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A Combined Fractional Order Proportional Integral Derivative Controller for Automatic Generation Control Integrated with Wind and Small Hydropower Plant Using Crow Search Algorithm

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ABSTRACT

Automatic generation control (AGC) is essential for maintaining the frequency stability of power systems. However, designing an optimal controller for AGC remains a challenge. To overcome this deficiency, a novel two-degree-of-freedom-combined fractional order PID (2DOF-combined FOPID) controller is proposed and tested on two-area interconnected power systems consisting of reheat thermal and hydro units. The controller's performance is compared with conventional PID, FOPID, 2-DOF-PID, and 2DOF-FOPID controllers. The objective is to reduce the area control error. Optimal controller gain parameters are determined using the crow search algorithm (CSA) to minimize the integral time absolute error objective function. The dynamic behavior of the system is investigated in response to a 0.01 p.u. load disturbance in area-1. The designed controller's performance is also explored using wind integration and a CSA-optimized small hydropower plant. Results show that the 2DOF-combined FOPID controller outperforms the other controllers in terms of stability indices, including overshoot (Osh), undershoot (Ush), and settling time response (Ts) in the dynamic responses of the power system.

***Index Terms*—**Two-degree-of-freedom-combined fractional order proportional integral derivative controller, automatic generation control, crow search algorithm, fractional order controller, frequency bias tie-line control

I. INTRODUCTION

The intent of automatic generation control (AGC) in a decentralized power system is unceasing regulation of the real power output of the generator in response to aberrations in frequency and tie-line power due to fluctuating load demand [1]. The progress in electrical power consumption, besides the depletion of fossil fuels and their environmental impact, has made the power system networks complex due to the penetration of intermittent energy sources and necessitated the development of intelligent controllers. In AGC, the elementary control to mitigate frequency error due to a load disturbance is accomplished by the speed governor characteristics of the power system. However, ancillary control is essential for prolonged disturbances to regulate frequency and power exchanges within scheduled limits [2]. Solar Photo Voltaic (PV) systems extract clean power without any complex mechanisms and are suitable to be implemented for frequency control operations. However, low efficiency, power conversion complexity, and reduced inertia drive them to be prohibitively uneconomical. Wind power plants attained accelerated involvement to contribute to the demand and alleviate ruinous effects on the environment. The kinetic energy of the wind power plants assists the frequency control when a suitable controller is implanted to address the innate uncertainty and volatility of the wind [3]. Various researchers across the globe have conducted exhaustive research on AGC. In the recent literature, researchers have focused on improving the performance of AGC by designing advanced controllers, integrating renewable energy sources, and implementing novel optimization techniques [4, 5]. Fuzzy controllers are more adept at dealing with non-linearities, but they tend to be computationally intensive and particularly vulnerable to variations in the system dynamics, necessitating regular fine-tuning for peak performance [6, 7]. Classical control techniques to address the frequency instability are extensively deployed in traditional power systems owing to their simple structure, low cost, ease of control, and practical realizability [8, 9]. In spite of that, the parameters of parallel PID and its

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partial models are not satisfactory to deal with the uncertainty and non-linearities of modern power systems. Cascaded combinations of P, I, and D controllers are employed to enhance the controller's robustness to fluctuations of Renewable Energy Sources (RES) and load variations. Cascaded controllers improve sequential adjustability to attenuate the error prior to its transmission through the slave controller and simulate a smooth transient response and quick error settling [10]. Superior to one-degree-of-freedom controllers (1DOF), higher DOF controllers with more independent control loops enable noise attenuation and disturbance rejection, which aid in shaping and stabilizing the system response. Teaching Learning Based Optimization (TLBO) and differential evolution (DE) algorithms are applied to determine the optimal parameters of the 2DOF-PID in nonlinear power systems [11]. Assimilation of fractional order calculus to the integer-order PID controller enhances their freedom and flexibility of control by expanding the stability region. Fractional order PID (FOPID) has two additional fractional tuning knobs that precisely adjust the transient response of AGC systems, similar to the higher integral order controller [12, 13]. Two-degree-of-freedo m-Tilt integralderivative (TID) controllers are applied to enhance the performance of AGC systems with nonlinear conditions [14]. The performance of the 2DOF-FOPID is investigated to grant enhanced dynamic characteristics in an interconnected power system with diverse sources of generation [15]. Three-degree-of-freedom-F OPID is investigated in hybrid power systems with small hybrid power plants (SHPPs), and performance parameters for exceptional response are tuned by the hybrid slap swarm algorithm-simulated annealing (hSSA-SA) algorithm [16]. Normally, the controller parameters can be evaluated by either classical methods or soft computing methods. In the classical methods, the design of the optimal controller parameters is based on the direct synthesis of complex mathematical models, which adds more difficulties to the design process. On the other hand, the metaheuristic based optimization algorithms have found great concern in determining the appropriate controller parameters to address the frequency stability problem meticulously, thereby aiding the suitability and selectivity of the controller [17]. Therefore, the selection of an effective algorithm is indispensable to avoid various complications like slump, deathtrap in local minima, more iterations, and initial constraints of the controller parameters. The crow search algorithm (CSA) has improved global search capability over other metaheuristic algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), and differential evolution (DE) due to its superior balance between exploration and exploitation phases. The CSA has a faster convergence rate, is insensitive to the initial values, and is less prone to getting stuck in local optima [18]. Higher DOF controllers with more independent control loops enable noise attenuation and disturbance rejection, which aid in shaping and stabilizing the system response. TLBO and DE algorithms are applied to determine the optimal parameters of the 2DOF-PID in nonlinear power systems [11]. Assimilation of fractional order calculus to the integer-order PID controller enhances their freedom and flexibility of control by expanding the stability region. Fractional order PID has two additional fractional tuning knobs that precisely adjust the transient response of AGC systems, similar to the higher integral order controller [12, 13]. Two-degree-of-freedom-TID controllers are applied to enhance the performance of AGC systems with nonlinear conditions [14]. The performance of the 2DOF-FOPID is investigated to grant enhanced dynamic characteristics in an interconnected power system with diverse sources of generation [15]. Three-degree-of-freedom-FOPID is investigated in hybrid power systems with SHPP, and performance parameters for exceptional response are tuned by the hSSA-SA algorithm [16]. Normally, the controller parameters can be evaluated by either classical methods or soft computing methods. In the classical methods, the design of the optimal controller parameters is based on the direct synthesis of complex mathematical models, which adds more difficulties to the design process. On the other hand, the metaheuristic based optimization algorithms have found great concern in determining the appropriate controller parameters to address the frequency stability problem meticulously, thereby aiding the suitability and selectivity of the controller [17]. Therefore, the selection of an effective algorithm is indispensable to avoid various complications like slump, deathtrap in local minima, more iterations, and initial constraints of the controller parameters. The CSA has improved global search capability over other metaheuristic algorithms such as GA, PSO, and DE due to its superior balance between exploration and exploitation phases. The CSA has a faster convergence rate, is insensitive to the initial values, and is less prone to getting stuck in local optima [18].

