

# FINE-TUNING LOAD FREQUENCY STABILITY IN THREE-AREA POWER SYSTEM: CUSTOMIZING PID CONTROLLER VIA HYBRID GALACTIC GRAVITATIONAL OPTIMIZATION

Amita Shukla<sup>1</sup>  
Amit Prakash Sen  
D. Ganesh  
B.P. Singh

Received 27.11.2023.  
Received in revised form 04.01.2024.  
Accepted 10.01.2024.  
UDC – 621.3.072.9

Keywords:

Load frequency control, Three Area Power System (3APS), PID controller, Hybrid Galactic Gravitational Optimization (HGGO).

A B S T R A C T

The Hybrid Galactic Gravitational Optimization (HGGO) method of Three-area power system (3APS) control of frequency is the main subject of this work. The suggested method has advantages of easy implementation, computing efficiency and consistent convergence. The goal is to use the HGGO algorithm to fine-tune the Proportional-integral-derivative (PID) controller and create stable, trustworthy system. A thorough simulation of the three-area Load Frequency Control (LFC) system is carried out in MATLAB-SIMLINK environment. By optimizing PID control settings. The previous subject moves to the gravitational search algorithm (GSA), which is known for its optimization ability but is hampered by problems with local optima. This is addressed by the clustering-based learning used by the Hybrid Galactic Gravitational Optimization, which divides the programmed into clusters and uses a variety of techniques. To validate the proposed HGGO controller, load disturbances are applied to the power system and simulated outcomes for several HGGO-based load configurations are obtained.



© 2024 Published by Faculty of Engineering

## 1. INTRODUCTION

The predicted frequency value in the production of electric power is altered by system disruptions brought by variations in load. For the power system to operate and manage to produce adequate, high-quality and dependable electricity, load frequency control (LFC), is vital (Gulzar et al., 2022). It follows that some degree of control over the net power flow on the tie-lines is essential (Ahmed et al 2022). This research endeavours to

optimize Proportional-Integral-Derivative (PID) controller performance via the use of Hybrid Galactic Gravitational Optimization (HGGO) to improve load frequency stability in a Three-Area Power System (Three-APS). Stabilizing to maintain the power system's dependability and reliability especially while dealing with load disturbances the main goal is to stabilize the load frequency. To minimize load disturbances and improve overall power system stability, hybrid generalized gradient optimization (HGGO) is utilized to adjust all

<sup>1</sup> Corresponding author: Amita Shukla  
Email: [amita.shukla@niet.co.in](mailto:amita.shukla@niet.co.in)

quantitative, fundamental, and derivation parameters of the PID controllers. To improve overall security and maximize the economic generation of electricity, LFC allows different utilities to switch power sources (Zhu et al., 2019). The load frequency fluctuation serves as a gauge for the power systems' typical operation. The frequency of other regions will be impacted when the load disturbance occurs (Chen et al., 2022). Different controllers employed in different sectors are unable to manage the frequency rapidly and effectively because of the nonlinearity in alternators and system components. Because the industrial and consumer loads fluctuate constantly, we know that a power system's active and reactive power requirements are never constant (Nayak et al., 2021). As a result, input supply, such as the water or steam input to hydro generators or turbo generators, needs to be correctly controlled. It is feasible to bring the frequency change to zero, but in reality, this is not achievable (Ghasemi-Marzbali (2020)). Therefore, there is a maximum amount that can accommodate the variability in frequency. Higher frequency fluctuations will be detrimental to the customers and might potentially cause significant damage to the pricey equipment used in the sector. In the current world, every system is connected to every other system. Therefore, a power system issue is nothing more than a problem with a multi-area system. (Saadatmand et al., 2020). The ineffectiveness of manual regulation in a large-scale, networked modern system necessitates the use of automatic electronic direction (Singh and Ghosh 2022). The frequency variances necessitate the construction of a durable and most significantly, straightforward controller. (PID) controllers are used in over 90% of sectors because of their well-known simplicity, obvious functioning and usability. However, several control experts noted that a PID controller adjusted using traditional methods lacked robustness. Advanced control methods were therefore required, at first, several control strategies were thought to be better than PID control design and approaches based on linear matrix inequality (LMI) (Wang et al., 2020). Because PID controllers are used and optimal control approaches have limitations, researchers found that it is necessary to integrate the user-friendly aspects of PID controllers with optimum tuning processes (Chen et al., 2020). Because of the other control mechanisms' complexity, this integration was considered essential. Specifically, this kind of controller performs better in cases with rejection of disturbances, non-minimum phase behavior and parametric uncertainty. This paper is a brief introduction to several PID-based control schemes. Its main goal is to gather different controller solutions for the recently suggested LFC problem.

