IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

Snake-Optimized Fuzzy Control for Three-Area Power Systems with EV Integration

Jagan Surwanshi[1] and Prashant Garg[2]
Research Scholar, Department of Electrical Engineering, Vikrant University Gwalior[1]
Asst. Prof., Department of Electrical Engineering, Vikrant University, Gwalior[2]

Abstract: *The growing penetration of renewable energy sources and electric vehicles (EVs) into modern power systems has introduced significant challenges for Automatic Generation Control (AGC), including nonlinearities, communication delays, and load uncertainties that conventional Proportional-Integral-Derivative (PID) controllers struggle to handle. This paper proposes a hybrid Fuzzy Fractional-Order Proportional-Integral (Fuzzy FOPI) and Tilt-Integral-Derivative (TID) controller for load frequency control (LFC) in a three-area interconnected power system comprising thermal, hydro, gas turbine, wind, solar photovoltaic, and EV resources. Controller parameters are optimally tuned using the Snake Optimization (SO) metaheuristic algorithm, with the Integral Squared Error (ISE) of frequency and tie-line power deviations adopted as the fitness function. A comprehensive mathematical model of the multi-source system is developed, and the proposed SO-tuned Fuzzy FOPI+TID controller is benchmarked against classical PID and Differential-Evolution (DE)-tuned Fuzzy FOPI+TID controllers under step load disturbances, random load variations, variable renewable penetration levels, and tie-line power exchange scenarios. Simulation results demonstrate that the proposed controller achieves the lowest ISE value (1.19×10^{-4}), substantially outperforming the SO-tuned PID (358.5×10^{-3}) and DE-tuned Fuzzy FOPI+TID (7.9×10^{-2}) controllers, while also reducing settling time, overshoot, and undershoot across all three areas. The findings confirm that intelligent, optimization-driven, fractional-order control provides superior robustness and resilience for frequency regulation in EV-integrated, renewable-rich, multi-source power systems.*

Keywords: Automatic Generation Control; Load Frequency Control; Fuzzy Logic; Fractional-Order PI; Tilt-Integral-Derivative Controller; Snake Optimization; Electric Vehicles; Renewable Energy Integration.

I. INTRODUCTION

Reliable and good-quality electrical supply at reasonable cost remains a central objective of power system planning. As power networks have grown from isolated stations into vast interconnected pools, the coordinated operation of generating units across control areas has become essential for both technical and economic reasons. Interconnection brings well-known advantages, including reduced reserve requirements, economical sharing of generation capacity, and improved system security, but it also demands a technically compatible transmission and control infrastructure to remain stable and reliable.

Within this operating environment, Automatic Generation Control (AGC) is the mechanism that continuously balances generation and load at minimum cost while regulating system frequency and tie-line power interchange. AGC processes the Area Control Error (ACE) — a weighted combination of frequency deviation and tie-line power deviation — and issues raise/lower signals to participating generating units roughly every one to two seconds. While primary (governor) control corrects small, fast deviations locally, AGC provides the supplementary secondary control needed to restore nominal frequency following larger disturbances, and emergency schemes such as under-frequency load shedding act as a last resort during severe imbalances.

The increasing integration of renewable energy sources — wind, solar photovoltaic (PV), and wave energy — together with the rapid growth of electric vehicles (EVs), has fundamentally altered the dynamics that AGC must manage. Renewable sources introduce stochastic variability that conventional AGC, designed around predictable thermal and hydro generation, was never intended to absorb. EVs add a further layer of complexity: acting simultaneously as controllable loads and, through vehicle-to-grid (V2G) technology, as distributed storage resources capable of injecting power back into the grid. Classical PI/PID controllers, while simple and easy to implement, are known to struggle with the nonlinearities, time delays, and parameter uncertainties that characterize such hybrid, multi-source, EV-integrated grids.

II. SYSTEM MODELING

Multi-Source Three-Area Interconnected System: The study system consists of three interconnected control areas coupled through AC tie-lines, each contributing a distinct mix of generation, storage, and load. Area 1 combines a non-reheat thermal power plant with wind generation, EVs, and local load. Area 2 comprises hydropower, solar PV, EVs, wave-energy disturbance, and load. Area 3 integrates hydropower, gas turbine generation, EVs, and load, with the gas turbine providing fast-response capability to compensate rapid load or generation changes. Wind and solar sources are assumed to contribute approximately 20% and 25% of installed capacity respectively, with thermal and hydro plants supplying the remaining 30% and 25%; EV battery capacity in each area is set equal to the renewable capacity connected there, providing flexibility to counter intermittency.

