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Frequency control of hybrid power system with fractional order secondary controller using improved biogeography-based krill herd algorithm

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ABSTRACT

To meet the demand of electrical power, structural changes of the power system from the generation side are necessary by integrating the renewable sources into the existing system. In the presence of renewables, the active power imbalances caused by both generation and demand are reduced with the classical units (like thermal) since the wind speed and irradiance (inputs of wind and solar plants) are volatile and nonlinear in nature. The frequency deviations triggered by such active power imbalances of the hybrid power system integrated with both conventional and renewable energy plants are minimized with better secondary control schemes. Therefore, this article suggests fractional order secondary controller (FOSC) for conventional units of the interconnected power system to strengthen the frequency stability of the system during the demand perturbations. The optimal gains of the FOSC are identified with an improved biogeography-based krill herd optimizer with the help of the performance indicator integral square error. To elevate the improvements of FOSC, comparisons are provided with classical controllers during the simple, random load perturbations with and without generation changes. Furthermore, sensitivity analysis on system parameters is performed to show the robustness of the FOSC over classical control strategies.

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1. INTRODUCTION

Automatic generation control (AGC) is essential to meet the power balance of isolated and interconnected power systems integrated with wind and solar during the load and generation variations happens continuously due to their volatilities. To effectively minimize these deviations, advanced control systems are essential. In the Indian scenario, the contribution of the renewable energy sources like wind, PV, and geothermal is increasing and therefore the issues of frequency stability are also increasing [1], [2]. The study on AGC issues helps to provide reliable solutions in future generation. Some of the existing studies on the AGC with renewables are presented below.

The existing works in [3]-[22] offer a comprehensive exploration of AGC strategies in different power system models, addressing renewable energy integration, energy storage utilization, and control mechanism optimization in AGC perspective. These AGC studies separately discussed the merits of the secondary control mechanisms in both large and small capacity plants. For example, a small, isolated power system is opted in [3] to real power and frequency control by designing the classical controllers such as proportional integral (PI) and proportional integral derivative (PID) with the help of particle swarm optimizer (PSO). In [4], PSO-based optimal controller design is suggested for the large capacity plant and investigates the impact of load parameter variations on AGC. Furthermore, the performance of different classical controllers is compared and highlighting the significance of controller selection in maintaining system frequency. Classical controllers provide significant improvements in AGC for isolated power system consisting of conventional sources like thermal. However, energy storage units are required for the small capacity plants (microgrids) integrated with renewable units to provide continuous power and to balance the generation and load. In this context, the work presented in [5] focused on optimizing battery energy storage systems (BESS) significance in frequency control of isolated power networks. The BESS enhances the stability of power systems in isolated mode by swiftly compensating for active power, particularly beneficial for systems with low grid inertia (due to renewables). Particularly for the isolated power system with low inertia, frequency stability is achieved with better coordination between the storage units and flexible loads according to the results presented in [6]. Apart from the storage challenges of isolated power system consisting of renewables, the mutual effects of the voltage and frequency control is another issue of the safe and stable operation of the system. For large systems, the voltage and frequency control strategies are different, and their dependence is negligible whereas for the small, isolated models there exist mutual effects between the AVR and frequency control loops [7]. The challenge of integrating variable renewable energy sources by proposing dynamic frequency control support using energy storage is presented in [8]. The low inertia of the system needs better control strategies to maintain the grid stability particularly with frequency [9]. Furthermore, a novel frequency control scheme utilizing fractional controllers for renewable-integrated isolated power systems is presented in [10]. The isolated system consists of the thermal and hydro plants along with large solar and wind systems used to investigate the frequency control studies in [10]. The challenges associated with the renewable integrated isolated power systems are minimized by effectively designing suitable AGC schemes.