The remaining portion of the research is as follows: The objectives of this study are compared with those of other studies of a similar nature in section 2. More information on the study methodology is given in section 3. Section 4 presents the result and discussion. The explanation of the conclusion is presented in section 5.

## **2. RELATED WORKS**

Load frequency control's main objective is to respond to variations in tie-line loads and system frequency by controlling an electric generator's power output in predetermined bounds. da Silva et al., (2021) addressed this permits tie-line power exchange with other locations and guarantees the maintenance of the scheduled system frequency. Three area power systems, customizing PID controller via hybrid galactic gravitational optimization LFCs primarily use integrated controllers, which adjust the integrator gain to minimize overshoot and provide fast transient recovery in the dynamic responsiveness of the system. Jood et al., (2019) proposed of its lack of robustness, difficulty in adjusting to changing operating circumstances, inability to generate unit non-linearity and sluggishness, this kind of controller was discouraged. Kumar and Pan (2022) described that the application of simple neural networks can be an efficient way to tackle this problem. The study does a succinct literature review with an emphasis on the design of a LFC energy systems PID controller. Kumar and Hote (2021) explored transfer functions that were developed to accommodate various power system topologies Li et al., (2018). PID tuning procedures were organized into four areas by the review: soft computing techniques, methods of PID design that use internal model control (IMC) and fractional order and resilient control schemes. Rajesh and Dash (2019) aimed to ensure a methodical presentation. Traditional controllers using constant gain constants has limitations when it comes to LFC, which was essential for modifying power output frequency signals when system loads change. Alayi et al., (2021) evaluated examination of PID controller designs; this study clarifies present practices and opens the door for further research into the unsolved problems of load frequency management. Sahin (2020) introduced the application of simple neural networks can be an efficient way to tackle this problem. Models of transfer functions were developed to accommodate various power system topologies. Abu-Hamden and Alnefaie (2019) aimed in PID tuning procedures that were organized into four areas by the review: soft computing techniques, fractional order-based PID design, IMC-based PID design approaches and resilient control schemes. The GSA is shown to solve a variety of optimization challenges. Its tendency to become caught in local optima, especially with complicated problems, slows convergence. GSA was modified to include a clustering-based learning technique (CLS) to create the galactic gravitational search algorithm. GSA is initially partitioned into various clusters, with different learning algorithms employed inside and across clusters. This method reduces GSA's main drawback, local optima involvement. The solution quality and convergence of GGSA are better than GSA and other methods, according to experiments. This ensures a methodical presentation. All design strategies are investigated in

detail and the report not only points out future issues that need to be rectified but also establishes the framework for any additional study. Sharma et al., (2019) focused on a traditional controllers using constant gain constants have limitations when it comes to LFC, which is essential for modifying power output frequency signals when system loads change. Through a thorough examination of PID controller designs, the study clarifies present practices and opens the door for further research into the unsolved problems of LFC.

### 2.1 Problem statement

Managing load frequency stability is essential for the dependable functioning of the linked grid in a Three-APS. The customization of PID controllers is the main area of attention for this study to handle the difficulty. Conventional PID controllers might not be best suited for the particular dynamics of the system. HGGO is a unique technique developed to improve their performance. The objective is to adjust PID controller parameters using HGGO's optimization powers to improve stability and load variation responsiveness. The goal of the study is to increase the power system's overall robustness and efficiency by fusing the advantages of PID control with the cutting-edge HGGO algorithm. This will help to create an energy infrastructure that is more stable and resilient in the face of dynamic load fluctuations in the three-area configuration. In order to effectively handle unpredictable demand variations within the Three-Area Power System architecture, the ultimate aim is to boost the power system's overall robustness and efficiency. The ultimate goal is to create a more stable and resilient energy infrastructure capable of efficiently managing dynamic load variations.

### 3. METHODOLOGY

Using the context of a Three-APS, this study employs hybrid Galactic Gravitational Optimization (HGGO) to fine-tune PID controllers to stabilize load frequency. All of the quantitative, fundamental and derivation parameters of the PID operator are modified throughout the optimization method. HGGO is responsible for optimizing PID controllers to reduce load disturbances and ensure that the power system continues to retain its dependability. Optimization and refinement of tuning are the means by which this is achieved. PID controllers and Hybrid Galactic Gravitational Optimization each function independently to improve the system's reaction to shifting loads, as well as the robustness and performance of the Three-APS. This is accomplished by the coordinated efforts of both of these technologies. This hybrid technique has the potential to deliver strong load frequency control, which is essential for preserving the stability of the power system in a range of circumstances, when the findings of the study are taken into consideration.