The AC tie-lines enable power sharing and improve overall reliability, but they also create strong dynamic coupling: a disturbance in one area — a load step, a renewable fluctuation, or EV charging/discharging activity — propagates through the tie-lines and can destabilize frequency in the adjacent areas if not properly controlled. System dynamics are expressed through frequency-deviation equations that incorporate area inertia, damping, mechanical power contributions from each source, and tie-line power exchange; the Area Control Error, defined as the weighted sum of local frequency deviation and tie-line power deviation, is the feedback signal driving the controller in each area.

Component Transfer-Function Models: Each generation source is represented by a linearized transfer-function model suited to load-frequency studies. The non-reheat thermal plant is modeled through cascaded governor and turbine transfer functions relating steam-valve position to mechanical power output. The hydropower plant model captures governor gate-opening dynamics, the reset time and transient droop of the governing system, and the non-minimum-phase behavior introduced by water starting time in the penstock. The gas turbine model comprises a valve positioner, a lead-lag-compensated speed governor, a fuel-system and combustor stage, and a single-time-constant compressor-discharge-volume element. Wind and solar PV subsystems are each represented by a first-order linear transfer function relating, respectively, wind-speed variation and solar-irradiance variation to output power. Representative parameter groups for each subsystem are summarized in Table 1.

Subsystem	Representative Parameters
Non-reheat thermal plant	Governor & turbine time constants, speed regulation
Hydraulic plant	Governor time constant, reset time, transient droop, water starting time
Gas turbine plant	Valve positioner, lead-lag governor, fuel & combustion, compressor time constants
Wind turbine	Linear gain and time constant relating wind speed to output power
Solar PV	Linear gain and time constant relating irradiance to output power
Electric vehicle bank	Battery capacity matched to area renewable capacity; V2G gain/time constant
Area & tie-line	Area inertia, damping coefficient, tie-line synchronizing coefficient, frequency-bias factor, speed droop

PID Baseline and Controller Structure: As a baseline, a classical PID controller acting on the Area Control Error of each area is formulated, with proportional, integral, and derivative terms providing immediate, cumulative, and rate-based correction respectively. Coordinated PID action across the three areas balances local ACE while preserving secure tie-line exchange, but — as shown in the results — proper gain tuning is critical, since poorly tuned gains readily produce instability or sluggish response in a system this tightly coupled and this rich in renewable and EV-driven variability.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

III. PROPOSED CONTROLLER AND OPTIMIZATION METHODOLOGY

Hybrid Fuzzy FOPI + TID Controller:

To overcome the limitations of fixed-gain PID control, this paper proposes a hybrid structure in which the ACE signal is processed in parallel by a Fuzzy-Logic Controller (FLC), a Fractional-Order PI (FOPI) stage, and a Tilt-Integral-Derivative (TID) stage, with their outputs combined to generate the final control action for each area. The FLC handles nonlinearities and uncertainty by mapping ACE and its derivative (dACE) onto six triangular linguistic sets — negative big, negative medium, negative small, zero, positive small, and positive big — through a Mamdani-type inference engine, using bisector defuzzification to obtain crisp proportional and integral gains (Kp, Ki) for the FOPI stage. The compact rule base governing this mapping is shown in Table 2, where output linguistic levels range from small (S) through very-very-big (VVB).

ACE \ dACE	NB	NM	NS	Z	PS	PB
NB	S	S	S	M	M	B
NM	S	S	M	M	B	VB
NS	S	M	M	B	VB	VB
Z	M	M	B	VB	VB	VB
PS	M	B	VB	VB	VVB	VVB
PB	B	VB	VB	VVB	VVB	VVB

The FOPI controller extends the classical PI structure with a fractional-order integral term, giving it additional tuning freedom and improved disturbance rejection relative to an integer-order PI. The TID controller replaces the proportional term of a standard PID with a tilted (fractional-power) element, characterized by a tilt gain, an integral gain, a derivative gain, and a fractional order, which together reduce sensitivity to parameter variation and simplify tuning while improving transient response. Combining TID's robustness and ease of tuning with the Fuzzy FOPI stage's adaptive, intelligent gain-scheduling allows the hybrid controller to respond effectively across the wide range of operating conditions introduced by renewable variability and EV charging/discharging behavior.