Based on the literature survey and taking into consideration the advantages of higher DOF and fractional order controllers, a novel 2DOF-combined FOPID controller is validated over the 2DOF-FOPID, 2DOF-PID, FOPID, and PID controllers in an interconnected thermal hydropower system with governor dead band and dead zone nonlinearities. The scaling factors and gain parameters of all controllers are optimized by the CSA to enhance the performance of the system. The integral time absolute error (ITAE) cost function, which exhibits better settling times, is minimized using a CSA and evaluated to yield a smoother response.

The major contributions of this paper are as follows:

- To simulate a two-area hydrothermal power system with nonlinearities that incorporates wind turbine generators as well as to model optimal PID-based small hydropower plants (SHPP).
- To design a novel 2DOF-combined FOPID controller and compare its performance with the classical PID, FOPID, 2DOF PID, and 2DOF-FOPID controllers.
- To determine the optimal gains of the controllers implanted individually using the CSA.
- To investigate the dynamic performance of the proposed controller by injecting Step Load Perturbation (SLP), Random Load Perturbation (RLP) wind, and SHPP to aid the load disturbance in each area.
- To examine the robustness and sensitivity of the controller for system parameter variations.

In Section I, various load frequency control techniques available in the literature are discussed and the gaps are identified. The remaining content of the article is structured as follows: Section II gives the system description, and modeling of wind turbine generators and SHPP is discussed. In Section III, the controller structure is explored, and Section IV describes the CSA. In Section V, the simulation results and analysis of transient responses for different case studies are presented. The analyses in Section VI represent the robustness and sensitivity of the proposed controller. Section VII concludes the findings and proposes future scope.

II. DESCRIPTION OF THE SYSTEM MODEL

The dynamic load frequency control behavior of two-area hydrothermal power plants is studied along with the boiler dynamics (BD) and governor dead band nonlinearities. The plants have distinctive energy sources and are integrated with varying wind energy and SHPP units. The overall system is portrayed in Fig. 1 using the transfer functions of each component. A comparison study of the proposed model with the default system parameters [6] was carried out. The output signals Δf_1 and Δf_2 denote the frequency deviations in area-1 and area-2, respectively; ΔP_{tie} is the tie-line power deviation; and ΔP_L is the cumulative change in the system loading condition. The linear aggregation of frequency error and tie-line power is the actuating quantity and is called the area control error (ACE). When the ACE is made zero, it implies that both the errors in frequency and tie-line power are nullified. Area control error and frequency deviation serve as error input signals to the controllers. A small load of 1% (0.01) in area-1 is implemented to study the dynamic response of the system. The proposed controllers are executed in each area to investigate the controller's potential to achieve the predominant performance of the system. The 2DOF-combined FOPID controller is determined to be a predominant controller over the 2DOF FOPID, 2DOF PID, FOPID, and PID controllers. The performance of the controller is analyzed with wind penetration in both areas and a SHPP in area-2. The sensitivity of deviations increases with respect to time, i.e., small deviations from the nominal value after a long time period are more sensitive than a large deviation earlier. Hence, ITAE is adopted as an objective function concerning errors (Δf_1, Δf_2, and ΔP_{tie}) and time, as described in (1).

$$ITAE = \int_0^t t.\left(\left|\Delta f_1\right| + \left|\Delta f_2\right| + \left|\Delta P_{tie}\right|\right)dt \tag{1}$$

where t denotes the simulation time. The controller parameters are subjected to the bounds $K_{\min} \le K_i \le K_{\max}$ for $i = 1,2,3, \ldots, n$, where "n" is the designed variables. The values of the controller gains must be small enough to avoid generator disturbances during small offsets.

A. Wind Turbine Model

The wind turbine generator can be modeled as a first-order equation based on the frequency change and variations in the wind speeds and is given as [3]:

$$G_{WTG} = \frac{K_{WTG}}{1 + sT_{WTG}} \tag{2}$$

The output wind power is given by

$$P_{WTG} = C_p\left(\lambda,\beta\right)\frac{1}{2}\rho A v^3 \tag{3}$$

where v is the wind velocity, ρ is the air density, A is the swept area, C_p is the coefficient of performance, λ is the tip speed ratio, and β is the blade pitch angle (3).