Furthermore, AGC strategies in power grids, exclusively focusing on the integration of renewable generating systems and storage devices to provide continuous power, to enhance system stability and performance available from [11]-[18]. The effect of variable renewable generation on system stability was studied in [11] to offer an effective technique, which explores the load frequency control (LFC) and dynamic response enhancement associated with energy storage units while taking uncertainty in renewable distributed generators into study. The merits of the suggested strategy in attaining better frequency regulation is demonstrated in [12], where particle swarm optimization (PSO)-based approach for two-area interconnected model including several renewable energy systems is provided. Several scenarios were considered to implement better AGC approaches in case of multi-area systems [13]-[16]. A new method of frequency regulation is presented in [17] with I-PD controller via peaks tracking cost function in presence of distributed sources, where the optimal gains are identified with cooperation search-based optimizer. The whale optimization algorithm's is adopted for tuning the AGC controller to improve the system frequency profile is demonstrated in [18]. An enhanced fractional integral controller was used in [19] to improve the power system's frequency profile using a load frequency control technique for linked power systems with renewable energy sources. An innovative method of frequency regulation is provided in [20] by the proposal of an imperialist competitive algorithm (ICA) assisted fractional order cascade controller for the AGC performance enhancement of interconnected power system model with reheat thermal units. The necessity of integrating a variety of energy sources for efficient frequency regulation was highlighted by the work described in [21], which examined the load frequency variations of multi-source power system model integrated with solar-thermal units and electric vehicles. The literature suggests that the fractional order (FO) and cascade controllers are more preferable with the help of optimization algorithms for tuning to maintain the load frequency stabilization and to improve system performance [22]-[25].

This paper suggests fractional order secondary controller (FOSC) for the power system model to minimize the power imbalances initiated by renewable and load uncertainties. The study investigates the effect of different types of disturbances of both generation and demand on the model test system and the ability of the presented FOSC controller over classical controllers to meet the power balance condition via secondary frequency control mechanism. Furthermore, parameter variations of the power system model are also verified via simulation studies with classical and FOSC controller. All the controller gain parameters are identified with the assistance of improved biogeography-based krill herd (IBBKH) algorithm using the integral square error (ISE) as fitness function of the IBBKH. A separate comparative assessment is also provided to showcase the merits of the work.

2. MODELLING OF THE TEST SYSTEM AND CONTROLLER

In order to compare the results of the suggested controller with classical controllers of AGC, test system in Figure 1 is opted to carry the variety of simulation studies. The popular AGC cost function, ISE is used as the performance metric to measure the deviations in both frequency and tie-line power measurements for optimization, and the controller parameters are tuned to minimize this error in frequency and tie-line power variations. The next subsections contain thorough explanations of the test system and controllers.

To study the impact of the renewable sources and FOSC controller on the system frequency and power flow in between the coherent areas, an interconnected power system model is simulated Simulink platform. Figure 1 shows the block diagram of the test system consists of 2 areas initially the power generated by thermal plants. Later, the wind and solar generating units are placed in area 1 of the test system.

The primary and secondary control mechanisms help to maintain the stability of the test system during the load and generation uncertainties and created with the help of step functions to show the sudden variations w.r.to time. To improve the frequency profiles, either classical controllers or FOSC are used in the secondary control loop of AGC as shown in Figure 1. In this work, FOSC controller is suggested and utilizes ACE to generate the plant control signal. The input of the test system for each area by FOSC controller is provided in (1).

$$u_i(s) = \left(ACE_i(s)\right)\left(k_{p_i} + \left(\frac{k_{i_i}}{s^{\alpha_i}}\right) + k_{d_i}s^{\beta_i}\right) \quad (1)$$

In (1), $k_{p_i}, k_{i_i}, k_{d_i}$, α_i and β_i are the decision parameters need to decide based on the physical constraints, limitations of the model to get the best response. One FOSC controller requires 5 such decision parameters and therefore, the total decision parameters of the optimization problem are 10. Because the test system consists of 2 controllable units for generation and therefore 2 controllers are essential with 10 parameter gains. So, the IBBKH algorithm is implemented with the 10 decision parameters generated randomly and updated with the help of ISE function values.