### 3.2 Linked power model for three areas

A Three-APS is examined in this study yet the governor, turbine and generator control units as well as the addition of regulatory feedback mechanisms are given special consideration. One of the main goals is to maximize the system's operational efficiency by adjusting the generator's step loads. A detailed block diagram showing how the different parts of the system interact with the controller is shown in Figure 1. The complexity of the procedure that is used is depicted in this diagram. The figure shows the variations in frequency ( $f_1$  and  $f_2$ ) between Areas 1 and 2, expressed in Hertz, together with the rises in load demand ( $Pd1$  and  $Pd2$ ). A logical manner to accomplish optimization, the study uses power system dynamic models, which are useful in a number of investigations. Providing a computer description of power system component processes, these models make it possible to conduct an in-depth investigation of how these components interact with one another and react to a variety of inputs. This enables the refining of control techniques and the increase of overall performance. Within the context of dynamic shifts in frequency and load demand, the focus placed on regulatory feedback highlights the need to fine-tune the governing, turbine and generator control units to preserve stability and efficiency. In the end, this study contributes to the advancement of knowledge of complex power system dynamics. It paves the way for control techniques that are more effective and have better operational results in multi-area power systems. Definition of Area Control Error (ACE) for its area: Traditional automated generation controllers use PID controllers with 9-form control equations.  $K_P K_I K_D$  represents the area's proportional, integral and derivative controller coefficients. Three connected regions were regarded as indistinguishable to simplify analysis. The parameter values were tuned to match  $KP1 = KP2 = K3 = KP$  and  $KI1 = KI2 = KI3 = KI$  and  $Kd1 = Kd2 = Kd3 = Kd$ .

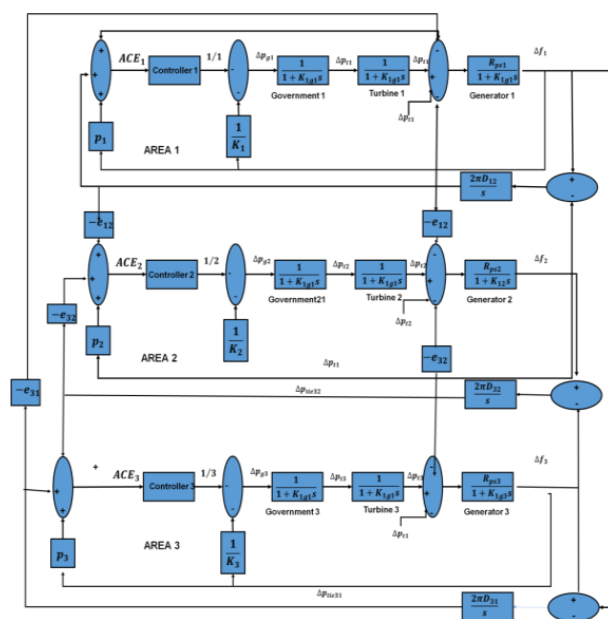
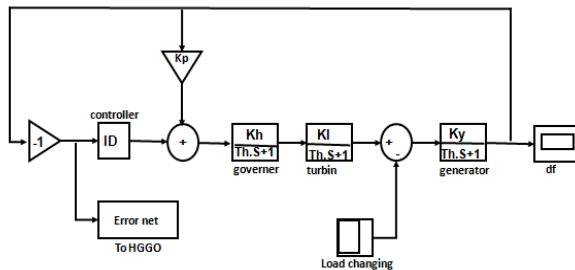


Figure 1. Three-APS controller simulation

Figure 2 shows the unique LFC method for a Three-APS using an HGGO-based self-tuning PID controller. The HGGO software explores a three-dimensional space to find optimal PID controller settings for the “Proportional (Kp), Integral (Ki) and Derivative (Kd)” parameters. The LFC PID controller uses these HGGO-optimized parameters for optimal performance. Figure 2 shows how the HGGO technique fine-tunes the PID operator for load frequency management using system data from Table 1. This graph shows the dynamic and adaptable character of the HGGO algorithm, which configures PID controller settings to maximize frequency regulation and stability in the Three-APS.

**Table 1.** Three APS parameters

Parameters are as follows: f=50Hz		
Area 1	Area 2	Area 3
R1=R2=R3=2.3 Hz/per unit MW, Tg1=Tg2=Tg3=0.07 sec.	Tp1= Tp2= Tp3=20 sec, tiemax=200MW, Pr1= Pr2= Pr3=2000 MW, Tt1= Tt2= Tt3=0.2 sec.	Kp1= Kp2= Kp3=119 Hz.p.u/MW,



