

A MOTH FLAME-PATTERN SEARCH OPTIMIZED FUZZY PIDN CONTROLLER FOR LOAD FREQUENCY CONTROL OF A TWO-AREA DEREGULATED POWER SYSTEM

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ABSTRACT

Deregulated power systems face the difficulty of load frequency control due to different transaction situations and system uncertainties. This paper assesses a Fuzzy PIDN controller that is being tuned via a Moth Flame-Pattern Search (MFO-PS) algorithm to a two-area thermal-gas system under Poolco, bilateral and contract violation conditions. It is hypothesized that the proposed controller has better dynamic performance when compared to GA-PID, DE-PID, TLBO-PID, TLBO-TID, and TLBO-PS:TID. It is done with a MATLAB/Simulink model and the performance is evaluated through settling time, peak deviations, and an integral square error (ISE). Results confirm consistent improvement. In the Poolco case, the proposed controller achieves settling times of 4.07 s (ΔF_1), 1.83 s (ΔF_2), 1.32 s ($\Delta PTie$) with ISE = 0.0135, outperforming TLBO-PS:TID (ISE = 0.0270). In the bilateral scenario, ISE reduces to 0.0075 compared to 0.0872, and under contract violation to 0.00251 compared to 0.1445. Sensitivity analysis shows stable performance with ISE varying from 0.0125 to 0.0135 under $\pm 25\%$ parameter changes. These findings indicate that the suggested approach can significantly improve damping and minimize frequency deviation compared to the existing best controller, which makes it highly applicable to operation of a deregulated power system.



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I. INTRODUCTION

Load Frequency Control (LFC) is a basic requirement of maintaining a balance between power generation and demand of interconnected power system. It makes sure that the deviations of the frequency and tie-line power across the system are within allowable parameter and therefore maintain the stability and reliability of the system [1], [2]. Multi-area power systems are such that imbalance in a single area will have an impact on the rest of the network and coordinated control is a necessity here [3], [4]. LFC strategies traditionally were created to work with vertically integrated utilities that have centralized control structures in which the operation of the system is relatively predictable [5], [6]. The operation of the system has been transformed with the redesigning of power systems to deregulated markets. Under deregulated conditions, several generation companies (GENCOs) and distribution companies (DISCOs) are involved in competitive electricity markets which results in complex power exchange dualism [7], [8]. These interactions are normally classified into Poolco-based, bilateral and contract violation transactions, with each having a different dynamic property [9], [10]. The systems based on poolco are based on centralized dispatch, bilateral contracts offer an opportunity to make direct agreements between participants [11], [12]. The violations of the contract also contribute to the complexity of the dynamics of systems that create discrepancies between planned and real power exchange, leading to more oscillations and variation of the frequencies [13], [14]. These threats make strict demands on LFC controllers so that their performance would be consistent in various operating conditions [15], [16]. Many methods of control have been suggested in order to deal with LFC challenges. Traditional Proportional Integral Derivative (PID) controllers are still known to be use popular because of their simple design and implementation [17], [18].

Have also been introduced variants e.g. Tilt Integral Derivative (TID) controllers to improve performance characteristics [19], [20]. Nevertheless, these controllers do not always perform optimally when subjected to nonlinearities of the system, parameter uncertainties, and when subjected to load variations [21], [22]. Consequently, tuning techniques using optimization have become very common in order to enhance controller performance. Genetic Algorithm (GA) and Differential Evolution (DE) examples of evolutionary and metaheuristic optimization methods have been used effectively in optimizing PID parameters related to LFC problems [23], [24]. The methods provide enhanced search features and convergence as opposed to the classical tuning techniques. Recently with much more focus, Teaching Learning Based Optimization (TLBO) has been popular because of the parameter-free form and its convergence properties [25], [26]. The use of TLBO-based PID controllers and TID controllers in interconnected systems has been reported to improve the performance of systems [27], [28]. Also hybrid methods, like TLBO-PS:TID, use a Pattern Search to optimize solutions and increase the local search power [29], [30]. In spite of these improvements, the current controllers continue to show weaknesses in recording low levels of integral square error (ISE) and rapid settling times under the various deregulated conditions. Specifically, deterioration of the performance is realized in the case of violation of contracts and change of parameters [31], [32]. Also, most studies concentrate on individual operating conditions but fail to show robustness in Poolco, bilateral and contract violation conditions at the same time [33], [34]. These loopholes demonstrate the necessity of more adaptive and robust control approach that could properly address nonlinearities and uncertainties of the system.

Controllers that use fuzzy logic have been extensively discussed as a way of solving these problems. The fuzzy controllers utilize linguistic rules and membership functions which give adaptive control action which enhances the system response when conditions change [35]. Nevertheless, the use of effective optimization methods is required to ensure the success of fuzzy controllers as the success of such systems highly relies on the proper tuning of their parameters. This paper presents a proposal of a Fuzzy PIDN controller that is tuned with a hybrid Moth Flame Optimization and Pattern Search (MFO) algorithm. The MFO algorithm has excellent global exploration power whereas Pattern Search offers the local refinement, which results in better convergence and the best parameter selection. The controller aims at operating with a minimum of the square error and enhancing the transient performance in regard to settling time and damping of oscillation. The main contribution of this research is the fact that it demonstrates that the suggested MFO-PS tuned Fuzzy PIDN controller is superior to the existing ones, most of all the most successful TLBO-PS:TID controller, in all deregulated situations. The outcomes demonstrate that the ISE is significantly reduced, the settling time is shortened, and the robustness of the system to parameter variations is enhanced. The above enhancements make the proposed method an efficient and confident way of managing the load frequency of current deregulated power grid.

