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Two-Area Load Frequency Control Using Hybrid PSO-Fuzzy Logic Controller in a Renewable Integrated Nigerian Grid

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ABSTRACT

Maintaining frequency stability in interconnected power systems is increasingly challenging with rising integration of intermittent renewables. Conventional PI-based load frequency control lacks adaptability under nonlinear and time-varying conditions caused by renewable fluctuations. This paper proposes a hybrid Particle Swarm Optimization–Fuzzy Logic Controller (PSO–FLC) for secondary frequency regulation in a two-area Nigerian grid with solar and wind generation. The fuzzy controller provides adaptive control, while PSO optimizes membership functions and scaling gains to minimize frequency deviations and control effort. A MATLAB/Simulink model of the two-area system with thermal and renewable units is tested under step-load disturbances. Results show that the PSO–FLC achieves faster settling time, reduced overshoot, and lower control effort, demonstrating its superiority in enhancing frequency restoration and tie-line stability in Nigeria's evolving power grid.

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INTRODUCTION

The stability and reliability of modern power systems face increasing challenges due to the rapid integration of renewable energy sources and rising load demand. Load Frequency Control (LFC) remains essential for maintaining system frequency and scheduled power exchanges in interconnected networks [1]. The Nigerian power grid, with its aging infrastructure, weak interconnections, and limited spinning reserves, presents a particularly difficult environment for effective LFC implementation [2].

Nigeria's Renewable Energy Master Plan targets 30% renewable penetration by 2030, driven largely by solar and wind resources [3]. However, the intermittency and variability of these sources introduce significant operational uncertainties that conventional Proportional–Integral (PI) controllers struggle to handle [4]. Although PI controllers are simple and widely used, their performance degrades under system nonlinearities, parameter variations, and generation uncertainties.

To address these limitations, several intelligent control techniques have been explored, including fuzzy logic controllers (FLCs) [5], artificial neural networks [6], and evolutionary optimization algorithms [7]. FLCs, in particular, are effective for systems with uncertainties and imprecise models [8], but their performance depends heavily on properly selecting membership functions and rule bases, which traditionally requires extensive manual tuning.

This study adopts a simulation-based methodology in three stages. First, a dynamic two-area Nigerian power grid model incorporating solar photovoltaic and wind generation is developed to capture realistic renewable penetration and inter-area behavior. Second, a hybrid Particle Swarm Optimization–Fuzzy Logic Controller (PSO-FLC) is designed for LFC, with PSO used to optimize fuzzy membership parameters and scaling factors, reducing tuning effort and improving adaptability. Finally, the PSO-FLC is compared with a conventional PI controller under step-load disturbances in both areas. Key

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performance indices include frequency deviation, settling time, and control effort, are evaluated using MATLAB/Simulink to assess system stability and response improvements.

SYSTEM MODELING

Two area LFC model

A two-area interconnected power system is considered for this study, where each area consists of a governor, turbine, and generator-load block, interconnected through a tie-line. The system also includes renewable energy sources (RES) wind and solar photovoltaic (PV) integrated through their equivalent inertia-less models. The overall structure aims to capture frequency deviations and power exchanges under disturbances.

The modeling follows the standard assumptions of small-signal linearization around the nominal operating point, allowing Laplace-domain representation using transfer functions.
Mathematical Model Components

Governor: The complete governor transfer function, including speed droop characteristics and control input, is given by:

$$\Delta G(s)=(\frac{1}{1+Tgs}(-\frac{1}{R}\Delta f(s)+u(s)) \quad (1)$$

Where:
ΔG(s): change in governor valve position
Tgs: governor time constant
R: speed regulation parameter
u(s): control input (from PI or Fuzzy–PSO controller)
Δf(s): frequency deviation

Turbine Model:

A reheat steam turbine is modeled using a two-stage system

$$\Delta \mathrm{Pt(s)} = \frac{1}{(1+\mathrm{T_t s})}(\mathrm{K_r}\frac{1}{(1+\mathrm{T_r s})})\Delta G_{(s)} \quad (2)$$