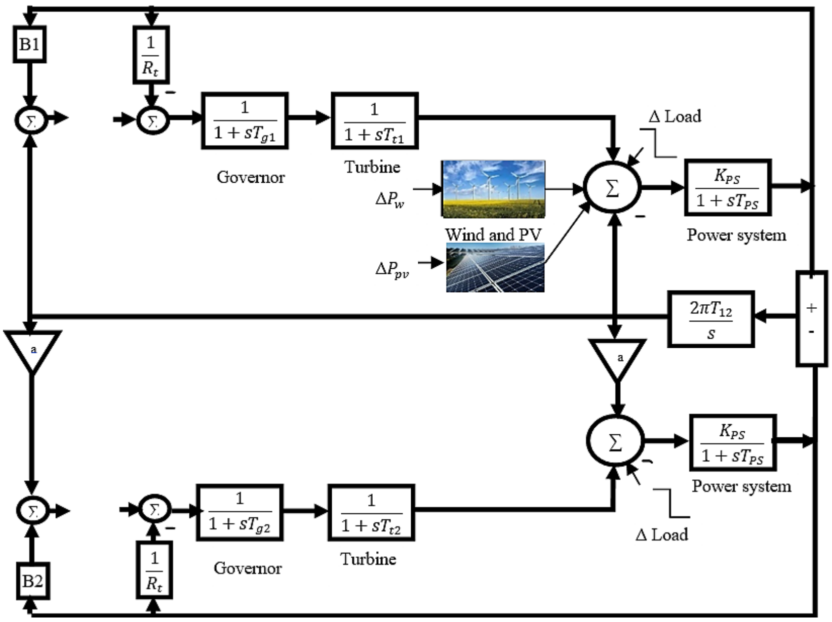


Figure 1. Test system block diagram

3. FITNESS FUNCTION AND TUNING ALGORITHM

In AGC, optimal system performance requires fine-tuning the controller gain parameters. Meta-heuristic and/or population search-based algorithms such as PSO, DE, TLBO, and CSA are increasingly being employed for finding the gains of the controllers. A critical aspect of this optimization is the fitness or cost function design, which quantitatively measures the performance of the system under different controller settings. Among the commonly used cost functions of AGC, the integral square error (ISE) is popular according to the literature survey in minimizing the control errors. The ISE function is expressed as (2).

$$ISE = \int_0^t \sum\{(\Delta f_i)^2 + (\Delta P_{ij})^2\}dt \quad (2)$$

Where Δf_i represents the deviation in frequency for the i^{th} control area and ΔPij represents the active power exchange error between the interconnected areas (i^{th} and j^{th} areas) via the tie-lines.

By minimizing the ISE, the controller ensures that both frequency deviations and tie-line power fluctuations are kept to a minimum, towards improve the system stability. In this context, the optimization algorithms iteratively search for the optimal gain parameters of the controllers of the power system, minimizing the ISE and hence reducing the frequency disturbances. This paper adopted IBBKH to tune the controller gains. The BBKH hybrid optimizer combines biogeography-based optimization (BBO) and the krill herd (KH) optimizer, utilizing the krill migration (KM) operator to improve the local search and exploitation abilities of the KH optimizer. The original BBKH optimization algorithm procedure consists of initialization where the solutions are randomly generated in the search space provided by the limits of the decision variables. Prior to initialization, the parameters like foraging speed (V_f), maximum speed (N_{max}), and maximum diffusion speed need to be defined to control the searching process along with common variables like number of krill and iterations. For each solution, the objective function value (provided in (2)) is calculated for updating mechanism. In the process of identifying an optimal solution of the problem, KM operator is crucial for enhancing the exploitation (local search) capability of the KH optimizer. The specific motion calculation and position update equations are found in [21] and are central to the performance of the BBKH algorithm. The original motion equation of KH operator is given by (3).

$$N_i^{new} = N^{max}\alpha_i + \omega_n N_i^{old} \quad (3)$$

In (3), the inertia weight (ω_n) is fixed value and is it updated in the modified BBKH to enhance its exploratory capabilities, making it an effective tool in avoiding local minima and ensuring a more reliable global solution.

$$N_i^{new} = N^{max}\alpha_i + \omega_{damp} N_i^{old} \quad (4)$$

In (4), the inertia weight (ω_{damp}) is a variable value. This mechanism increases the search ability of the algorithm. The modified BBKH is used to tune the gains of FOSC to minimize the error between the demand and generation.