B. Modeling of Small Hybrid Power Plants

Small hydropower can provide clean, renewable, and relatively inexpensive energy. An SHPP is implemented to enhance control and mitigate the deviation in frequency and tie-line power. The spillage water from the hydropower plant can be recycled to generate power using SHPP. In this work, a 20 MW SHPP is installed in area-2

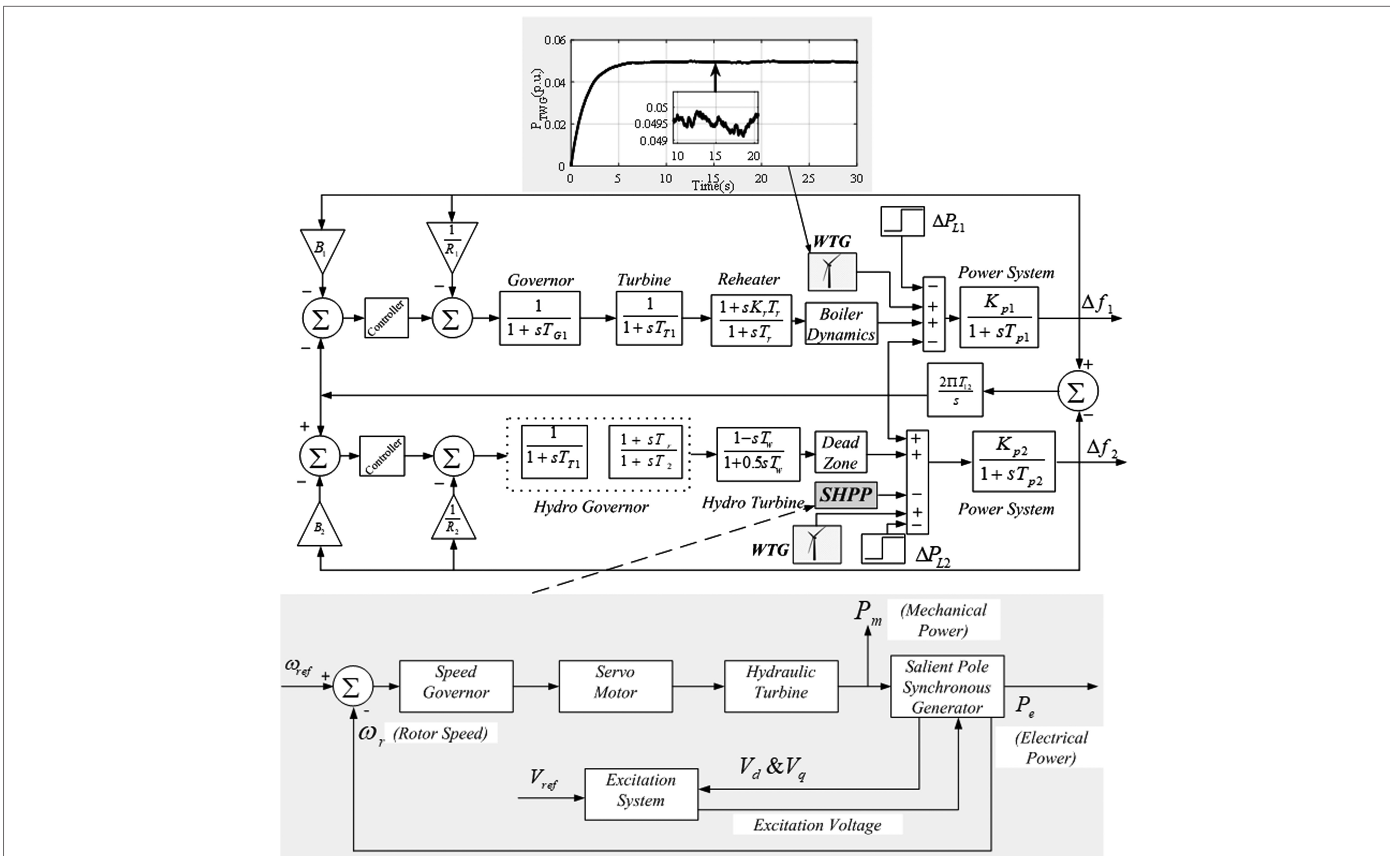

Fig. 1. Power system model.

of the power system. The mathematical modeling of SHPP includes the simulation of the speed governor, turbine, and voltage excitation system. The optimal PID controller is employed to regulate the speed governor valve for the generator and to minimize the error in output power and terminal voltage of the SHPP. The detailed modeling of SHPP is available in [16]. The block diagram is depicted in Fig. 1.

III. TWO DEGREE-OF-FREEDOM–COMBINED FRACTIONAL ORDER PID CONTROLLER

The system performance principally depends upon the design of the controller. So, the selection of optimal gains is a vital factor. A 2DOF-PID controller is superior to a conventional PID controller, furnishing better damping to the oscillations in the system over extensively varying load disturbances and system indices. The assimilation of fractional calculus to classical controllers enables additional flexibility and robustness for integer-order controllers. Fractional calculus suggests the peculiar FOPID controller is a neoteric approach. The non-integral (fractional) values of orders of the integration and differentiation (λ and μ) enable profound solutions to the errors. Riemann–Liouville proposed fractional order integration and differentiation given by (4) and (5).