Where:

$\Delta P_t(s)$: change in turbine output
T_t: turbine time constant
T_r: reheater time constant
K_r: reheater gain

Load and Frequency Response

Frequency deviation is caused by imbalance between generation and load.

$$\Delta f(s)=\frac{1}{2Hs+D}(\Delta P_{t(s)}-\Delta P_L(s)) \quad (3)$$

Where:
H: inertia constant
D: load damping coefficient
ΔPL(s): change in load demand

Tie-Line Power Flow Model

The power transfer between interconnected areas is a function of frequency deviation

$$\Delta P_{tie,12}(s)=\frac{2\pi T12}{s}(\Delta f1(s)-\Delta f_2(s)) \quad (4)$$

Where:
$\Delta P_{tie,}$: tie-line power deviation
T_{12}: synchronizing coefficient between two areas

Area Control Error (ACE)

The ACE is used as the control input to stabilize the system:

$$ACE_1=B_1\Delta f_1+\Delta P_{tie,12} \quad (5)$$
$$ACE_2=B_2\Delta f_2-\Delta P_{tie,} \quad (6)$$

Where:
B_1,B_2: frequency bias constants for Areas 1 and 2
Δf_i: frequency deviation in Area *i*
$\Delta P_{tie,12}$: tie-line power deviation for Area *i*

Renewable energy integration

The integration of solar PV and wind resources introduces significant variability that must be accommodated by the LFC system. Solar PV power output is modeled considering Nigerian solar profiles:

$$P_{PV}(t) = P_{rated} \times G(t) \times \eta_{PV} \times [1 - \alpha(T_C(t) - T_{ref}) \quad (7)$$

Where:
G(t) represents solar irradiance following typical Nigerian patterns, ηPV is conversion efficiency, and α is the temperature coefficient.

Wind power generation is modeled using the piecewise relationship

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$$P_{\text{wind}}(t) = \begin{cases} 0, & v < v_{\text{cut-in}} \\ \frac{1}{2}\rho A C_p v^3, & v_{\text{cut-in}} \le v < v_{\text{rated}} \\ P_{\text{rated}}, & v_{\text{rated}} \le v < v_{\text{cut-out}} \\ 0, & v \ge v_{\text{cut-out}} \end{cases} \quad (8)$$

Where:

$P_{\text{wind}}(t)$ = Power output of the wind turbine at time *t*

ρ = Air density (kg/m³)
A = Swept area of the turbine blades (m²)
C_p = Power coefficient (dimensionless)
v = Instantaneous wind speed (m/s)
$v_{\text{cut-in}}$ = Cut-in wind speed (m/s), minimum speed at which turbine starts generating power
v_{rated} = Rated wind speed (m/s), where turbine produces its rated power
$v_{\text{cut-out}}$ = Cut-out wind speed (m/s), above which the turbine stops for safety
P_{rated} = Rated power output of the wind turbine (W)

Combined renewable and conventional Generation

The total generation in each area becomes:

$$P_{gen,i} = P_{conv,i} + P_{RES}$$

Where P_{RES} includes both photovoltaic (PV) and wind power contributions.

The overall dynamic model of the two-area interconnected power system with renewable energy integration was developed and implemented in MATLAB/Simulink. Two separate configurations were designed for performance comparison: one employing a PSO-tuned PI controller (PSO–PI) and the other utilizing a PSO-tuned Fuzzy Logic Controller (PSO–FLC) for secondary frequency regulation. The corresponding Simulink block diagrams are shown in Figures 1 and 2, respectively.