4. RESULTS AND DISCUSSION

Simulations are performed on the model system (available in Figure 1) to evaluate the FOSC controller behaviour at various conditions starting from simple load perturbations to critical generation perturbations of the wind and solar units. The analysis is demonstrated to show the improvements of the FOSC over PI and PID controller to meet the requirements of AGC mechanism. For unique observations, IBBKH technique is used to tune the gains of the controllers with ISE as performance metric to record the changes in the frequency and tie-line power deviations. These optimal values of the controllers achieved by IBBKH algorithm are tabulated in Table 1 and results are provided in the following sub sections.

Table 1. Gains of the controllers and their optimal values using IBBKH

Gain parameter	PI	PID	FOPID	PI	PID	FOPID
k_p	-0.897	-0.897	-0.983	0.593	0.416	-0.232
k_i	-0.805	-0.779	-0.967	-0.753	-0.737	-0.935
k_d	--	-0.794	-0.892	--	-0.761	-0.933
α	--	--	-0.975	--	--	-0.907
β	--	--	0.992	--	--	0.937

4.1. Load perturbations in area 1 and area 2

A step change of 0.05 p.u. is applied in area 2, while the renewable generation and load variations in the other interconnected areas are at constant operating conditions. The resulting changes in area 1's frequency, reflecting the impact of this load, are illustrated in Figure 2(a). These results include the effects of both primary and secondary control loops. In Figure 2(b), the tie-line active power changes between the two areas, followed by Figure 2(c), which shows the frequency variations in area 2 are presented. The load change is negative, indicating a decrease in demand, which leads to an increase in system frequency above its nominal value. Consequently, the frequency deviation is negative, as evidenced in Figures 2(a) and 2(c).

A load of 0.05 p.u. is increased in area 1, and the corresponding frequency deviations are reported in Figure 2(d). This scenario is further analysed in Figures 2(e) and 2(f), which present the tie-line power disturbances and the frequency deviations in area 2, respectively, when a sudden load perturbation of 5% is initiated in area 1 at time t = 20 seconds. In this case, the perturbation in area 1 demand increases, resulting in positive frequency disturbances in both areas as shown in Figures 2(d) and 2(f). In both loading scenarios, the FOSC demonstrates superior performance compared to the conventional PI and PID controllers. The fractional order controllers achieve significantly lower peak overshoot, faster settling times, and reduced ISE values, as clearly presented in the figures. These results highlight the improved response provided by the FOSC over PI and PID controllers, making them a more effective solution for managing frequency deviations and tie-line power fluctuations in interconnected power systems.

4.2. Generation variations from wind and solar systems

To examine the impact of control mechanisms against the variations in wind and solar power inputs, generation changes from renewable sources are incorporated into this case study. Specifically, a generation perturbation of 0.1 p.u. (5% in each) is introduced in area 1 at time t = 10 seconds, simulating a sudden change in wind and solar power generation. During this scenario, all input changes in area 2, including both renewable generation and load variations, are maintained at zero to isolate the effect of the renewable perturbation in area 1. The study aims to assess the system's dynamic response to these changes, with a focus on the comparative performance of different controllers. The results clearly indicate that the proposed FOSC enhanced the AGC mechanism over the previous controllers, such as PI and PID, by reducing the frequency and tie-line power fluctuations triggered by both load and generation perturbations. This superior performance is measured with reduced overshoot during peak changes, less settling times, and lower performance metric values. Detailed results of this investigation are presented in Figure 3. Figure 3(a) illustrates the frequency deviations in area 1, showing how the fractional controller effectively mitigates the impact of the renewable generation changes. Figure 3(b) provides the power deviations in the AC link between the interconnected areas, highlighting the controller's ability to maintain power balance. Finally, Figure 3(c) shows the frequency variations in area 2, demonstrating the proposed controller's robustness in preserving system stability despite the disturbance in area 1. These findings underscore the FOSC effectiveness in allowing the system stability and reliability in the presence of green energy generation variability, making it an acceptable solution for recent power systems configurations with high renewable energy.