**Figure 2.** Single area networks HGGO PID block diagram

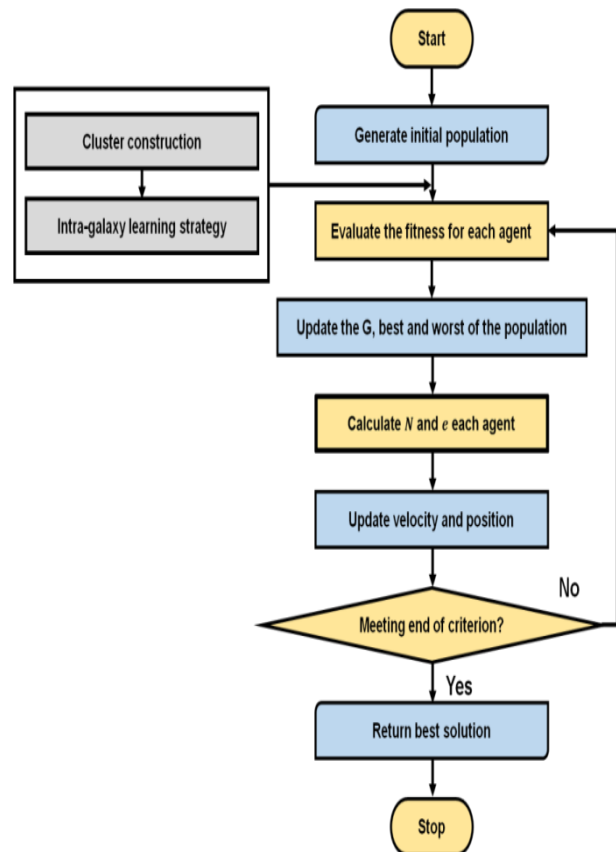
### 3.2 Typical PID controller design

PID controller settings have been configured in several ways during the last 50 years. Ziegler-Nichols closed-loop tuning calculates  $K_c$  from the final get value ( $K_u$ ) and resonance period. Due to its adaptability across systems of various orders, this 1940 approach is used for PID controller tuning. Rarely has the Ziegler-Nichols technique outperformed other tuning approaches in recent years.  $K_u=1.16$  and  $P_u=1.33$  are the system's ultimate gain and oscillation periods. Ziegler-Nichols tuning yields  $K_p=0.68234$ ,  $K_i=0.6264$  and  $K_d=0.16624$ . The following paragraphs compare the speed of its reacting Ziegler-Nichols-tuned PID system to our suggested tuning approach.

### 3.3 Hybrid Galactic Gravitational Optimization (HGGO)

GSA is subject to becoming trapped in local optimal solutions, as it was discussed before. Additionally, it lacks early exploration, which slows convergence and

it has limited exploration capacity, which prevents efficient solutions from being found. This research presents the original GSA population with a grouping mechanism that is in the process of evolving. By making this adjustment, early population exploration is improved while maintaining information diversity remained. Therefore, the exploration and utilization of the GSA are in equilibrium. Figure 3 shows HGGO's fundamentals. Gravitational forces enable entities to communicate information and hunt for the ideal solution via cooperative and competitive interactions in GSA. Initially, the algorithm hinders information transfers among people, resulting in repeated searches and ineffective search capabilities. To improve search efficiency, representative persons must get more influential information. CLS increases information sharing between people and improves GSA performance. CLS includes cluster creation, intra-galaxy learning and inter-galaxy learning.



**Figure 3.** Flow of HGGO

### 3.4 The Galaxy Method

They use the popular K-means clustering technique to construct clusters in this investigation. The K-means method group's n items into K clusters, a user-defined input parameter, guaranteeing that objects in the group share similarities while some do not. The K-means clustering process is below:

- Starting with a random pick of  $K$  people, the first segmentation is constructed by finding the cluster's center of mass using the seed.
- A cluster is formed by allocating each person to the nearest centroid.
- Enhance each cluster centroid using Euclidean distance while maintaining the cluster count.
- Steps (2) and (3) should be repeated until clusters stop changing or the stopping condition is met.

The notion of the galactic gravitational search algorithm is brought as a result of the incorporation of  $K$ -means clustering into the HGGO. Using object mean values to determine a center of gravity inside each cluster,  $K$ -means clustering is an essential component of this hybrid technique.

It plays a crucial role in determining the degree to which clusters are like each other. The theory is evocative of how stars gravitate towards one another and create galaxies in the universe. In the case of HGGO, the initial population of the GSA goes through a process that clusters it into  $K$  clusters, which is analogous to the way that stars become grouped. The algorithm's capacity to explore and optimize solution spaces is improved as a result of the addition of clustering concepts. A galactic metaphor is introduced in HGGO as a result of the synergy between GSA and  $K$ -means clustering. This metaphor represents the collective dynamics of celestial bodies in the cosmos. The HGGO algorithm provides an innovative approach to problem-solving by utilizing gravitational principles and clustering techniques. This allows the algorithm to capitalize on the strengths of both components, resulting in improved efficiency and performance in optimization tasks. Within the field of optimization algorithms, this combination of gravitational and clustering principles constitutes a novel and potentially fruitful line of investigation.

