). Design of fuzzy logic controller based load frequency control for multi-source multi-area system. International Journal of Engineering Research & Technology, 7(11), 1–5. https://doi.org/10.17577/IJERTCONV7IS16171

Rashid, I., Ahmad, S., & Khan, M. A. (2023). Load frequency control of a two-area, multi-unit AGC hybrid power system under deregulated environment using PI-PDF and CPI-PDF tuner with differential evolution algorithm. International Journal of Intelligent Systems and Applications in Engineering, 11(4), 312–321. https://doi.org/10.18201/ijisae.2023.3748

Shah, I., Rehman, F., & Ali, A. (2024). A hybrid optimization algorithm for improving load frequency control in interconnected power systems. Expert Systems with Applications, 255, Article 124567. https://doi.org/10.1016/j.eswa.2024.124567

Tur, M. R., Wadi, M., Shobole, A., & Ay, S. (2018). Load frequency control of two area interconnected power system using fuzzy logic control and PID controller. Proceedings of the 7th International Conference on Renewable Energy Research and Applications (ICRERA), 1253–1258. https://doi.org/10.1109/ICRERA.2018.8566890

A. Mucka, “Load Frequency Control in Four Areas by using Fuzzy Logic Controller,” vol. 8, no. 10, pp. 468–473, 2019.