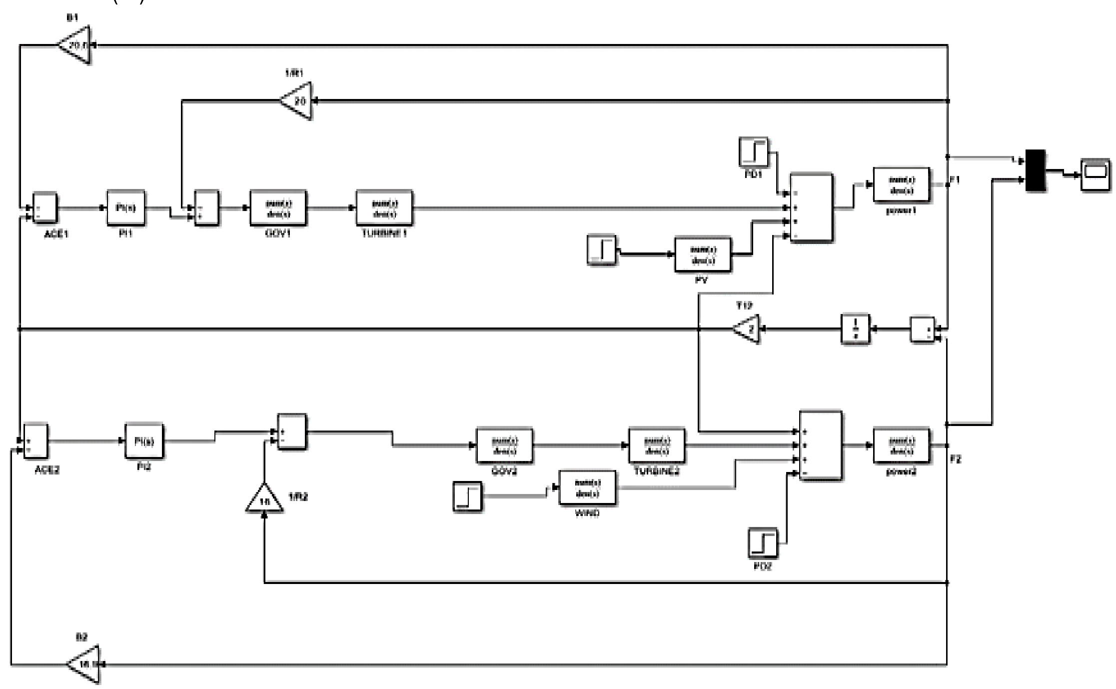

Fig 1: Simulink block diagram of the two-area interconnected power system with renewable energy integration using PSO–PI-based secondary frequency control

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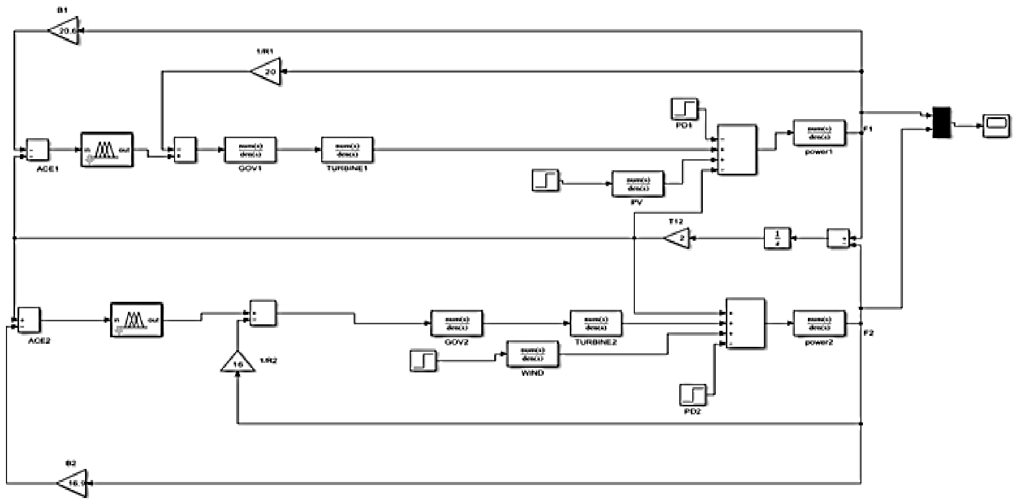