II. METHODOLOGY

The work is built on a two-area interconnected model of power system and is developed in MATLAB/Simulink R2021a, with both control areas being a combination of both thermal reheat and gas generating units. The dynamic response of any region is indicated by conventional transfer function models, which are the governor, turbine, and power system elements. The two regions are linked together through the tie line and the power exchange between the two regions is controlled through synchronization of coefficients. The system is managed through a deregulated model whereby several generation and distribution companies respond to one another based on the contractual basis. The control signal to control system dynamics is Area Control Error (ACE) which is a combination of frequency deviation and tie-line power deviation. This modeling method is useful in providing the correct inter-area coupling, as well as operating conditions that are realistic in a variety of transaction situations.

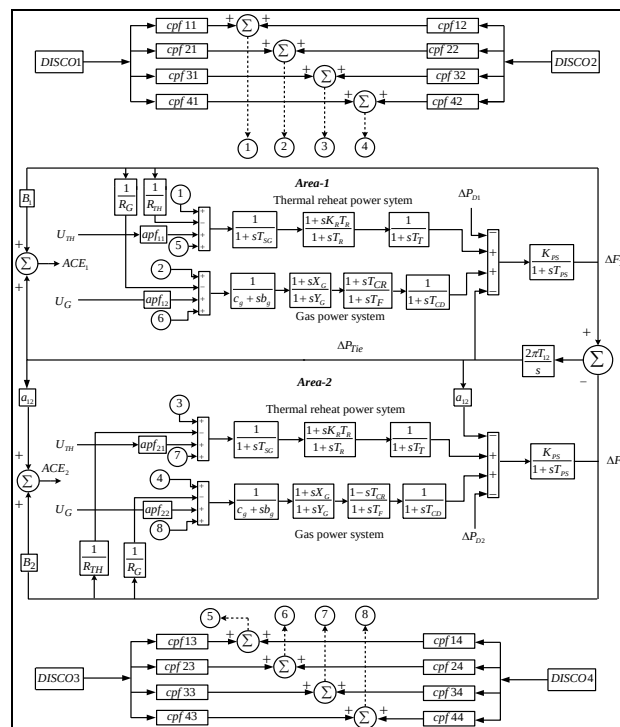


Figure 1: MATLAB/Simulink model of two-area power system under deregulated environment.

Source: Authors, (2026).

The figure illustrates the full dynamic model, which comprises the interdependent generation units, control loops and the tie-line power exchange. It brings out the interrelationship between regions and spread of disturbances throughout the system. The structure is such that both local and global system responses have been captured, which gives an opportunity to assess the effectiveness of the controller in the suppression of oscillations and restoration of nominal conditions during deregulated operation. The control approach relies on the Fuzzy PIDN controller that combines the traditional PIDN control action and the fuzzy inference system to increase flexibility. The PIDN model comprises proportional, integrating, derivative, and filter subsystems and the fuzzy system adjusts control signals according to the amount of error in the system as well as its rate of change. The controller takes Area Control Error (ACE) and its variation as inputs to allow it to react dynamically to both steady-state and transient disturbances. This hybrid design enhances the capacity of the controller to deal with nonlinearities and changing operating conditions that fixed-gain controllers cannot deal with.

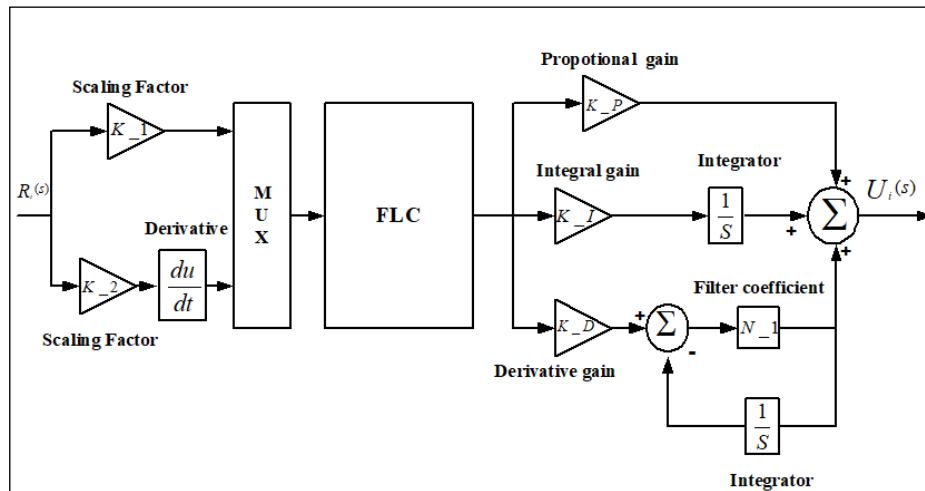


Figure 2: Structure of Fuzzy PIDN controller.
Source: Authors, (2026).

The figure shows the detailed architecture of the controller such as scaling factors, fuzzy inference block, and PIDN components. It demonstrates the interaction of the fuzzy system with proportional, integral and derivative paths to modify the control effort. This arrangement allows gain modulation in an adaptive way, which leads to better damping properties and quicker stabilization of the system. Fuzzy inference system is formed with the help of the known membership functions and rule-based system. The input variable (error) is fuzzy-fied into linguistic values, and actions controlled are made by a series of logic rules. The process of defuzzification is then carried out to give a sharp control signal to the PIDN structure.

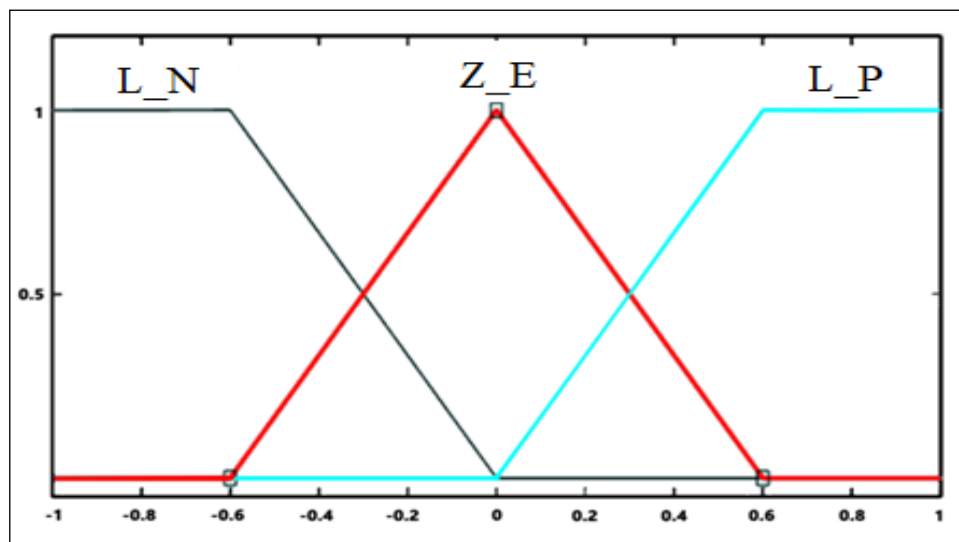


Figure 3: Membership functions for error.
Source: Authors, (2026).