### 3.5 Learning Strategy within Galaxies

This section describes the intra-galaxy learning approach employed inside the galaxy. Galaxy stars act similarly due to their position and choices. Improving information flow between these stars can improve GGSA's ability to search. Improving internal communication inside galaxies is an excellent technique to convey reliable information and solve optimization challenges. Information interaction involves two processes.

**Galactic Replacer:** Make a comparison between the galactic centre of each galaxy and the star that is the worst in that galaxy. Replace the galactic center if it is in better condition than the star with the lowest quality.

**Operator Learning Internally:** Every single star in a galaxy is able to speak with its closest cousins. During the process of learning (details to come), a trial star is developed. Each heavenly and tribulation level contributes to select few individuals for the operator. Due to the fact that they possess profoundly beneficial information, high-performing stellar beings are among the most promising candidates for information sharing with all starlight according to universe starlight. By using this strategy, it is ensured that every star gains knowledge from more advanced stars than the most powerful stars in its galaxy. Therefore, to improve their chances of advancing to a better position with better responses, stars are recommended.

### 3.6 Designing an HGGO-based controller

An effective technique for improving tie-power regulation and the Load Frequency Control (LFC) system in a Three-APS is the HGGO approach. Achieving optimal system behavior through efficient management of oscillation damping, inter-area tie-power and frequency is the main goal. The PID controller settings ( $K_p$ ,  $K_i$ , and  $K_d$ ) that are best for the LFC system are determined in large part by HGGO. The method starts by creating a population at random in the 0th generation, giving each member a unique performance index value. HGGO simulates successive generations by utilizing this starting population and adjusting the controller parameters according to the performance indicator. Reproduction, crossover and mutation operators are used in the iterative process to aid in the solution space exploration. By using this evolutionary method, HGGO generates the best values for the PID controller settings by iterating over generations until convergence is reached. This methodological approach highlights HGGO's ability to fine-tune PID controllers, leading to an enhanced LFC system that improves frequency control, handles load disturbances and guarantees the power system's stability and dependability. The algorithm's capability to traverse the solution space and approach optimal solutions emphasizes how well it handles the intricate dynamics of power systems, indicating the possibility of its use in real-world situations.

## 4. RESULT AND DISCUSSION

This study uses MATLAB-SIMLINK extensively. Windows 10 on an Intel Core i7 laptop. The HGGO program receives the controller's error signals  $Df1, Df2$  and tie line power during simulation. Velocities are limited to  $[V_{min}, V_{max}]$  and particle locations are limited to user-specified parameters. After a 0.01 p.u demand increase to A1, the quantity variations of the "first area ( $Df1$ ), second area ( $Df2$ ) and inter-area tie-power signals are examples of the system that is open to loops can

be found in Figures 4, 5 and 6. Figure 6 illustrates the frequency variations of the systems that are permanently first area ( $Df1$ ), second area ( $Df2$ ) and inter-area tie-power signals after a 0.01 demand step increase in A2. Simulation findings show an improvement in time domain requirements for 0.01 p.u step loads.

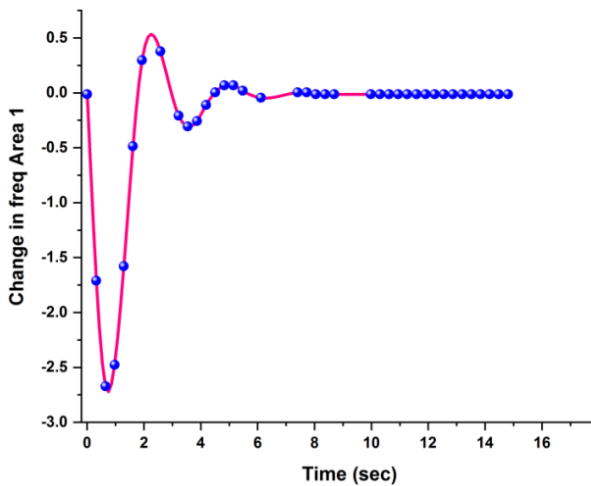
To handle the frequency and tie-line power changes across two separate regions, a full assessment of PID and HGGO PID controllers is shown in Table 2 and Figure 4, respectively. In the evaluation, the primary emphasis is placed on important metrics, particularly the settling time and the maximum deviation, which are used to quantify the degree of departure from the

goal condition per unit. When it comes to A1, the PID controller displays a calm period of 9.2 sec and a maximum variation of 1.0163 per unit. As a point of comparison, the HGGO PID controller exhibits greater performance, exhibiting faster settling periods and smaller maximum deviations in both area 1(A1) and area 2 (A2) respectively. The results of this study highlight the improved control efficiency of the HGGO PID controller. The findings of this research give useful insights into the comparative capabilities of various controllers. We provide a basis for choosing effective control techniques in power system applications, which are situations in which minimizing settling time and deviations, is essential for achieving optimum performance.