Snake Optimization for Controller Tuning

The gains of the Fuzzy FOPI+TID controller — and, where applicable, the input/output scaling of the fuzzy stage — are tuned using the Snake Optimization (SO) algorithm, a population-based metaheuristic. SO initializes a uniformly distributed random population within the problem's lower and upper bounds and splits it equally into male and female sub-populations. Best-performing male and female individuals are identified in each generation, a notional 'food' position is established, and temperature and food-quantity parameters are updated as functions of the current and maximum iteration counts, governing the balance between exploration and exploitation as the search progresses. The optimization objective is the Integral Squared Error (ISE) of the frequency deviations in each area and the tie-line power deviations, integrated over the simulation horizon; minimizing this fitness function drives the controller toward gains that suppress oscillations and minimize steady-state error. In this study, SO is run with a population size of 30 over 100 iterations, with the maximum-iteration count serving as the stopping criterion, and its performance is compared against Differential Evolution (DE) tuning of the same controller structure and against SO-tuned classical PID.

IV. RESULTS AND DISCUSSION

The proposed SO-tuned Fuzzy FOPI+TID controller was compared with SO-tuned PID and DE-tuned Fuzzy FOPI+TID controllers under four conditions: stability analysis, 10% step load perturbation (SLP), random load variation, and different renewable-penetration levels with tie-line power exchange.

Stability Analysis: The fractional-order closed-loop stability was evaluated using MATLAB’s FOMCON toolbox on the Riemann surface. The characteristic roots of the three-area system remained in the stable region, confirming closed-loop stability and supporting the time-domain results.

DOI: 10.48175/IJARSCT-38152

ISSN 2581-9429 IJARSCT

Error-Index Comparison: For a simultaneous 10% SLP in all three areas, the proposed controller achieved an ISE of 1.19×10^{-4}, compared with 358.5×10^{-3} for SO-tuned PID and 7.9×10^{-2} for DE-tuned Fuzzy FOPI+TID. Thus, the proposed scheme provides substantially better error minimization, demonstrating the combined benefit of fuzzy-fractional control and SO-based tuning.

Controller	Best ISE value (10% SLP)
SO-tuned Fuzzy FOPI + TID (proposed)	1.19×10^{-4}
SO-tuned PID	358.5×10^{-3}
DE-tuned Fuzzy FOPI + TID	7.9×10^{-2}

Response to Step Load Disturbance: Under the 10% SLP, the proposed controller produced the lowest maximum overshoot and undershoot and the shortest settling time. It restored frequency and tie-line power more rapidly than both benchmark controllers, while the DE-tuned scheme showed comparatively weaker performance.

Response to Random Load Variation: For random load changes between 0 and 0.2 p.u. at 20-s intervals, all areas experienced frequency fluctuations, with Area 2 showing the strongest oscillations due to its multiple renewable sources. The proposed controller effectively reduced oscillation amplitude, improved damping, and accelerated recovery compared with PID and DE-based control.

Effect of Renewable Penetration: At renewable penetration levels of 20%, 50%, and 80%, increasing renewable share resulted in larger oscillations and slower damping. Area 2 experienced the most pronounced variations, while Area 3 showed deeper deviations at high penetration. The optimized Fuzzy FOPI+TID controller significantly improved damping and recovery, particularly at 80% renewable penetration.

Influence of Tie-Line Power Exchange: Unoptimized control allowed disturbances to propagate between areas, increasing frequency deviations and ACE. The proposed SO-tuned Fuzzy FOPI+TID controller effectively damped these disturbances, reduced ACE, accelerated convergence, and maintained more balanced tie-line power exchange, thereby improving overall inter-area coordination.

V. CONCLUSION AND FUTURE SCOPE

This paper presented a comprehensive AGC framework for a three-area, multi-source interconnected power system integrating thermal, hydro, gas turbine, wind, solar PV, and electric-vehicle resources. A hybrid Fuzzy FOPI+TID controller, tuned using the Snake Optimization algorithm, was proposed and evaluated against classical PID and DE-tuned alternatives. Simulation results across step load disturbances, random load variation, variable renewable penetration, and tie-line exchange scenarios consistently show that the proposed controller achieves the lowest ISE, the fastest settling time, and the smallest overshoot/undershoot among the tested schemes, while EV integration with V2G support further improved system resilience and reduced frequency deviations. Incorporating practical constraints such as the Generation Rate Constraint and Governor Dead Band gave the model a more realistic representation of real power-system behavior, reinforcing the practical relevance of the reported findings.