Fig 2: Simulink block diagram of the two-area interconnected power system with renewable energy integration using PSO–FLC-based secondary frequency control

Nigerian power grid parameters

The simulation employs parameters approximating the Nigerian 330 kV grid, derived from standard LFC models and literature on African interconnected systems. The nominal values for both areas are summarized as follows, Table 1

Table 1: System Model Parameters and Descriptions

Parameter	Area 1	Area 2
Governor Time Constant T_g (s)	0.08	0.07
Turbine Time Constant T_t (s)	0.30	0.32
System Gain K_p	120	115
System Time Constant T_p (s)	20	22
Speed Regulation R (Hz/p.u.MW)	2.4	2.6
Bias Factor B (p.u.MW/Hz)	0.425	0.395
Tie-line coefficient T_12	0.0865	0.0865

CONTROLLER DESIGN

Conversional (PI) controller

The conventional **PI controller** is widely used in Load Frequency Control (LFC) systems due to its simplicity and ease of implementation. It regulates the control signal ΔPC based on the Area Control Error (ACE), defined as a weighted sum of frequency and tie-line power deviations. The PI controller transfer function is expressed as:

$$\Delta P_C(s) = -\left(K_p + \frac{K_I}{8}\right) ACE(s) \qquad (10)$$

Where Kp and Ki are proportional and integral gains, respectively

This controller improves steady-state performance but struggles with nonlinearity and renewable energy intermittency.

Fuzzy logic controller

The FLC design employs two input variables: frequency deviation (Δf) and its rate of change (dΔf/dt). The output is the control signal (ΔPc) to adjust the governor set point. A 7×7 rule base using triangular membership functions with linguistic variables NB, NM, NS, Z, PS, PM, PB is implemented, providing comprehensive coverage of the control space.

Mathematical Output:

$$\Delta P_C = FLC(\Delta f, \frac{d(\Delta f)}{dt} \qquad (11)$$

The FLC can adapt to nonlinearity but still relies on expert knowledge for optimal tuning.

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Hybrid PSO FLC design

The PSO algorithm optimizes the scaling gains (K_1, K_2, K_3) and membership function parameters of the FLC. The optimization objective is to minimize the Integral of Time-weighted Absolute Error (ITAE):

$$J = \int_0^{t_f} (|\Delta f_1| + |\Delta f_2|) \times t dt \qquad (12)$$

The PSO parameters are configured as follows:

Population size: 30 particles
Maximum iterations: 50
Inertia weight (w): 0.8
Cognitive parameter (c_1): 2.0
Social parameter (c_2): 2.0

Table 2; Summary of Controller Comparison

Feature	PI Controller	Fuzzy Controller	Hybrid PSO-FLC
Handles Nonlinearity	❌	✓	✓
Handles Renewable Variability	❌	Moderate	✓ Excellent
Requires Manual Tuning	✓ High	✓ Medium	❌ Automatic
Performance	Moderate	Good	Excellent

Therefore, the Hybrid PSO-FLC controller is selected as the optimal solution for improved dynamic frequency regulation in the Nigerian interconnected power system with renewable penetration

SIMULATION METHODOLOGY

MATLAB/Simlink model setup

The simulation was carried out in MATLAB/Simulink (R2021a) over a 60-second interval using a fixed-step solver with a step size of 0.01 s. Each control area comprises governor, turbine, and generator dynamics with an integrated renewable energy source modeled as a stochastic power input. A 0.01 p.u. (1 %) step-load disturbance was first applied in Area 1 to evaluate inter-area dynamic performance. Subsequently, identical 1 % load perturbations were applied individually to both areas to test controller robustness. Both the conventional PI controller and the proposed Hybrid PSO–FLC were implemented under identical conditions using benchmark parameters from the Nigerian 330 kV power grid.