$$ {}_{\alpha}D_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_{\alpha}^{t} (t-\tau)^{n-\alpha-1} f(\tau) d\tau \tag{4} $$

$$ {}_{\alpha}D_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_{\alpha}^{t} (t-\tau)^{\alpha-1} f(\tau) d\tau \tag{5} $$

where ${}_{\alpha}D_t^{\alpha}$ denotes is the fractional operator, α is the calculus order, n is the first integer greater than α, i.e. $n - 1 \le \alpha < n$, and $3(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t} dt$ is called the gamma function. Incorporation of fractional order to 2DOF-PID controller enhances the performance of the controller action in addition to noise attenuation and disturbance rejection. The structure of 2DOF-combined FOPID controller is shown in Fig. 2. The transfer functions of 2DOF-combined FOPID controller is described in (6–8).

$$ F(S) = \frac{(P_w k_p + D_w k_d) S^{(+)} + (P_w k_p NS \; + k_i S \;) + k_i N}{(k_p + k_d N) S^{(+)} + (k_p NS \; + k_i S \;) + k_i N} \tag{6} $$

$$ C_1(S) = \frac{(k_p + k_d N) S^{(+)} + (k_p NS \; + k_i S \;) + k_i N}{S \; (S \; + N)} \tag{7} $$

$$ C_2(S) = \frac{k_{dc} S^{(+)} + k_{pc} S \; + k_{ic}}{S} \tag{8} $$

where $F(s)$ is the fraction order prefilter reference signal. The weights are P_W and D_W. k_P, k_I, k_D, and N are the designed variables of PID and filter coefficient. The significant range of controller designed variables are chosen in the bounds of $0 \le k_P$, k_I, and $k_D \le 2$, $0 \le P_W$, $D_W \le 5$, and $10 \le N \le 300$. The system stability is preserved by virtue of fractional (non-integral) order, and it gives superior control to the classical PID controller. The application of FOPID in AGC minimizes the frequency deviations due to its additional flexibility in the design of the controller. The additional tuning of the gains provided by fractional values λ and μ supplemented by the CSA optimization technique for interconnected power systems provides better dynamic performance than the conventional controllers. The additional two DOFs provide quality control in tracking the set point and noise rejection. The series filter with a derivative term suppresses the disturbances and enhances the system stability.

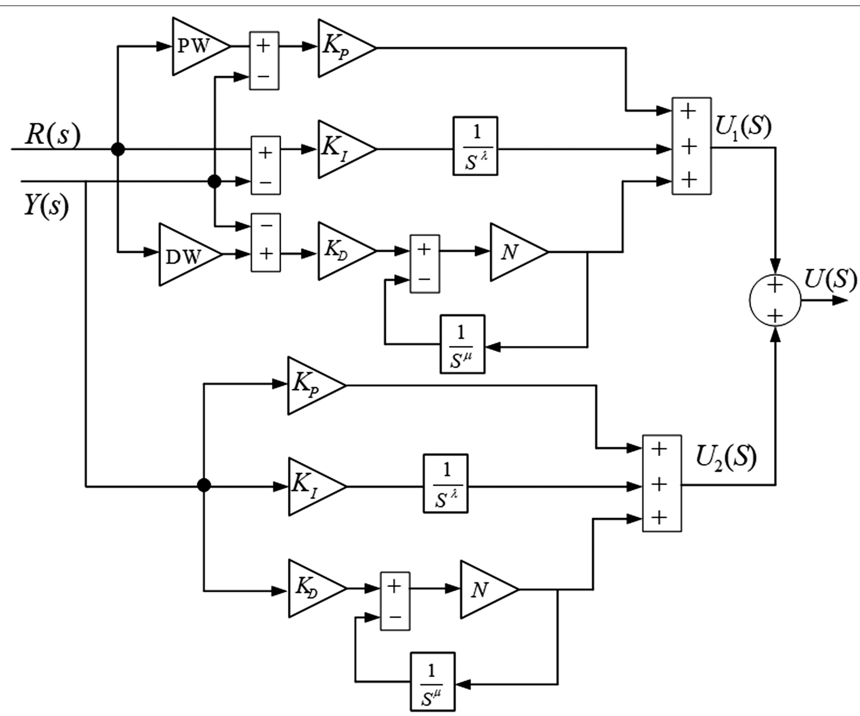

Fig. 2. 2DOF-combined FOPID controller structure. DOF, degree-of-freedom; FOPID, fractional order PID.

IV. CROW SEARCH ALGORITHM-BASED OPTIMIZATION TECHNIQUE

Crows have earned a reputation as some of the most intelligent creatures on the planet, and numerous studies have confirmed this notion. They have been observed displaying high levels of self-awareness and the ability to identify and utilize tools in various mirror experiments. Another interesting observation is that crows can recognize human faces, which allows them to take precautions against potential dangers. Additionally, they have been known to communicate in advanced ways and are capable of investigating where they have hidden their food before retrieving it. The reason for this behavior is linked to the fact that crows are social animals that use awareness probability (AP) to protect the location of their food caches [18]. Considering a region (boundary) of d-dimension containing a total of *N* crows, vector $X^{i,j}$ denotes the position of *i*th crow for j^{max} highest possible number of repetitions is given by (9).

$$X^{i,j} = \left[X_1^{i,1}, X_2^{i,2}, \ldots\ldots X_d^{i,j}\right] \tag{9}$$

Every crow has a mental map of its nesting territory. Hiding spot of crow i in the *j*th iteration is memorized as the current best position at $m^{i,j}$. Each crow has a distinct memory associated with the location of its most memorable event. Birds like the crow are always on the move as they look for new and better places to eat. Let us assume that crow i is interested in returning to its nest $m^{i,j}$ at iteration. At this point, crow k has decided to follow crow i to find out where the crow *i* has hidden food. There are two possible outcomes here.