**Table 2.** Load regulation in the Simulink model analysis

Controller	Improvement in A1 regularity		Improvement in A2 regularity		Tie-line control shift	
	Arranging periods	Greatest variation	Arranging periods	Greatest variation	Arranging periods	Greatest variation
PID	9	1.0163	9.1	1.0112	7.3	1.0036
HGGO PID	3.8	0.0114	2.5	0.0064	2.5	0.00216

Note: Arranging periods (sec), greatest variation (p.u)



**Figure 4.** The frequency shift in A1

A comparative comparison of the PID and HGGO controllers in terms of how they react to differences

in frequency across two areas is shown in Table 3 and Figure 5, respectively. A frequency change of 1.0112, an arranging period of 9.3 sec and a maximum power variation of 1.0163p.u are shown by the PID in A1. HGGO demonstrates greater performance, as it has a frequency change of 2.6, a settling time that is less than three seconds and a power fluctuation that is reduced to 0.0095 p.u when compared to PID; these data demonstrate that HGGO is more effective in reducing power fluctuation and attaining quicker reaction times. Because of the large variations in settling times and power fluctuations, it seems that HGGO has the potential to improve the management of power systems. Both the table and the figure provide the findings, which highlight the benefits of HGGO in comparison to PID. These findings indicate that HGGO has the potential to contribute to a more robust and stable management of frequency changes in the locations that were investigated.

**Table 3.** Conventional PID vs Novel HGGO Controller

Controller	Improvement in A1 regularity		Improvement in A2 regularity		Tie-line control shift	
	Arranging periods	Greatest variation	Arranging periods	Greatest variation	Arranging periods	Greatest variation
PID	9	1.0112	9.3	1.0163	7.3	1.00377
HGGO PID	2.6	0.0095	3	0.0144	2.2	0.002156

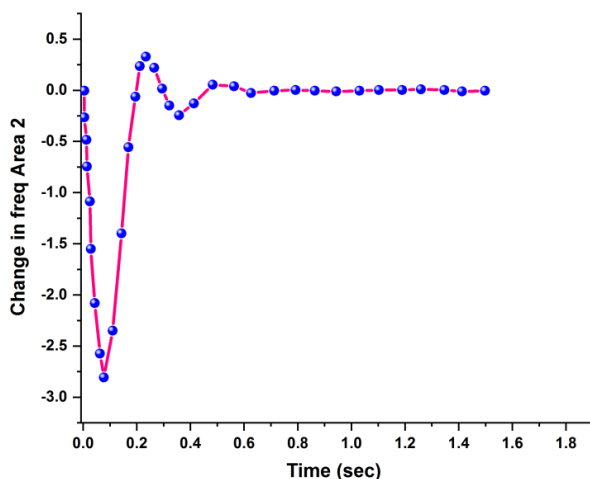


Figure 5. The frequency shift in A2

A complete comparison of the performance of PID and HGGO controllers in addressing frequency and power changes across two separate regions is shown in Table 4 and Figure 6, respectively. Two distinct areas are compared. A frequency change of 1.0112, an Arranging period of 9.3 sec and a maximum power fluctuation of 1.0163p.u are the characteristics that PID controller displays in A1. The performance of HGGO is superior to that of PID since it demonstrates a much lower frequency change of 2.6, a shorter arranging period of 3 sec and a minimized power fluctuation of 0.0096 parts per unit. These findings highlight the higher efficiency of HGGO in comparison to PID in terms of obtaining shorter settling times and less power variability. This indicates that HGGO has the potential to improve the management of power systems. The data shows that applying HGGO can help to control and stability in power networks, which makes it a potential choice for optimizing the performance of these systems. HGGO stands for high-level grid optimization.

Table 4. Assess controllers with a 1% load

Controller	Improvement in A1 regularity		Improvement in A2 regularity		Tie-line control shift	
	Arranging periods	Greatest variation	Arranging periods	Greatest variation	Arranging periods	Greatest variation
PID	9	1.0112	9.3	1.0163	7.3	1.00377
HGGO PID	3.6	0.0095	3	0.0144	2.2	0.002156