The membership functions of the input variable are given in the figure. These operations determine the mapping of values of numerical errors with the language terms like negative, zero, and positive. The overlap of the membership functions that are symmetrical in nature makes the transition between the control regions smooth which helps to maintain a stable and continuous control action without spikes. The fuzzy rule base determines the correlation between the input conditions and the controller output. It is made to address all the potential operating areas of the system such that the corrective action against various error conditions is taken.

Table 1: Rule based system.

e	$\dot{e}$		
	L_N	Z_E	L_P
L_N	L_N	L_N	Z_E
Z_E	L_N	Z_E	L_P
L_P	Z_E	L_P	L_P

Source: Authors, (2026).

The table illustrates the entire fuzzy regulations applied in the controller. It outlines the way in which input lingo variable combinations are transformed into control outputs. These structured rule base increases the ability of the controller to respond to both small and large disturbances, which improves the transient performance and steadily state error. The hybrid optimization which combines Moth Flame Optimization (MFO) and Pattern Search (PS) is used to controller parameter tuning. Optimization is implemented in the MATLAB system, where starting values of the parameters are updated in a cyclical manner in order to achieve the lowest possible value of the objective function. MFO offers the exploration of the search space globally, avoiding early convergence, and Pattern Search localizes the solution refinement to fine-tuning. The objective function is derived to be the Integral Square Error (ISE) that measures the cumulative error of system variables with time. Minimization of ISE means better overall dynamic performance with minimized oscillations and higher settling.

Table 2: Moth Flame-PS Fuzzy PIDN controller parameter of first test system.

Controller parameters		Poolco Based	Bilateral	Contract Violation
Area-1	K1	1.7970	0.8236	0.5606
	K2	1.2363	0.6750	0.9296
	KP1	9.7684	4.6357	4.9667
	KI1	87996	3.6599	4.8279
	KD1	4.1383	3.9439	3.1540
	N_1	115.7509	3.2460	7.7489
Area-2	K3	0.5757	0.7027	0.9889
	K4	0.8290	0.1536	0.0005
	KP2	7.2968	4.5346	3.6544
	KI2	6.3641	1.7973	4.8995
	KD2	5.2791	4.4088	1.1257
	N_2	59.1086	468.2084	496.7847
ISE		0.0135	0.0342	0.0310

Source: Authors, (2026).

The table shows the optimal parameters of the controller that were achieved in both areas using different operating conditions. The fact that the parameters change under different situations is an indication of the flexibility of the optimization. These optimized parameters have a direct effect on system response, allowing better damping, lower overshoot as well as a faster adaptation to steady-state conditions. The proposed controller is tested in three different scenarios of simulation that include Poolco-based, bilateral, and contract violation. These cases constitute the variants of the functioning of deregulated power systems, each of which poses its own dynamical problem. The Poolco-based situation mirrors centralized conditions of dispatch, bilateral dealings create direct contractual dealings, and breach of contracts reflects a lack of correspondence between planned and actual power dealings. Testing the controller in all the three conditions will be a thorough test of the robustness, flexibility, and viability of the controller to keep the system stable in varying operating environments.

III. RESULTS AND ANALYSIS

Dynamic performance of the proposed MFO-PS tuned Fuzzy PIDN controller is tested in three deregulated operating conditions namely Poolco-based, bilateral and contract violation. The analysis focuses on frequency deviations (ΔF_1 , ΔF_2) and tie-line power deviation (ΔP_{tie}), which directly reflect system stability and control effectiveness Besides the usual performance measures like settling time, overshoot, undershoot and ISE, the response properties are examined as oscillation damping, trajectory smoothness and convergence speed. This numerical and graphical analysis will give a complete picture on controller behavior under various operating conditions. In the Poolco-based case, the system is running on a centralized dispatch, in which a coordinated control is necessary to ensure the system balance. This situation is used as a reference due to the structured power exchange conditions at which the performance of controllers will be evaluated.