Case (i): Crow i is unaware of crow k presence. Consequently, crow k will approach crow i hideout. Here's how to find crow i new position given by (10).

$$X^{i,j+1} = X^{i,j} + rand_i\, fl^{i,j}\left[m^{i,j} - X^{i,j}\right] \tag{10}$$

where $rand_i$ is random number in [0,1] and $fl^{i,j}$ denotes the flight length of crow i in the *j*th iteration.

Case (ii): Crow i is aware of crow k is chasing. Consequently, to preserve its cache, crow i fools crow k by travelling to a random location in the search space based on the AP of crow i in iteration j. When AP is low, it is employed for exploitation, and when it is high, it is used for exploration of the search space.

V. RESULTS AND ANALYSIS

The transfer function model of the two-area hydrothermal system along with BD and dead band nonlinearities is investigated in MATLAB 2016 with the parameters in Appendix A. Initially, 1% SLP in area-1 is enforced in scenario 1. The CSA technique is run for 200 simulations with a population of 50 and an AP of 0.1 to achieve the optimal controller gains portrayed in Table I. The settling times are evaluated for a tolerance band $\pm$ 0.005. The proposed controller is further investigated with 10% SLP in area-1 along with wind integration in both areas in scenario 2. Further in scenario 3, the SHPP is integrated into a hydro unit to enhance the transient behavior of the system. The significance of the proposed controller is extracted using simulation studies of the test system under generation uncertainties, random load disturbances, and parameter sensitivities portrayed in Figs 3–14 and Tables I–IV. In all scenarios, comparisons are made with the PID, FOPID, 2DOF-PID, and 2DOF-FOPID controllers.

A. Scenario 1: Investigation of System with 1% SLP in Reheat Thermal Plant

The CSA algorithm is employed to attain the optimal gains of the proposed 2DOF-combined fractional order controller, and its superiority over the 2DOF FOPID, 2DOF-PID, and PID controllers is portrayed in the dynamic response of the system with a 1% step load perturbation added in area-1 at time $t=0$ s. The controller parameters are tuned for optimal values to yield the optimal value of the cost function, and the gains are tabulated in Table I. The deviations

TABLE I. OPTIMAL PARAMETERS OF CSA-TUNED CONTROLLERS

		PW	*DW*	K_P	K_I	K_D	λ	μ	*N*
2DOF-combined FOPID	Area-1	0.8126	4.4182	2.0000	1.9822	1.1238	0.0010	0.4948	214.4194
		—	—	1.4483	1.5415	2.0000	0.9947	0.6285	251.2513
	Area-2	1.0843	2.1512	0.0221	0.1953	0.8554	0.0010	0.1549	300.0000
		—	—	0.8831	0.3489	1.9199	0.3788	0.0010	76.9502
2DOF-FOPID	Area-1	4.8785	3.8002	1.5434	1.8719	1.5738	0.9999	1.0000	181.5887
	Area-2	1.0812	0.4680	0.0016	2.4015	0.4605	0.0083	0.7541	90.9575
2DOF-PID	Area-1	5.0000	0.0010	2.0000	2.0000	1.6869	—	—	10.00
	area-2	0.3004	0.6895	1.2931	0.0010	1.5273	—	—	300.00
FOPID	Area-1	—	—	2.0000	2.0000	2.0000	1.0000	1.0000	300.0000
	Area-2	—	—	0.0010	2.0000	0.8633	0.0010	1.0000	10.0000
PID	Area-1	—	—	2.0000	2.0000	1.8591	—	—	—
	Area-2	—	—	0.0010	0.0010	0.8610	—	—	—

CSA, crow search algorithm; DOF, degree of freedom; FOPID, fractional order PID.

of the output variables from their scheduled values are portrayed in Figs 3–5 for the system considered. The performance specifications to evaluate the finest responses, such as the peak overshoot, undershoot, and settling time when a load disturbance of 20 MW is applied in area-1 are reported in Table II. Due to connectivity, area-2 shows modest frequency shifts (Fig. 4). The obtained results

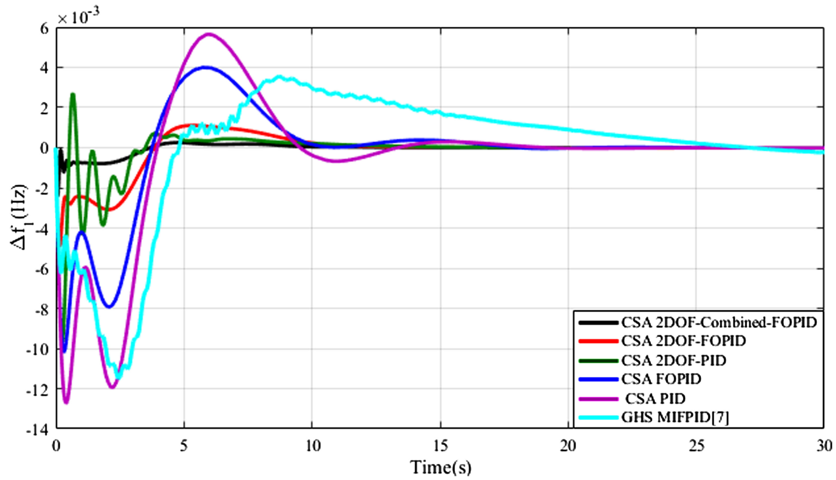

Fig. 3. Frequency deviation in area-1 (Hz).