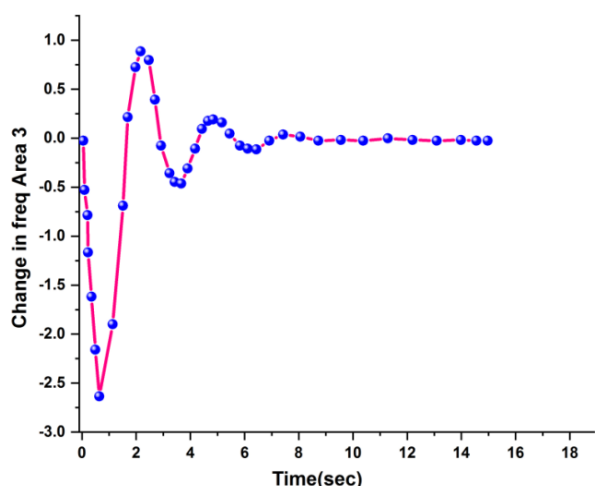


Figure 6. The frequency shift in A3

The simultaneous finding of global and local solutions is made possible by HGGO, which helps to improve the fine-tuning of controller parameters. A comparison is made between the old method and the HGGO algorithm-derived PID value in terms of its responsiveness and stability.

Table 2 presents tabulated temporal domain comparison parameters, including max exceed maximum, increase and set durations, in response to

0.01p.u at A1. The results indicate a significant reduction in overshoot with the implementation of the HGGO-based controller. Furthermore, improvements are observed in settling time, rise time and peak time. The HGGO-based controller outperforms the traditionally tuned controller using the Zeigler-Nichols criterion. Table 3 shows results for a 0.01 p.u step adjustment in A2. The simulation has 10 generations and 5 people. The constants c1 and c2, are 0.12 and 1.2.

### 5. CONCLUSION

This work investigates a HGGO-based LFC system for a Three-APS. Time domain specifications improved on analytical and graphical analysis, including shorter rising time, peak time, settling time and overshoot. Ziegler-Nichols controllers perform worse than HGGO controllers. Using clustering-based learning, the article addresses the constraints of the GSA. The findings indicate that GSA with clustering-based learning improves search and population diversity during convergence. This discovery allows clustering-based learning future research should address flexible and several goals concerns. The suggested HGGO-PID controller generates high-quality, dependable electric energy with little system parameter information.

## 5.1 Future work and limitation

Further studies should investigate the applicability of the proposed HGGO-PID controller in real-world power systems and the flexibility and potential multi-objective optimization of clustering-based learning in

gravitational search algorithms. Hybrid Galactic HGGO based LFC for Three-APS improve time domain specifications over Ziegler-Nichols controllers. However, the suggested HGGO-PID controller's computational complexity and scalability concerns require additional study for practical implementation.

## References:

- Abu-Hamden, N., &Alnefaie, K. (2019). Techno-economic comparison of solar power tower system/photovoltaic System/wind turbine/diesel generator in supplying electrical energy to small loads. *Journal of Taibah University for Science*, 13(1), 216-224.<https://doi.org/10.1080/16583655.2018.1556916>
- Ahmed, I., Rehan, M., Basit, A., Malik, S. H., & Hong, K. S. (2022). Multi-area economic emission dispatch for large scale Multi-fueled power plants contemplating inter-connected grid tie-lines power flow limitations. *Energy*, 261, 125178.<https://doi.org/10.1016/j.energy.2022.125178>
- Alayi, R., Zishan, F., Seyednouri, S. R., Kumar, R., Ahmadi, M. H., &Sharifpur, M. (2021). Optimal load frequency control of island microgrids via a PID controller in the presence of wind turbine and PV. *Sustainability*, 13(19), 10728.<https://doi.org/10.3390/su131910728>
- Chen, P., Zhang, D., Yu, L., & Yan, H. (2022). Dynamic event-triggered output feedback control for load frequency control in power systems with multiple cyber attacks. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 52(10), 6246-6258.<https://doi.org/10.1109/TSMC.2022.3143903>
- Chen, Z., Zha, H., Peng, K., Yang, J., & Yan, J. (2020). A design method of optimal PID-based repetitive control systems. *IEEE Access*, 8, 139625-139633. <https://doi.org/10.1109/ACCESS.2020.3012506>
- da Silva, G. S., de Oliveira, E. J., de Oliveira, L. W., de Paula, A. N., Ferreira, J. S., &Honório, L. M. (2021). Load frequency control and tie-line damping via a virtual synchronous generator. *International Journal of Electrical Power & Energy Systems*, 132, 107108.<https://doi.org/10.1016/j.ijepes.2021.107108>
- Ghasemi-Marzbali, A. (2020). Multi-area multi-source automatic generation control in deregulated power systems. *Energy*, 201, 117667. <https://doi.org/10.1016/j.energy.2020.117667>
- Gulzar, M. M., Iqbal, M., Shahzad, S., Muqet, H. A., Shahzad, M., & Hussain, M. M. (2022). Load frequency control (LFC) strategies in renewable energy-based hybrid power systems: A review. *Energies*, 15(10), 3488.<https://doi.org/10.3390/en15103488>
- Jood, P., Aggarwal, S. K., & Chopra, V. (2019). Performance assessment of a neuro-fuzzy load frequency controller in the presence of system non-linearities and renewable penetration. *Computers & Electrical Engineering*, 74, 362-378. <https://doi.org/10.1016/j.compeleceng.2019.02.009>
- Kumar, A., & Pan, S. (2022). Design of fractional order PID controller for load frequency control system with communication delay. *ISA transactions*, 129, 138-149.<https://doi.org/10.1016/j.isatra.2021.12.033>
- Kumar, M., &Hote, Y. V. (2021, February). PID2 Controller Design Based on Internal Model Control Approach for a Non-Ideal DC-DC Boost Converter. In *2021 IEEE Texas Power and Energy Conference (TPEC)* (pp. 1-6). IEEE. <https://doi.org/10.1109/TPEC51183.2021.9384954>
- Li, S., Yuan, F., Yu, Y., Ji, J., Todo, Y., &Gao, S. (2018). Galactic gravitational search algorithm for numerical optimization. In *Advances in Swarm Intelligence: 9th International Conference, ICSI 2018, Shanghai, China, June 17-22, 2018, Proceedings, Part I 9* (pp. 397-409). Springer International Publishing.[https://doi.org/10.1007/978-3-319-93815-8\\_3](https://doi.org/10.1007/978-3-319-93815-8_3)
- Nayak, P. C., Nayak, B. P., Prusty, R. C., & Panda, S. (2021). Sunflower optimization-based fractional order fuzzy PID controller for frequency regulation of solar-wind integrated power system with hydrogen aqua equalizer-fuel cell unit. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1-19.<https://doi.org/10.1080/15567036.2021.1953636>
- Rajesh, K. S., & Dash, S. S. (2019). Load frequency control of autonomous power system using adaptive fuzzy-based PID controller optimized on improved sine cosine algorithm. *Journal of Ambient Intelligence and Humanized Computing*, 10, 2361-2373.<https://doi.org/10.1007/s12652-018-0834-z>
- Saadatmand, M., Mozafari, B., Gharehpetian, G. B., &Soleymani, S. (2020). Optimal PID controller of large-scale PV farms for power systems LFO damping. *International Transactions on Electrical Energy Systems*, 30(6), e12372.<https://doi.org/10.1002/2050-7038.12372>