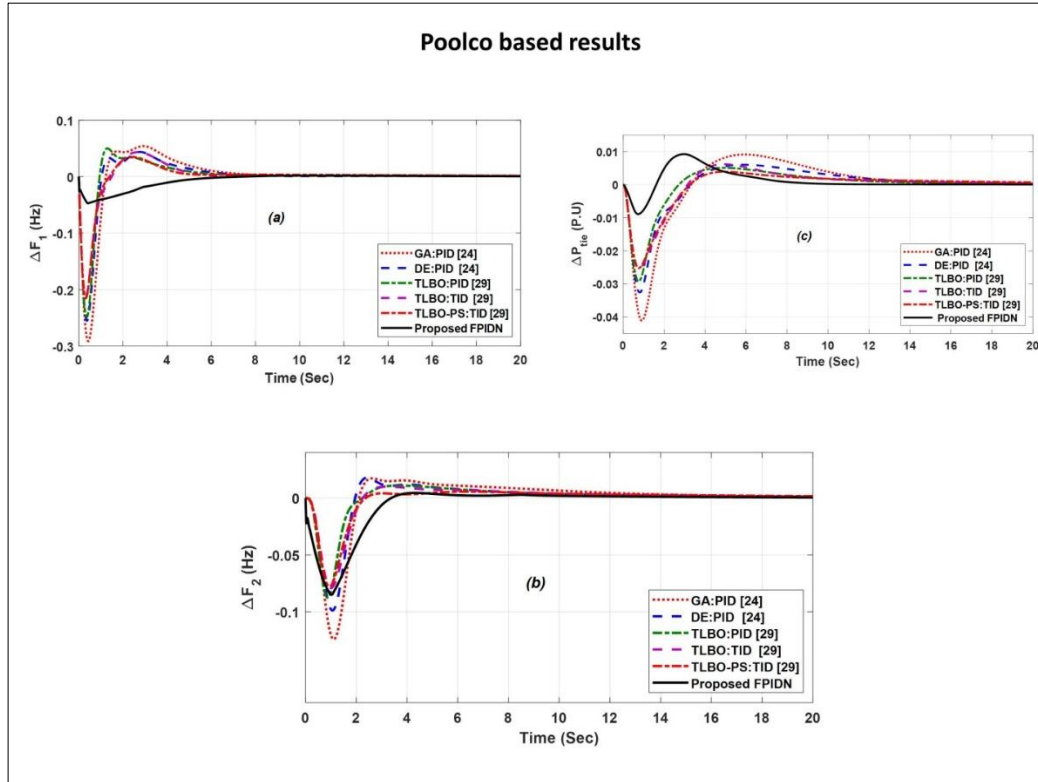


Figure 4: Poolco based results.
Source: Authors, (2026).

The figure demonstrates the time responses of ΔF_1 , ΔF_2 , and ΔP_{tie} . The proposed controller has fast attenuation of oscillations with much smoother trajectories than other controllers. The first perturbations are well baked away and the system is brought to steady state without any long period astronomic activity. Other controllers, in contrast, exhibit higher undershoots and longer oscillations, which is a sign of poorer damping behaviour. The response properties seen emphasize that the proposed controller brings about an improvement in the transient behavior by minimizing the magnitude of deviation and the time-span of deviations. Increased energy dissipation in the system is a result of the faster decay of oscillations and this is a positive contributor to stability. Also, the harmonic convergence indicates that the controller does not become aggressive in its control initiating actions and therefore there is no secondary oscillation. This conduct is especially necessary in networks that are connected in nature, where an overabundance of control effort in one area may spread disturbances to other areas. The enhanced damping further means less mechanical stress to the system components, which increases the reliability of operation. The decreased oscillatory behavior also implies that the controller achieves the balance of responsiveness and stability well. As opposed to the traditional controllers which could possibly operate fast with a higher overshoot, the proposed approach offers controlled transients and yet a speedy stabilization process. This is the main sign of strong control design in the deregulated conditions.

Table 3: Performance index of Poolco Based Scenario.

Parameters	Settling times T_s			Peak over shoot			Under shoot			ISE
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
GA: PID [24]	6.11	6.79	2.40	0.0503	0.0138	0.0086	-0.2916	-0.1191	-0.0397	0.0935
DE: PID [24]	5.52	4.51	1.88	0.0409	0.0120	0.0057	-0.2574	-0.0946	-0.0315	0.0548
TLBO: PID [29]	4.83	4.65	1.66	0.0498	0.0109	0.0051	-0.2489	-0.0878	-0.0292	0.0356
TLBO: TID [29]	4.68	3.40	1.64	0.0432	0.0101	0.0061	-0.2133	-0.0791	-0.0254	0.0288
TLBO-PS: TID [29]	4.17	1.99	1.64	0.0347	0.0056	0.0039	-0.2155	-0.0779	-0.0252	0.0270
Proposed : Fuzzy PIDN	4.07	1.83	1.32	0.0017	0.0045	0.0122	-0.0473	-0.0751	-0.0004	0.0135

Source: Authors, (2026).

The graphical observations are validated by the table that provides quantitative performance metrics. The proposed controller has lower settling times and ISE of 0.0135 as opposed to TLBO-PS:TID of 0.0270. The reduced overshoot and undershoot ensure that there is controlled transient response. These improvements in numbers indicate that the controller improves dynamic, as well as steady-state, performance when operated by Poolco. The bilateral case has a greater degree of coupling because of the direct contractual relations between regions. This makes the system dynamics more complicated as perturbations are more powerfully propagated across the tie-line. In this case, the control cannot be effective without local regulation, as well as the coordinated response across the areas.