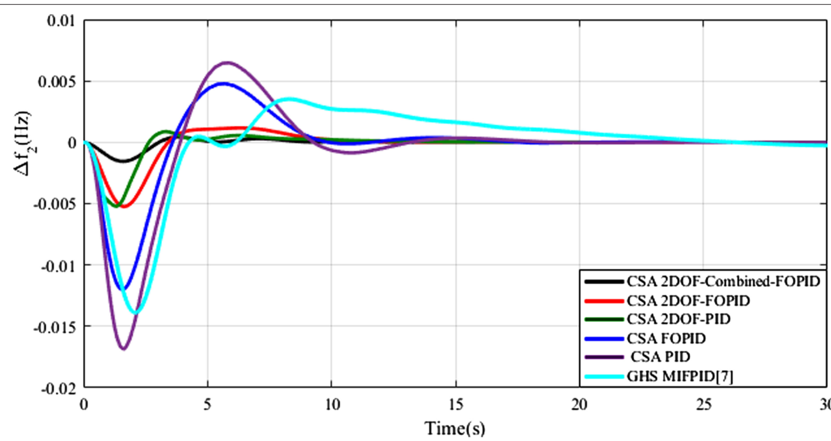

Fig. 4. Frequency deviation in area-2 (Hz).

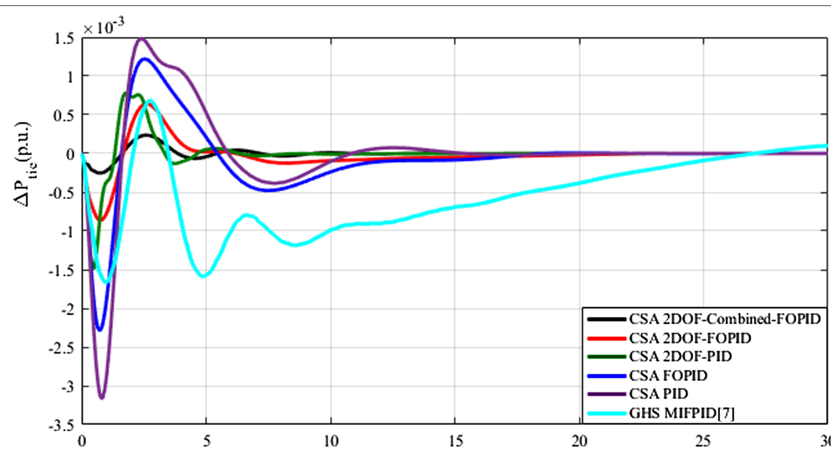

Fig. 5. Tie-line power deviation (p.u.).

TABLE II. PERFORMANCE RESPONSES OF THE SYSTEM WITH VARIOUS CONTROLLERS OPTIMIZED BY CSA

	Change in Frequency Area-1 (Hz)			**Change in Frequency Area-2 (Hz)**			**Change in Tie-Line Power(p.u.)**			**ITAE**
2DOF-combined FOPID	Osh	Ush	Ts	Osh	Ush	Ts	Osh	Ush	Ts	
	0.0003	**–0.0025**	**2.8034**	**0.0002**	**–0.0003**	**4.908**	**0.0002**	**–0.0003**	**4.908**	**0.0026**
2DOF-FOPID	0.0011	–0.0049	8.6222	0.0012	–0.0052	8.6222	0.0006	–0.0009	14.7402	0.6062
2DOF-PID	0.0028	–0.0097	4.7974	0.0009	–0.0052	6.7426	0.0008	–0.0015	5.71	1.9328
FOPID	0.004	–0.0102	8.9517	0.0048	–0.012	8.9517	0.0012	–0.0023	16.3106	2.3464
PID	0.0056	–0.0127	11.6079	0.0065	–0.0168	11.6079	0.0015	–0.0032	13.3365	2.6000
GHS-MIFPID [7]	0.3963	–0.1159	20.8658	0.0691	–0.0240	29.5224	0.0024	–0.0061	41.0284	–

CSA, crow search algorithm; DOF, degree of freedom; FOPID, fractional order PID; ITAE, integral time absolute error.

substantiate the improved competence of the proposed controller over other conventional control approaches. The combined non-integral controller not only handles frequency oscillations better than traditional controllers, but it also handles changes in tie-line power better. This is true for both traditional hydro and thermal generators with nonlinearities.

B. Scenario 2: Investigation of System with High Wind Penetration in Both Areas

Furthermore, the performance of the combined controller is investigated in the presence of an 85 MW wind turbine generator implanted in both the control areas to assist the system response subjected to 10% load disturbances. The volatility of the wind disturbances is considered along with the step load disturbance to exploit the behavior of the controller in nonlinear conditions. The dynamic responses of the system in the resilient circumstances are displayed in Figs 6–8. The gain values of the controllers for this scenario, conceding the minimum value of the objective function, are shown in Table III. The combined controller outperforms other controllers in damping frequency oscillations in wind-integrated circumstances, regardless of the strength and variations of the wind. It is evident from the results that the combined controller in the secondary control loop of the producing units reduces power oscillations on the tie lines to a great extent, especially when compared to the 2DOF-FOPID controller. The ITAE values are 0.0011, 0.2346, 0.6062, 2.6000, and 10.009, respectively, for each controller.