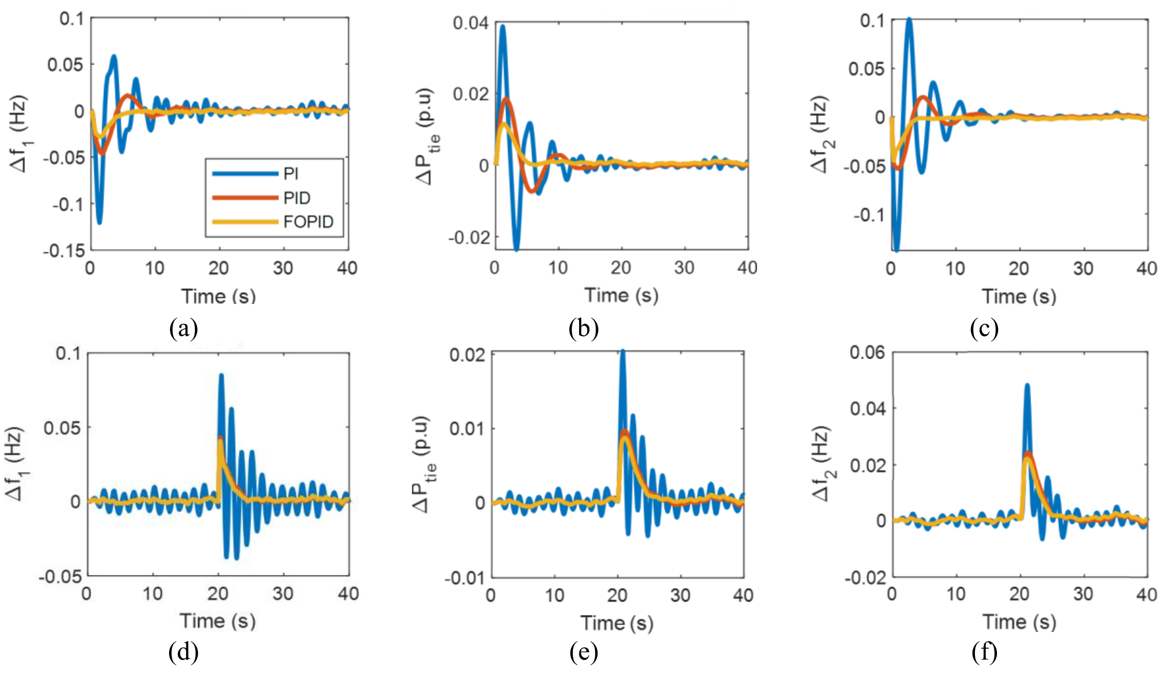
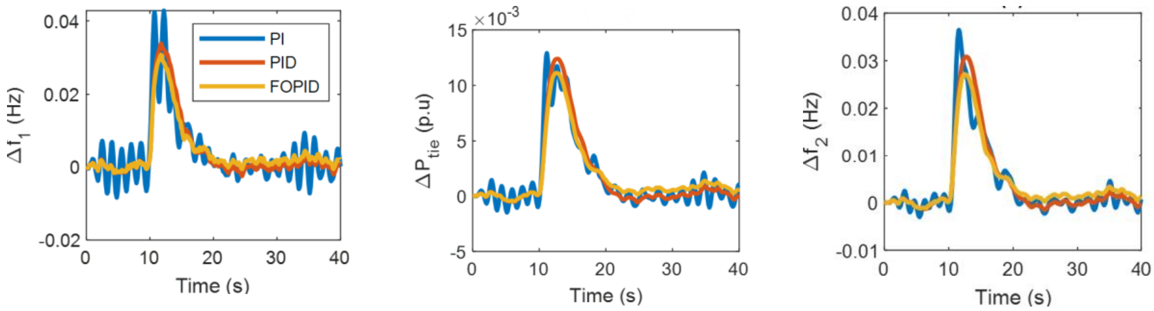


Figure 2. Results of load perturbations (LP): (a) area 1 frequency errors with respect LP of 1% in area 1, (b) active power errors w.r.to LP of 1% in area 1, (c) area 2 frequency errors w.r.to LP of 1% in area 1, (d) area 1 frequency errors w.r.to LP of 0.05 p.u. in area 1, (e) active power errors w.r.to LP of 5% in area 1, and (f) area 2 frequency errors w.r.to SLP of 5% in area 1



(a) (b) (c)