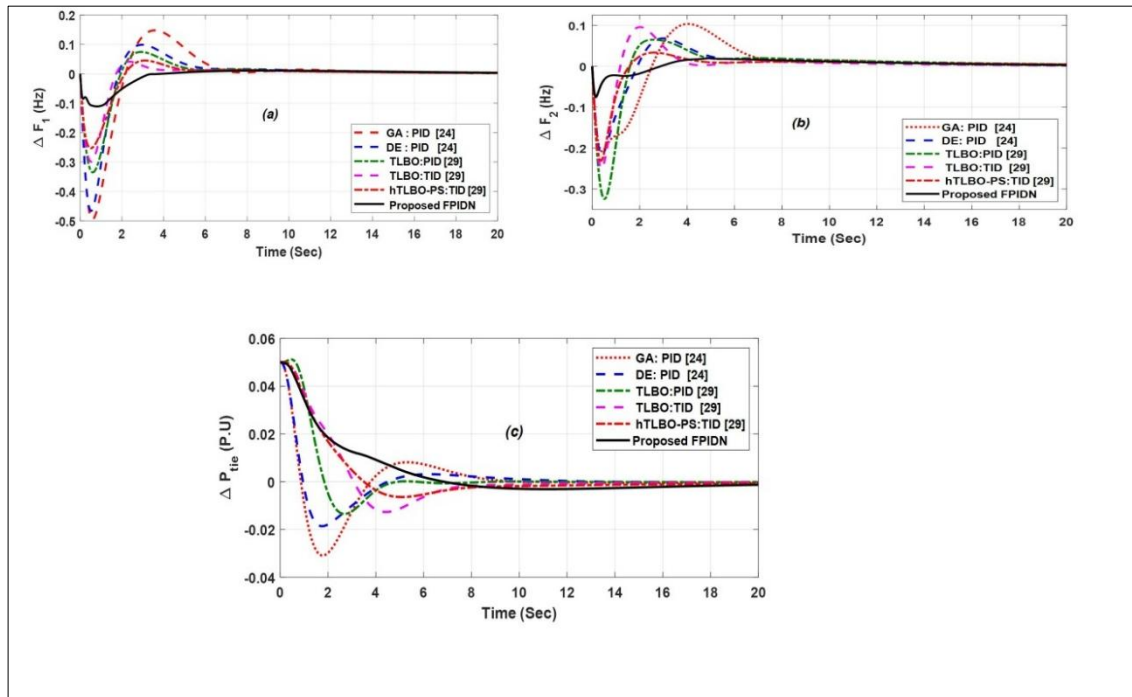


Figure 5: Bilateral based Results.

Source: Authors, (2026).

The figure demonstrates that the proposed controller will stabilize and well-damped responses regardless of the increased inter-area interactions. These oscillations are damped faster as well as the deviation amplitudes are very less than in other methods. The response curves show that there is enhanced coordination among regions, which avoids enhancement of disturbances. The behavior in the figure indicates that the proposed controller is efficient to control coupled dynamics since it coordinates the control measures in the two regions. The smaller oscillation amplitude shows that interaction of energy across the tie-line is more controlled and so areas are not unstable in terms of their interaction due to feedback. In addition, the enhanced convergence illustrates that the controller is capable of restoring equilibrium fast even in cases when the system variables are very interdependent. The other notable point is that the response in the two regions was homogenous. The coinciding damping trends in ΔF_1 and ΔF_2 show that there is balanced control action, which is important in bilateral transactions excessive response might result in sustained oscillations. The suggested controller will make sure that the areas play their role in stabilizing the system so that overall coordination and reliability will be enhanced. The fact that its performance is better also means that the controller has the ability to support decentralized control structures, meaning that decisions are determined by more than one entity. This is especially so in the current power systems where bilateral agreements are dominant and there is no centralized coordination.

Table 4: Performance index of bilateral scenario.

Parameters	Settling times T_s			Peak over shoot			Under shoot			ISE
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
GA: PID [24]	12.50	12.64	3.20	0.1478	0.1036	0.05	-0.4949	-0.2089	-0.0150	0.7348
DE: PID [24]	10.87	11.47	3.08	0.0988	0.0683	0.05	-0.4667	-0.2158	-0.0186	0.4945
TLBO: PID [29]	9.92	11.42	3.29	0.0745	0.065	0.051	-0.3352	-0.3242	-0.0135	0.2017
TLBO: TID [29]	8.58	8.32	5.25	0.0412	0.096	0.05	-0.299	-0.249	-0.0126	0.0926
TLBO-PS: TID [29]	5.82	6.67	2.53	0.0450	0.0336	0.05	-0.253	-0.2312	-0.0064	0.0872
Proposed Fuzzy PIDN	5.43	6.38	2.30	0.0029	0.0155	0.019	-0.0093	-0.0071	-0.00050	0.0075

Source: Authors, (2026).

The table affirms that the proposed controller has ISE of 0.0075 that is a lot lower than 0.0872 of TLBO-PS:TID. The times taken to settle are also less meaning that they stabilize faster. These findings confirm that the controller is useful in reducing inter-area oscillations and stabilizing the system during higher system interaction. The worst operating condition is the violation of the contract, in which the big disturbances are introduced by the mismatches between planned and actual power demand. This case is demanding when it comes to assessing the strength and disturbance rejection of the controller.

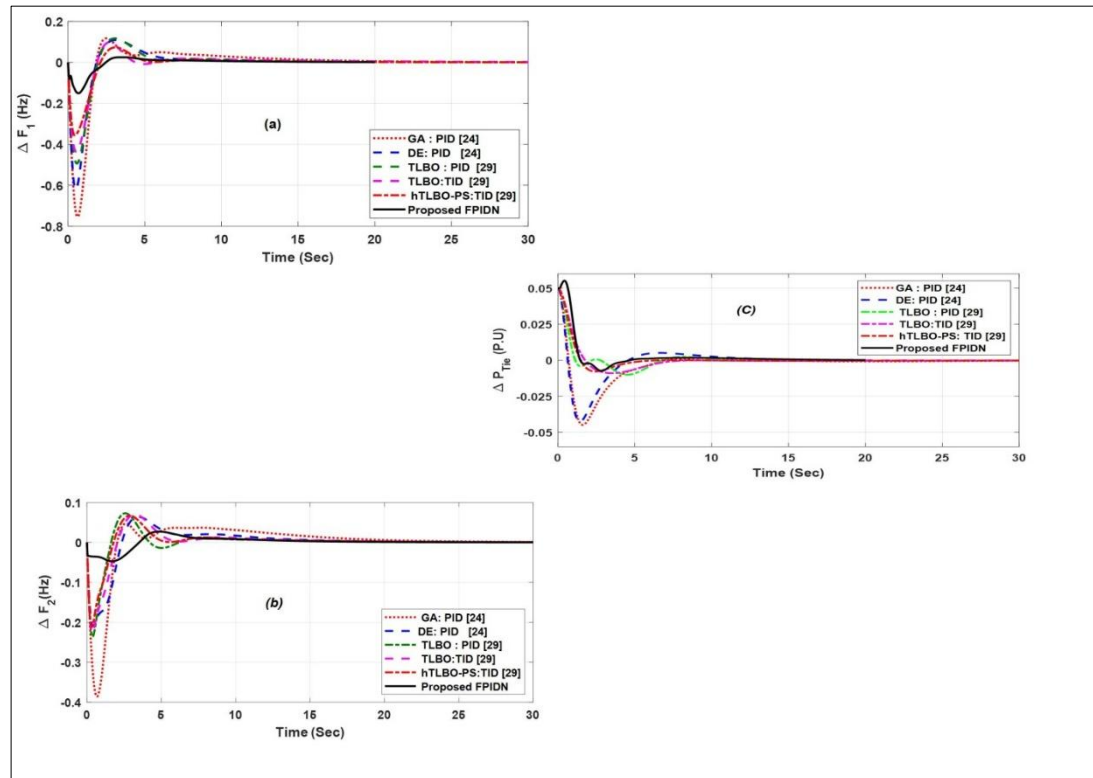


Figure 6: Contract Violation.
Source: Authors, (2026).