C. Scenario 3: Investigation of System with High wind Penetration in Both Areas and Small Hydropower Plant in Hydel Plant

In the third case, an SHPP is installed in area-2 along with wind and step load perturbations to utilize the spillage water of the hydropower plant. The dynamic model of the 25 MVA, 20 MW, 11 KV, 60 Hz three-phase salient pole synchronous generator (SHPP) was developed in MATLAB/Simulink. The output power is regulated using PID controllers to regulate the deviation in frequency-controlled active power and voltage-controlled reactive power. A 0.1 p.u. sudden load is connected to reciprocate the SHPP generation at 0 s. The system responses are measured, and a comparative analysis is presented with and without the contribution of SHPP by various controllers, as shown in Figs 9–11. A fair observation is illustrated to determine the supremacy of the 2DOF-combined FOPID controller optimized by the CSA algorithm and minimizing the transiency (undershoot, overshoot, and settling time) of the system. The response parameters and ITAE of the 2DOF FOPID controller are minimal. Settling times are evaluated within a tolerance band of ±0.005%.

The contribution of Wind Turbine Generator (WTG) and SHPP is demonstrated in Fig. 12. Initially, no load is added to the system.

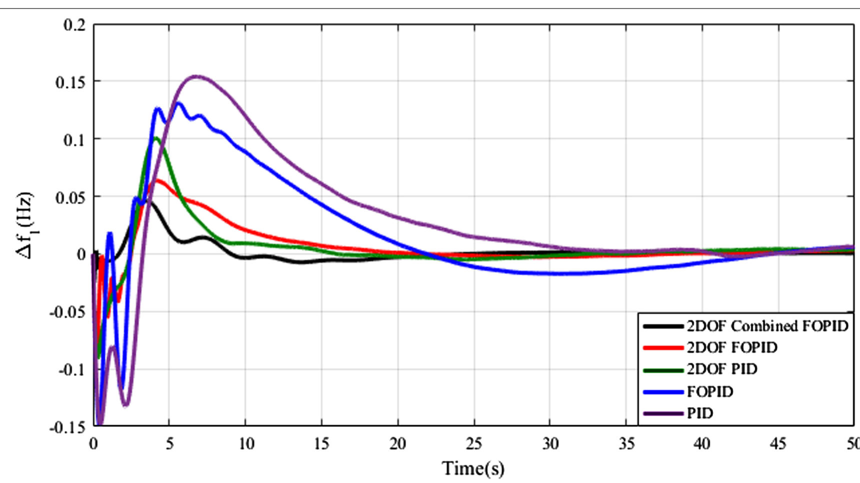

Fig. 6. Frequency deviation in area-1 with wind penetration (Hz).

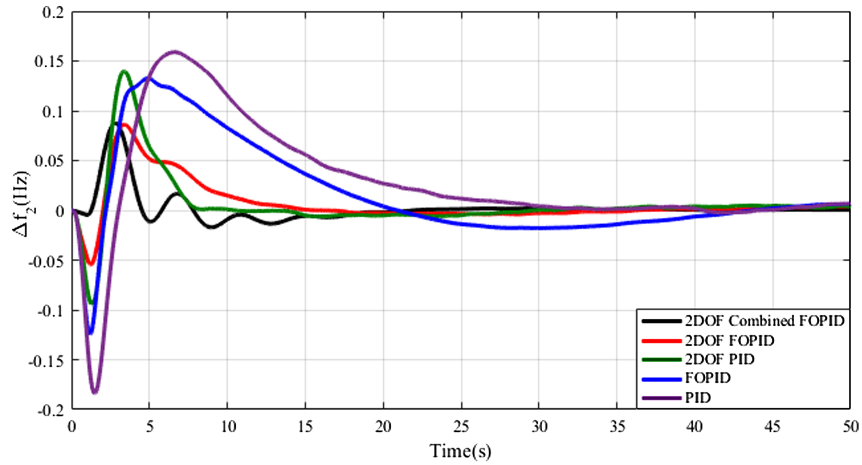

Fig. 7. Frequency deviation in area-2 with wind penetration (Hz).

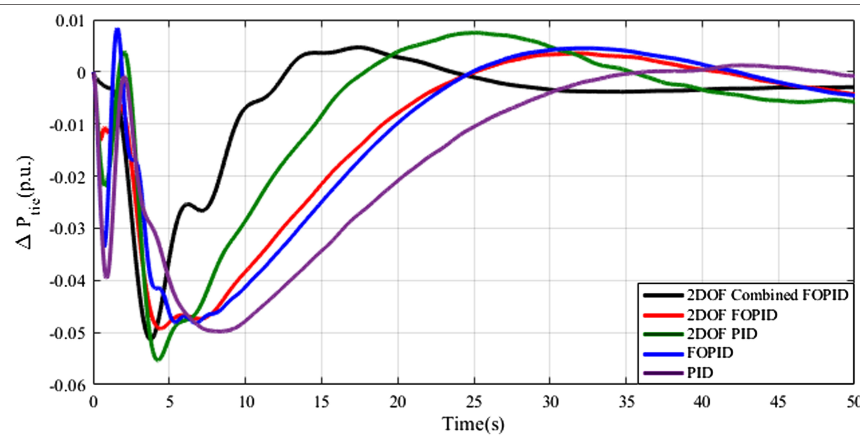

Fig. 8. Tie-line power deviation with wind penetration (p.u.).