Future work can extend this study by scaling the framework to larger multi-area grids with higher renewable diversity and cyber-physical constraints, validating performance through real-time hardware-in-the-loop testing, exploring AI-driven predictive models for adaptive online tuning under uncertainty, incorporating stochastic large-scale EV fleet charging/discharging behavior, and developing cybersecurity-aware frequency-control architectures capable of withstanding communication delays and malicious cyber threats in smart grid environments.

REFERENCES

[1] Ibraheem, P. Kumar, and D. P. Kothari, "Recent philosophies of automatic generation control strategies in power systems," IEEE Trans. Power Syst., vol. 20, no. 1, pp. 346–357, 2005.
[2] P. Kundur, Power System Stability and Control. New York, USA: McGraw-Hill, 1994.
[3] H. Bevrani and T. Hiyama, Intelligent Automatic Generation Control. UK: CRC Press (Taylor & Francis), 2011.

[4] A. Fathy and A. M. Kassem, "Antlion optimizer–ANFIS load frequency control for multi-interconnected plants comprising photovoltaic and wind turbine," ISA Trans., vol. 87, pp. 282–296, 2019.

[5] D. K. Gupta, G. Dei, A. K. Soni, A. V. Jha, A. Bhargav, N. Bizon, A. Srinivasulu, and N. Philibert, "Fractional order PID controller for load frequency control in a deregulated hybrid power system using Aquila Optimization," Results Eng., vol. 23, p. 102442, 2024.

[6] P. J. Krishna, V. P. Meena, and N. Patnana, "Grey wolf optimizer-assisted R-method-based weighted minimization for automatic generation control in two-area interconnected power system," Int. J. Dyn. Control, vol. 11, pp. 1779–1796, 2023.

[7] D. Kumar, G. L. Raja, M. Alkhatib, A. K. Deep, and U. R. Muduli, "Smith predictor based fractional LFC strategy for storage supported thermal power system amid communication dead time and cyber threats," IEEE Trans. Ind. Appl., vol. 61, no. 3, pp. 4515–4529, 2025.

[8] B. Mohanty, S. Panda, and P. K. Hota, "Controller parameters tuning of differential evolution algorithm and its application to load frequency control of multi-source power system," Electr. Power Energy Syst., vol. 54, pp. 77–85, 2014.

[9] A. A. Mahmoud, K. Sayed, A. Daraz, Y. Arya, and M. Khamies, "PO-optimized cascaded FOIAN-PTD strategy for frequency control of wind-PV-thermal power system with energy storage systems," Eng. Sci. Technol., Int. J., vol. 70, p. 102173, 2025.

[10] A. Panwar, G. Sharma, and R. C. Bansal, "Optimal AGC design for a hybrid power system using hybrid bacteria foraging optimization algorithm," Electr. Power Compon. Syst., vol. 47, no. 11–12, pp. 955–965, 2019.

[11] B. K. Sahu, S. Pati, P. K. Mohanty, and S. Panda, "Teaching-learning-based optimization algorithm based fuzzy-PID controller for automatic generation control of multi-area power system," ISA Trans., vol. 27, pp. 240–249, 2015.

[12] H. Shayeghi, A. Rahnama, and H. H. Alhelou, "Frequency control of fully-renewable interconnected microgrid using fuzzy cascade controller with demand response program consideration," Energy Rep., vol. 7, pp. 6077–6094, 2021.

[13] A. Tepljakov, E. Petlenkov, J. Belikov, and M. Halás, "Design and implementation of fractional-order PID controllers for a fluid tank system," in Proc. Am. Control Conf., Washington, DC, USA, 2013, pp. 1777–1782.

[14] A. H. Yakout, M. A. Attia, and H. Kotb, "Marine predator algorithm based cascaded PIDA load frequency controller for electric power systems with wave energy conversion systems," Alexandria Eng. J., vol. 60, no. 4, pp. 4213–4222, 2021.

[15] S. H. Nagarsheth and S. N. Sharma, "Control of non-minimum phase systems with dead time: a fractional system viewpoint," Int. J. Syst. Sci., vol. 51, no. 11, pp. 1905–1928, 2020.