The figure shows that the proposed controller quickly suppresses high initial deviations and puts the system in steady state with minimum oscillations. The response is much smoother as compared to other controllers and it has faster damping. The characteristics of the response reveal that the controller has good disturbance rejection ability. The quick decrease in the margin reveals that the controller is capable of responding to the abrupt imbalances, and they do not spread throughout the system. The decreased oscillation period also indicates that the controller limits the fluctuations in the energy exchanges, which is the key to ensuring the integrity of the system in the conditions of unpredictability. Besides, the controlled and stable behavior is manifested by the possibility to cope with big disturbances without a dramatic increase. It is especially relevant with a case of contract violation where unforeseen delays might result in the cascading failures when they are not handled correctly. The suggested controller is resilient in that it is able to sustain itself even in such unfavorable situations. The enhanced transient response also means that the controller is able to respond to any change which happens in the dynamics of the system very fast and therefore offers consistency. Such flexibility is a mandatory need in the real world where the operating conditions might change without any prior notice.

Table 5: Performance index of contract violation scenario.

Parameters	Settling times T_s			Peak over shoot			Under shoot			ISE
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
GA: PID [24]	17.19	17.43	4.25	0.1177	0.0474	0.05	-0.7542	-0.3856	-0.0449	1.2967
DE: PID [24]	11.71	12.49	3.47	0.1093	0.0641	0.05	-0.6192	-0.2089	-0.0150	0.7605
TLBO: PID [29]	10.60	10.98	4.32	0.1175	0.0732	0.05	-0.4935	-0.2363	-0.01	0.3376
TLBO: TID [29]	10.57	10.65	1.26	0.0973	0.0697	0.05	-0.4357	-0.2250	-0.0089	0.2212
TLBO-PS: TID [29]	9.65	9.25	1.09	0.0734	0.0668	0.05	-0.3556	-0.2111	-0.0077	0.1445
Proposed Fuzzy PIDN	8.58	7.96	1.05	0.0029	0.0058	0.02	-0.02081	-0.00581	-0.00029	0.00251

Source: Authors, (2026).

As indicated in the table, the proposed controller attains ISE of 0.00251 which is much lower than 0.1445 of TLBO-PS:TID. Settling period is also enhanced and maximum deviations are reduced. These findings support the strength and efficiency of the controller to manage extreme disturbances. When comparing all scenarios, the proposed controller will always have better results than the already existing and best method, TLBO-PS:TID. The changes in ISE and settling time under conditions of Poolco, bilateral and contract violation conditions indicate that the controller performs high irrespective of the operating scenario. Such consistency shows that the hybrid MFO-PS optimization with the fuzzy logic is flexible and accurate at control action. The table below shows the performance of the system with variations of parameters in the range of 25%.

ISE is also in a close range of 0.0125 to 0.0135 with little variations in settling time and maximum deviations. This means that the controller is not sensitive to changes in parameters but its performance remains constant. The findings validate high robustness, which implies that the suggested controller can be applicable in real-life situations when parameters in the system can change with time.

Table 6: Sensitive analysis under Poolco based transaction.

Parameter Variation	% Change	Settling Time in (Sec)			Peak overshoot			Peak undershoot			ISE
		ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	0	4.07	1.83	1.32	0.0017	0.0045	0.0123	-0.0473	-0.0751	-0.0004	0.0135
Loading Condition	-25	4.11	1.85	1.35	0.0017	0.0042	0.0118	-0.0497	-0.0861	-0.0009	0.0129
	+25	4.17	1.76	1.36	0.0017	0.0048	0.0124	-0.0462	-0.0843	-0.0004	0.0126
T_G	-25	4.12	1.82	1.34	0.0017	0.0045	0.0122	-0.0470	-0.0850	-0.0004	0.0127
	+25	4.15	1.98	1.36	0.0017	0.0045	0.0122	-0.0475	-0.0851	-0.0004	0.0127
T_T	-25	4.16	1.87	1.38	0.0017	0.0045	0.0121	-0.0464	-0.0846	-0.0004	0.0126
	+25	4.14	1.85	1.35	0.0017	0.0046	0.0122	-0.0483	-0.0857	-0.0004	0.0128
T_{12}	-25	4.19	1.90	1.41	0.0016	0.0061	0.0111	-0.0475	-0.0871	-0.0004	0.0130
	+25	4.17	1.89	1.42	0.0017	0.0032	0.0129	-0.0471	-0.0832	-0.0004	0.0125

Source: Authors, (2026).

IV. DISCUSSION

The effectiveness of the superior performance of the proposed controller may be explained by the joint influence of the Fuzzy PIDN structure and hybrid optimization. The combination of fuzzy logic and PIDN controller facilitates the adaptive control response to an error dynamic of the system so that the controller can adapt successfully in nonlinear and variable operating conditions [36], [37]. The fuzzy mechanism also offers better damping and decreased oscillatory behavior due to the control effort of the conventionally fixed-gain controllers is dynamically adjusted by the fuzzy mechanism. This is further enhanced by the addition of the derivative filter (N component) that narrows down the transient response by minimizing noise amplification, which also adds to the smoother system trajectories and improved stability. The importance of the MFOPS optimization rests in the ability to obtain optimum controller performance. Moth Flame Optimization offers a global search, which means that it will explore a large solution space, whereas Pattern Search offers local refinement of parameters [38]. This mixed method gives time to convergence without any premature convergence and fine tuning of the controller gains. As can be seen in the results, optimization of the parameters results in significant changes to ISE and settling time in all cases, meaning that the tuning process is efficient in balancing the responsiveness and stability. The combination of global exploration and local exploitation is one of the critical aspects of attaining steady performance increase. In a practical view, the proposed controller has a high potential in the utilization in deregulated power systems.