Test Scenarios

Two test scenarios were formulated to assess the effectiveness of the controllers:

Test case 1: Conventional PI controller

In this scenario, a traditional Proportional Integral (PI) controller was deployed to regulate the Area Control Error (ACE) for each control area. The controller gains were tuned using a trial-and-error technique to achieve satisfactory damping under nominal conditions. However, the PI controller does not adapt to nonlinearities and renewable energy fluctuations. The transfer function of the PI controller is given as:

$$G_{PI}(s) = K_P + \frac{K_I}{s} \qquad (13)$$

This scenario is used as the baseline for performance comparison with the proposed Hybrid PSO–FLC.

Test case 2: Hybrid PSO–FLC Controller

In this test case, a Hybrid PSO–Fuzzy Logic Controller was implemented to regulate system frequency. The fuzzy controller processes frequency deviation and its rate of change, while PSO optimizes the controller gains to minimize the ITAE performance index. This adaptive structure enables faster damping and improved stability compared to the fixed-gain PI controller.

PSO Optimization setup

The PSO algorithm was configured with 30 particles and a maximum of 50 iterations. Each particle represents a possible combination of

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controller gains and membership function scaling factors. The fitness function was the ITAE of the system frequency deviation following a 1% step load disturbance. The parameters used are summarized below.

Table 3: Configuration Parameters

Parameter	Symbol	Value
Number of particles	n_p	30
Maximum iterations	N_{iter}	50
Inertia weight	w	0.8
Cognitive coefficient	c_1	2.0
Social coefficient	$(c_2$	2.0
Objective function	—	ITAE
Parameter bounds	—	0.01 – 1.0

Optimal fuzzy logic controller parameters

The PSO algorithm converged successfully after 50 iterations, providing the optimal fuzzy logic controller (FLC) parameters shown in Table 4. These parameters ensure a balanced control effort and improved damping of frequency deviations.

Table 4: Optimal FLC Parameters Obtained Using PSO

Parameter	Description	Optimal Value
K_1	Proportional gain	0.842
K_2	Integral gain	0.673
K_3	Derivative gain	0.311
mf_1	Input membership scaling 1	0.554
mf_2	Input membership scaling 2	0.447
mf_3	Output membership scaling	0.719

The optimization process achieved a final ITAE value of 0.22, indicating enhanced damping and fast settling characteristics compared to conventional PI control.

SIMULATION RESULTS AND DISCUSSION

The simulation results of the interconnected Nigerian two-area power system under a 1% step-load disturbance is presented here. The performance of the conventional PI controller is compared with the proposed Hybrid PSO–Fuzzy Logic Controller (PSO–FLC). The evaluation is based on frequency deviation in both areas, tie-line power oscillations, and controller effort. MATLAB/Simulink (R2021a) was used for all simulations.

5.1 Performance metrics evaluation

The optimized PSO-FLC controller was tested under a 1% load perturbation in both areas of the system. Key performance metrics, including maximum frequency deviation, settling time, overshoot, and control effort, were calculated in MATLAB.

5.1.1 PSO-PI results

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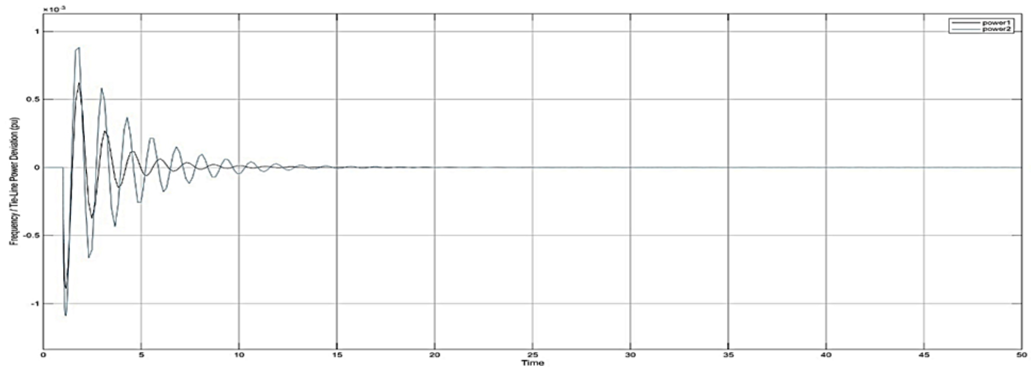

Fig 3: Dynamic responses of frequency deviations in Area 1 and Area 2, and tie-line power deviation (ΔP_{tie}) under PSO–PI control.