Figure 3. Results associated with generation disturbances: (a) area 1 frequency errors w.r.to GSC of 1% in area 1, (b) tie-line power errors w.r.to 1% of generation disturbance in area 1, and (c) area 2 frequency errors w.r.to GSC of 1% in area 1

4.3. Load-generation simultaneous changes (LGSC)

In this case study, a demand side change of 10% at t = 0 sec and a generation side change (GSC) of 0.05 p.u. from both wind and solar systems are introduced at t = 20 seconds to validate the behaviour of the controller. The performance is then compared against traditional PI and PID controllers under these challenging conditions. The comparative results of PI, PID, and FOSC controllers are presented in Figures 4, 5, and 6, which illustrate the frequency deviations in area 1, AC link power fluctuations between the areas, and frequency deviations in area 2, respectively. Each of these results reveals that the proposed controller significantly outperforms the conventional controllers in terms of maintaining system frequency in the allowable range. The FOSC not only effectively dampens frequency oscillations but also restores stability more rapidly in response to the disturbances. Specifically, Figure 4 shows a rapid return to the nominal frequency in area 1, indicating the controller's superior capability to manage local load variations, and similar observations in other cases reveal the robustness and reliability of the FOSC controller.

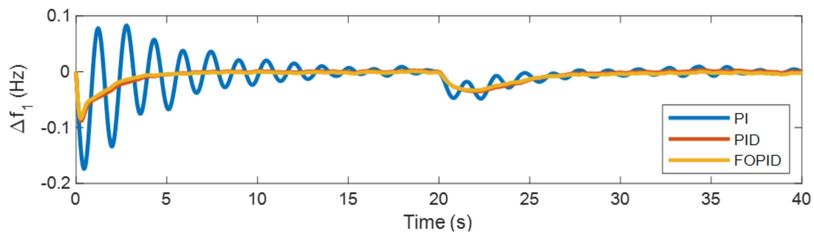


Figure 4. Area 1 frequency perturbations under LGSC

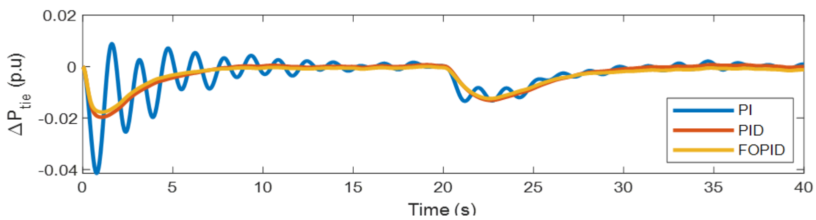


Figure 5. Power deviations in AC link under LGSC

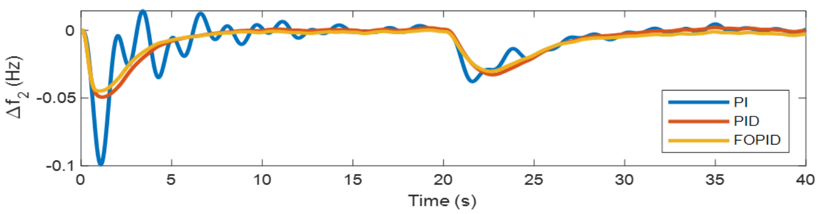


Figure 6. Area 2 frequency deviations under LGSC

4.4. Parameter sensitivities

All the controller gains were initially determined using the IBBKH algorithm under constant system parameters. However, in practical power systems, these parameters can vary significantly due to dynamic operating conditions, which may affect the performance of the controllers. To validate the robustness and effectiveness of the FOSC under such variable conditions, a sensitivity analysis is conducted on the test system, focusing on one key system parameter (system gain K_p). In normal operating conditions, the power system gain is set at 120, and the controller's performance has been optimized for this value using the IBBKH algorithm. For the sensitivity analysis, the power system gain is altered to 100, while maintaining the same set of optimal controller gains derived for the original system configuration. This allows for an assessment of the FOSC controller handles parameter variations without re-tuning. The results of this analysis are presented in Figure 7.