The stability capacity under the poolco, bilateral and contract violation conditions also means that it is resilient to different operational conditions. Less deviation in frequency and tie-line oscillation would directly translate into better grid reliability and minimized instability risk [39]. The predictable behavior of the controller in various situations implies that the controller is applicable in managing uncertainties in the market-driven power exchanges and can therefore be used in the current operation of the power systems. In a comparative analysis of trends in all situations, the proposed controller is seen to be able to attain lower ISE and shorter settling time than the best existing option, TLBO-PS:TID. This enhancement is specially great in the case of violation of contract where the system suffers intense disruptions. It means that the suggested approach not only improves normal performance but also enhances the disturbance rejection ability. The similarity in the behavior of the performance in various situations underscores the flexibility of the controller, which is critical to the application in the real world. In spite of these benefits, one should take into consideration some limitations. The experiment is done with a two area system and this might not be adequately representative of the complexity of large scale interconnected networks. The study is also conducted with respect to particular system parameters and scenarios and more confirmation in other configurations and renewable integration would be useful [40]. The computational complexity of hybrid optimization can also be dependent on the size of the system and this should be taken into consideration in real life.

V. CONCLUSIONS

In this paper we provide a MFO-PS tuned Fuzzy PIDN controller of load frequency control in a two-area deregulated power system. The findings show that dynamic performance in the cases of Poolco, bilateral and contract violation has been improved significantly. In the Poolco case, the proposed controller has ISE of 0.0135 as compared to 0.0270 in TLBO-PS:TID, 0.0075 in the bilateral case as compared to 0.0872 and 0.00251 in the contract violation case as compared to 0.1445. Settling times and peak deviations are also always minimized. The comparative study demonstrates that the proposed controller outsmarts the best existing technique, TLBO-PS:TID in every case. The sensitivity analysis also illustrates the robustness where ISE is between 0.0125 and 0.0135 in the case of a variation of parameters over a range of $\pm 25\%$. These findings make the suggested solution a solid and effective solution to LFC in free markets. The results portray great practical relevance, the controller is suitable to preserve the stability of the system in different operating conditions and disturbances. Future research can be based on the fact that the approach can be extended to multi-area systems, use renewable energy sources, and discuss the real-time aspects of implementation in order to prove its performance in contemporary power systems.

VI. AUTHOR'S CONTRIBUTION

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VII. REFERENCES

- [1] P. C. Nayak, R. C. Prusty, and S. Panda, "Adaptive fuzzy approach for load frequency control using hybrid moth flame pattern search optimization with real time validation," *Evolutionary Intelligence*, vol. 17, no. 2, pp. 1111–1126, 2024.
- [2] D. Mohanty and S. Panda, "A modified moth flame optimisation technique tuned adaptive fuzzy logic PID controller for frequency regulation of an autonomous power system," *International Journal of Sustainable Energy*, vol. 40, no. 1, pp. 41–68, 2021.
- [3] G. V. Raju and N. V. Srikanth, "Frequency control of an islanded microgrid with multi-stage PID control approach using moth-flame optimization algorithm," *Electrical Engineering*, vol. 107, no. 7, pp. 8861–8878, 2025.
- [4] U. C. Prusty, P. C. Nayak, R. C. Prusty, and S. Panda, "An improved moth swarm algorithm based fractional order type-2 fuzzy PID controller for frequency regulation of microgrid system," *Energy Sources, Part A*, vol. 47, no. 2, Art. no. 2038735, 2025.
- [5] N. K. Gupta, A. K. Singh, and R. N. Mahanty, "Load frequency control with moth-flame optimizer algorithm tuned 2-DOF-PID controller of the interconnected unequal three area power system with and without non-linearity," *International Journal of System Assurance Engineering and Management*, vol. 14, no. 5, pp. 1912–1932, 2023.
- [6] P. Mohanty, R. K. Sahu, P. C. Pradhan, and S. Panda, "Design and analysis of the 2DOF-PIDN-FOID controller for frequency regulation of the electric power systems," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 4463–4476, 2022.
- [7] P. C. Pradhan, R. K. Sahu, and S. Panda, "Comparative performance analysis of hybrid differential evolution and pattern search technique for frequency control of the electric power system," *Journal of Electrical Systems and Information Technology*, vol. 8, no. 1, p. 11, 2021.
- [8] M. Sharma, R. K. Bansal, S. Prakash, and S. Dhundhara, "Frequency regulation in PV integrated power system using MFO tuned PIDF controller," in *Proc. IEEE 8th Power India Int. Conf. (PIICON)*, 2018, pp. 1–6.
- [9] M. Nandi, C. K. Shiva, and V. Mukherjee, "Moth-flame algorithm for TCSC- and SMES-based controller design in automatic generation control of a two-area multi-unit hydro-power system," *Iranian Journal of Science and Technology, Trans. Electrical Engineering*, vol. 44, no. 3, pp. 1173–1196, 2020.
- [10] S. Rangi, S. Jain, and Y. Arya, "SSA-optimized cascade optimal-PIDN controller for multi-area power system with RFB under deregulated environment," *Optimal Control Applications and Methods*, vol. 44, no. 4, pp. 1972–1994, 2023.
- [11] A. M. El-Rifaie, "A novel lyrebird optimization algorithm for enhanced generation rate-constrained load frequency control in multi-area power systems with proportional integral derivative controllers," *Processes*, vol. 13, no. 4, p. 949, 2025.
- [12] P. Kurukuri, *Frequency Deviations Stabilizations in Restructured Power Systems Using Coordinative Controllers*, 2021.
- [13] W. Younis et al., "Robust load frequency control in renewable integrated multi-area grids using hybrid SA and QIO tuned PIDF controller," *Scientific Reports*, vol. 15, no. 1, p. 36848, 2025.
- [14] B. Dekaraja and L. C. Saikia, "Combined voltage and frequency control of multiarea multisource system using CPDN-PIDN controller," *IETE Journal of Research*, vol. 69, no. 9, pp. 6457–6472, 2023.
- [15] M. Ranjan and R. Shankar, "Effect of electric vehicles and renewable sources on frequency regulation in hybrid power system using QOAOA optimized type-2 fuzzy fractional controller," *International Journal of Fuzzy Systems*, vol. 26, no. 3, pp. 825–848, 2024.
- [16] P. M. Dash, A. K. Baliarsingh, and S. K. Mohapatra, "Application of fuzzy PID controller in automatic generation control using hybrid African vultures optimization algorithm-pattern search optimization algorithm," *Electrica*, vol. 23, no. 3, 2023.
- [17] E. Çelik, N. Öztürk, and E. H. Houssein, "Influence of energy storage device on load frequency control of an interconnected dual-area thermal and solar photovoltaic power system," *Neural Computing and Applications*, vol. 34, no. 22, pp. 20083–20099, 2022.
- [18] M. S. Ayas and E. Şahin, "A reinforcement learning-cooperated dynamic controller parameter optimisation for frequency control in a nonlinear power system," *International Journal of Systems Science*, pp. 1–21, 2026.
- [19] C. N. S. Kalyan et al., "Hybrid fuzzy PID control with HAEFA optimization for simultaneous voltage and frequency stabilization in multi-area diverse source power systems," *Cogent Engineering*, vol. 11, no. 1, Art. no. 2391958, 2024.
- [20] K. A. Jose, G. R. Dheep, and T. S. Gorripotu, "Moth flame optimization algorithm optimized modified TID controller for automatic generation control of multi-area power system," in *Proc. Int. Conf. Computational Intelligence in Pattern Recognition*, 2022, pp. 644–652.
- [21] M. Aly et al., "Optimized non-integer load frequency control scheme for interconnected microgrids in remote areas with high renewable energy and electric vehicle penetrations," *Mathematics*, vol. 11, no. 9, p. 2080, 2023.