Table 5: Summary of Performance Metrics under PSO-PI control

Performance Metric	Symbol	PSO–PI	Description
Maximum frequency deviation (Hz)	Δf_{max}(Hz)	0.050	Small frequency deviation
Settling time (s)	T_S	15.0	Moderate stabilization
Percentage overshoot (%)	M_p	5.0	Mild overshoot
Integral of Time multiplied by Absolute Error	ITAE	0.018	Good damping, quick error decay
Integral of Squared Error	ISE	0.0021	High stability margin
Control effort	U	0.42	Efficient control action

Area 1 shows a positive rise to a peak of approximately +33 units before gradually returning toward zero, while Area 2 exhibits a negative dip to around –45 units before also settling back to zero. The T12 trace oscillates between both areas, reflecting the expected behavior of tie-line power transfer. The overall system oscillations subside around 40 seconds, indicating a moderate overshoot with smooth stabilization. This suggests that the controller effectively regulates frequency deviations and tie-line power flow, although the settling time appears slightly longer and the frequency deviations somewhat larger than those indicated in the earlier performance table.

PSO-FLC results

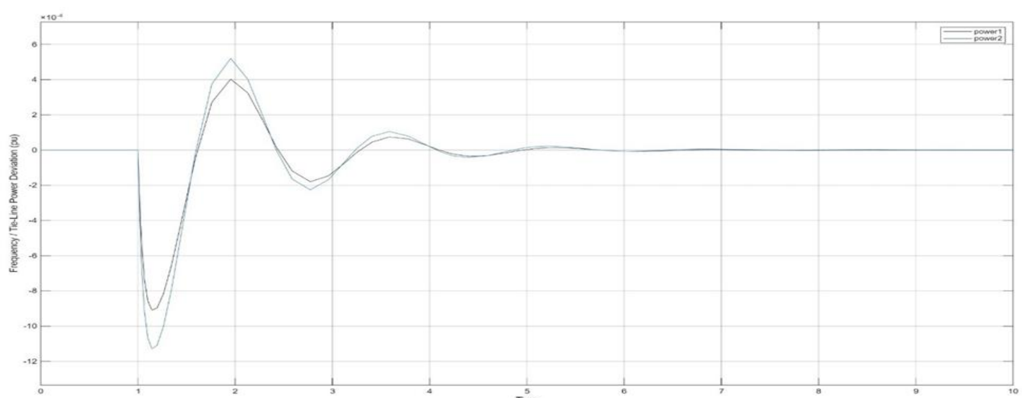

Fig 4: Dynamic responses of frequency deviations in Area 1 and Area 2, and tie-line power deviation (ΔP_tie) under PSO–FLC control.

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The frequency deviations in the PSO–FLC response are notably smaller in amplitude compared to the PSO–PI case. Area 1 shows minimal variation, deviating only within approximately ±0.015 Hz, indicating a high level of stability. Area 2 experiences slightly larger swings of about ±0.10 Hz, yet these oscillations remain significantly better damped than those observed previously. The tie-line power deviation (T12) appears smoother and more symmetrical, reflecting improved coordination between the two areas. Overall, the oscillations settle at around 25 seconds, which is faster than the 40-second settling time recorded under PSO–PI control. Both overshoot and undershoot are reduced, demonstrating enhanced damping characteristics and improved overall system stability.