- Sahin, E. (2020). Design of an optimized fractional high-order differential feedback controller for load frequency control of a Multi-area multi-source power system with nonlinearity. *IEEE Access*, 8, 12327-12342. <https://doi.org/10.1109/ACCESS.2020.2966261>
- Sharma, J., Hote, Y. V., & Prasad, R. (2019). PID controller design for interval load frequency control system with communication time delay. *Control Engineering Practice*, 89, 154-168. <https://doi.org/10.1016/j.conengprac.2019.05.016>
- Singh, A., & Ghosh, A. (2022). Comparison of quantitative feedback theory dependent controller with conventional PID and Sliding mode controllers on DC-DC boost converter for microgrid applications. *Technology and Economics of Smart Grids and Sustainable Energy*, 7(1), 11. <https://doi.org/10.1007/s40866-022-00133-2>
- Wang, L., Liu, J., & Li, Y. (2020). The optimal controller design framework for PID-based vibration active control systems via non-probabilistic time-dependent reliability measure. *ISA transactions*, 105, 129-145. <https://doi.org/10.1016/j.isatra.2020.06.007>
- Zhu, Y., Tang, S., Wang, C., Jiang, W., Yuan, X., & Lei, Y. (2019). Bifurcation characteristic research on the load vertical Vibration of a hydraulic automatic gauge control system. *Processes*, 7(10), 718. <https://doi.org/10.3390/pr7100718>.

---

**Amita Shukla**

Noida Institute of Engineering & Technology,  
Greater Noida, Uttar Pradesh, India  
[amita.shukla@niet.co.in](mailto:amita.shukla@niet.co.in)  
ORCID 0009-0000-3677-4188

**Amit Prakash Sen**

Arka Jain University,  
Jamshedpur, Jharkhand, India  
[dr.amit@arkajainuniversity.ac.in](mailto:dr.amit@arkajainuniversity.ac.in)  
ORCID 0000-0002-8196-6549

**D. Ganesh**

Jain (Deemed to be University),  
Bangalore, Karnataka, india.  
[d.ganesh@jainuniversity.ac.in](mailto:d.ganesh@jainuniversity.ac.in)  
ORCID 0000-0002-4220-3821

**B.P. Singh**

Maharishi University of Information Technology,  
Uttar Pradesh, India  
[bhanupratapmit@gmail.com](mailto:bhanupratapmit@gmail.com)  
ORCID 0000-0001-5346-4309

---