- [22] A. F. Güven et al., “Optimization of automatic generation controllers in renewable multi-area power systems using the Fata Morgana algorithm,” *Scientific Reports*, vol. 15, no. 1, p. 43342, 2025.
- [23] S. K. Ramoji and L. C. Saikia, “Maiden application of fuzzy-2DOFTID controller in unified voltage-frequency control of power system,” *IETE Journal of Research*, vol. 69, no. 7, pp. 4738–4759, 2023.
- [24] P. K. Hota and B. Mohanty, “Automatic generation control of multi source power generation under deregulated environment,” *International Journal of Electrical Power & Energy Systems*, vol. 75, pp. 205–214, 2016.
- [25] A. Daraz et al., “Frequency stabilization of interconnected diverse power systems with integration of renewable energies and energy storage systems,” *Scientific Reports*, vol. 14, no. 1, p. 25655, 2024.
- [26] S. O. Oladipo, *Enhanced meta-heuristic algorithm with application to automatic generation control system*, Univ. Johannesburg, 2021.
- [27] T. Ali et al., “Dandelion optimizer-based combined automatic voltage regulation and load frequency control in a multi-area interconnected power system,” *Energies*, vol. 15, no. 22, p. 8499, 2022.
- [28] B. Singh, A. Slowik, and S. K. Bishnoi, “Review on soft computing-based controllers for frequency regulation of diverse power systems,” *Energies*, vol. 16, no. 4, p. 1917, 2023.
- [29] D. Khamari et al., “Automatic generation control of power system in deregulated environment using hybrid TLBO and pattern search technique,” *Ain Shams Engineering Journal*, vol. 11, no. 3, pp. 553–573, 2020.
- [30] M. D. Upadhaya et al., “Influence of FOTID controller on load frequency control of interconnected thermal and renewable energy power system using FSO technique,” *SSRN*, 2023.
- [31] S. Patel, B. Mohanty, and K. S. Simhadri, “Frequency stability analysis using competition over resources technique optimized PIDA controller,” *Iranian Journal of Science and Technology*, vol. 46, no. 1, pp. 57–75, 2022.
- [32] N. A. Orka et al., “An enhanced gradient based optimized controller for load frequency control,” in *Engineering Applications of Modern Metaheuristics*, Springer, 2022, pp. 79–107.
- [33] E. M. Ahmed et al., “Modified frequency regulator based on TI λ -TD μ FF controller for interconnected microgrids,” *Mathematics*, vol. 11, no. 1, p. 28, 2022.
- [34] N. S. Shahi and A. Ahmed, “An enhanced gradient based optimized controller for load frequency control of a two area system,” 2023.
- [35] A. Saha et al., “Impact of spotted hyena optimized cascade controller in load frequency control,” *Energies*, vol. 15, no. 19, p. 6959, 2022.
- [36] R. K. Singh and V. Verma, “ANN-tuned PIDN controller for LFC with modified HVDC tie-line,” *International Journal of Information Technology*, vol. 15, no. 8, pp. 4193–4210, 2023.
- [37] G. Dei et al., “A novel TID+IDN controller tuned with coatis optimization algorithm,” *Scientific Reports*, vol. 15, no. 1, p. 4838, 2025.
- [38] V. Kumar et al., “A state-of-the-art review on voltage and frequency regulation problems,” *Energy Sources, Part A*, vol. 47, no. 1, pp. 16–49, 2025.
- [39] M. M. Gulzar et al., “Frequency and voltage stabilization of multiarea hybrid power system considering communication delay,” *Electric Power Components and Systems*, pp. 1–15, 2023.
- [40] Y. L. Karnavas and E. Nivolianiti, “Harris hawks optimization algorithm for load frequency control,” *International Journal of Emerging Electric Power Systems*, vol. 25, no. 4, pp. 555–571, 2024.