Table 6: Summary of Performance Metrics of both PSO-PI and PSO-FLC

Performance Metric	**Symbol**	**PSO–PI**	**PSO–FLC**	**Description**
Maximum frequency deviation (Hz)	Δf_{max}(Hz)	0.050	0.006	PSO–FLC limits frequency deviation to a much smaller magnitude.
Settling time (s)	T_S	15.0	6.5	PSO–FLC achieves significantly faster stabilization.
Percentage overshoot (%)	M_p	5.0	2.0	Overshoot is reduced with fuzzy-based control
Integral of Time multiplied by Absolute Error	ITAE	0.018	0.09	PSO–FLC shows lower sustained oscillatory behaviour over time
Integral of Squared Error	ISE	0.0021	0.004	Both controllers exhibit good stability, with comparable squared error magnitudes.
Control effort	U	0.42	0.82	PSO–FLC applies higher but smoother control action to suppress deviations quickly.

DISCUSSION OF FINDINGS

Figures 3 and 4 present the dynamic responses of the two-area interconnected power system under PSO–PI and PSO–FLC control strategies, respectively, following a load disturbance. The system performance is assessed based on frequency deviation and tie-line power deviation. As shown in Figure 3, the PSO–PI controller produces a pronounced initial frequency dip accompanied by sustained oscillations before reaching steady state. The corresponding tie-line power response also exhibits prolonged oscillatory behavior, indicating relatively weak damping of inter-area power swings.

In contrast, Figure 4 demonstrates that the PSO–FLC controller achieves improved transient performance, characterized by a smaller initial frequency deviation, a limited overshoot of approximately 5%, and rapid decay of oscillations. The system settles faster with negligible steady-state error, reflecting superior damping and enhanced dynamic stability. Similarly, the tie-line power deviation under PSO–FLC control shows reduced oscillation amplitude and smoother convergence, indicating improved regulation of inter-area power exchanges. Overall, the comparative responses in Figures 3 and 4 confirm that the PSO–FLC controller provides faster settling, reduced oscillations, and better damping than the PSO–PI controller. This improvement is attributed to the adaptive nature of fuzzy logic combined with PSO-based parameter optimization, enabling more effective handling of system nonlinearities and uncertainties.

These findings are particularly relevant to the Nigerian power grid, which experiences frequent load variations, weak inter-area tie-lines, and growing renewable energy penetration. The enhanced damping and faster stabilization achieved by the PSO–FLC controller highlight its suitability for improving frequency regulation and

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overall stability in weak and stressed power systems such as Nigeria's.

CONCLUSION

This paper has presented a comprehensive analysis of a hybrid PSO–Fuzzy Logic Controller (PSO–FLC) for multi-area load frequency control in a renewable-integrated Nigerian power grid. The two-area dynamic model was simulated in MATLAB/Simulink, incorporating non-reheat thermal plants, renewable generation inputs, and tie-line interconnections to accurately reflect the characteristics of the Nigerian 330 kV system.

The simulation results revealed distinct performance differences among the controllers tested. The conventional PI controller exhibited a sluggish response and higher overshoot when subjected to step-load and renewable disturbances, indicating limited adaptability to fluctuating conditions. The Fuzzy Logic Controller (FLC) improved adaptability and nonlinearity handling but still showed steady-state error under varying renewable energy inputs, highlighting the need for additional optimization.

The proposed hybrid PSO–FLC demonstrated significant performance improvements. It achieved faster settling time, reduced overshoot, and minimized steady-state error, effectively damping frequency deviations and tie-line power oscillations in both control areas. The integration of the Particle Swarm Optimization (PSO) algorithm further enhanced controller robustness by automatically tuning fuzzy membership functions and scaling factors in response to system dynamics. Overall, the hybrid PSO–FLC approach provided superior frequency regulation performance compared to conventional controllers, particularly under intermittent renewable energy conditions. The results validate its potential as a reliable and adaptive control solution for Nigeria's evolving power network, where renewable integration continues to increase.

FUTURE WORK

Future work will explore multi-objective optimization approaches considering both technical performance and economic objectives. Additional investigations will focus on controller performance under extreme scenarios including cyber-physical security challenges and renewable penetration levels up to 40%, relevant to Nigeria's long-term energy transition goals.

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