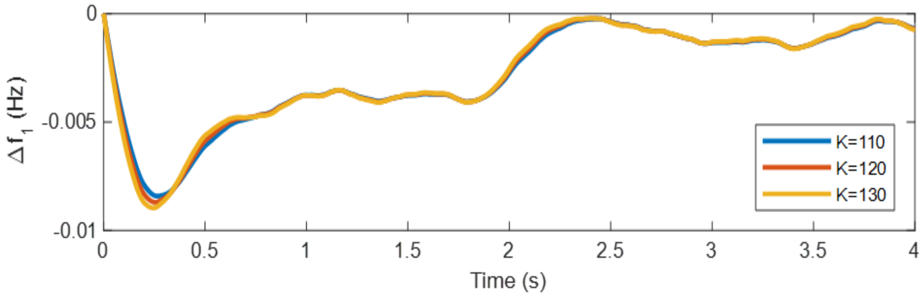
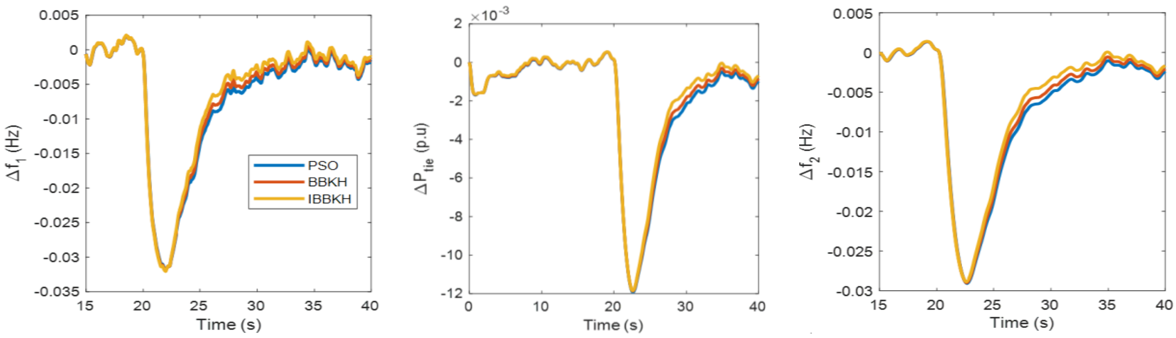


Figure 7. Area 1 frequency perturbations with K_p changes

5. COMPARISONS

The IBBKH technique is utilized to fine-tune the gains for PI, PID, and FOPID controllers during the synthetic disturbances. During simulation studies, these optimized values are applied to minimize power fluctuations and frequency deviations within the system. Moreover, the performance of the proposed tuning algorithm is compared against established methods such as PSO [4] and BBKH [10]. The results of these comparisons are illustrated in Figure 8. The frequency deviations of area-1 are presented in Figure 8(a), tie-line power deviations in Figure 8(b), and area-2 frequency deviations in Figure 8(c). These results are based on the optimal tuning values obtained from the best runs, highlighting the effectiveness of the technique.



(a) (b) (c)

Figure 8. Comparisons of the responses of PSO, BBKH, and IBBKH tuned controllers via: (a) area-1 frequency, (b) tie-line power, (c) area-frequency deviations during load changes

6. CONCLUSION

In order to reduce frequency disturbances in an interconnected power system that integrates solar and wind power, this study proposed a FOSC controller. When it comes to simple load perturbations, generation changes, and load and generation simultaneous variations, the suggested controller outperforms traditional PI and PID controllers. The efficiency of the suggested controller is demonstrated by sensitivity analysis performed on the test system. By identifying better tuning gains of the FOSC controller instead of the BBKH algorithm, the IBBKH optimizer improves the system's stability. Compared to the PSO, BBKH, the peak overshoot reduces to 8.3% and 7.84% respectively. The robustness of the scheme is evident from the parameter sensitivity performed in the study.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kukkamalla Kiran Kumar	✓	✓	✓	✓	✓	✓		✓	✓					
Gobinathan Balaji		✓				✓		✓		✓	✓	✓		
Kanta Rao Pedakota	✓		✓				✓			✓	✓	✓	✓	
Majahar Hussain Mahammad			✓	✓		✓			✓					✓
Syed Suraya				✓	✓		✓			✓				✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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