TABLE III. OPTIMAL PARAMETERS OF CSA-TUNED CONTROLLERS UNDER VARIABLE WIND CONDITION IN BOTH AREAS

		PW	DW	K_P	K_I	K_D	λ	μ	N
2DOF-combined FOPID	Area-1	0.4367	3.7702	2.0000	1.5221	1.7717	0.2867	0.7038	267.6523
		—	—	0.4833	1.9700	2.0000	0.1094	0.3173	182.5158
	Area-2	0.2010	3.9982	1.4175	1.2387	0.8384	0.1816	0.6971	300.0000
		—	—	2.0000	0.9358	1.3829	0.0010	0.2805	273.3482
2DOF-FOPID	Area-1	1.0020	3.4006	1.9170	0.8032	1.3883	0.8423	0.8769	10.0000
	Area-2	1.0068	0.3546	0.7719	1.8300	0.0010	0.1462	0.6800	95.9021
2DOF-PID	Area-1	1.1200	0.4952	1.5835	1.0554	1.2166	—	—	167.289
	Area-2	3.3750	4.0403	1.9896	0.0178	0.5914	—	—	246.5221
FOPID	Area-1	—	—	1.9855	1.5397	2.7726	0.5398	0.5100	142.5720
	Area-2	—	—	2.8228	0.0677	0.5442	0.7713	0.6168	60.9925
PID	Area-1	—	—	1.6574	0.2688	1.3078	—	—	—
	Area-2	—	—	1.9948	0.0188	0.0056	—	—	—

CSA, crow search algorithm; DOF, degree of freedom; FOPID, fractional order PID.

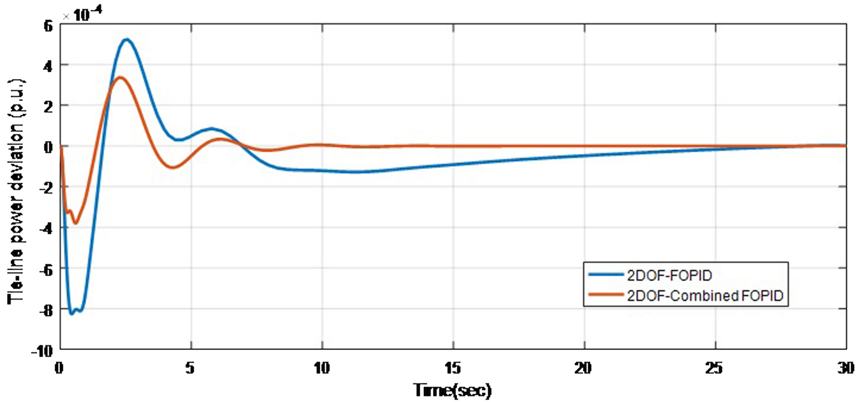

Fig. 9. Frequency deviation in area-1 with wind and SHPP (Hz).

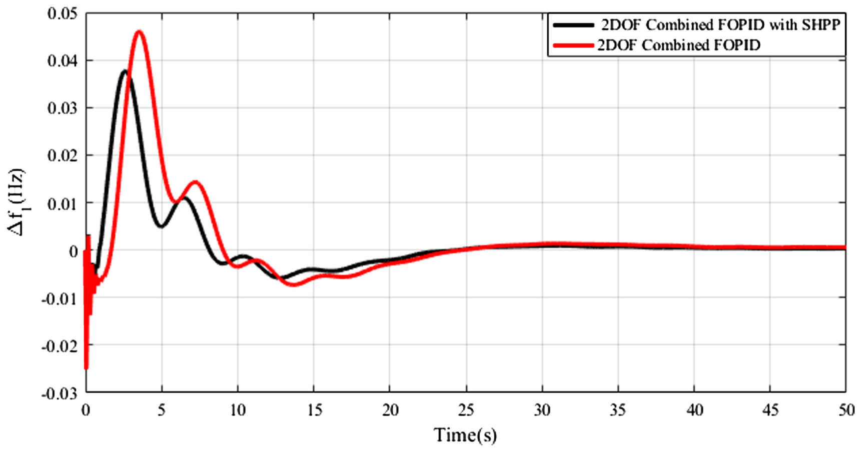

Fig. 10. Frequency deviation in area-2 with wind and SHPP (Hz).

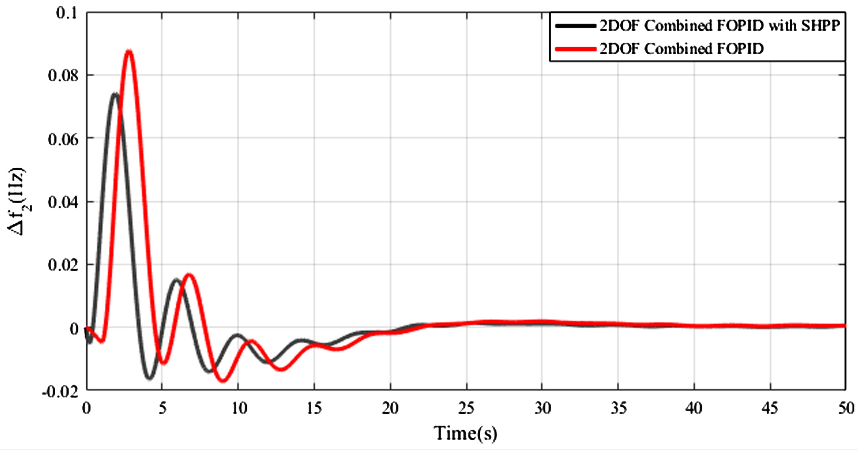

Fig. 11. Tie-line power deviation with wind and SHPP (p.u.). SHPP, small hydropower plant.

It is observed that the power generated by renewable energy sources is utilized by the thermal and hydropower plants to maintain a balance in generation. However, at $t=25$ seconds, a sudden load of 0.2 p.u. is introduced in area-1. The thermal and hydro generators immediately supplied the load to address the AGC. To analyze the performance of the renewable energy generation in isolated mode, the applied load is shared by all units at $t=0$ s. However, at $t=35$ s, the thermal and hydro generators are disconnected from the grid. The total load is then distributed to WTG and SHPP, as illustrated in Fig. 13.

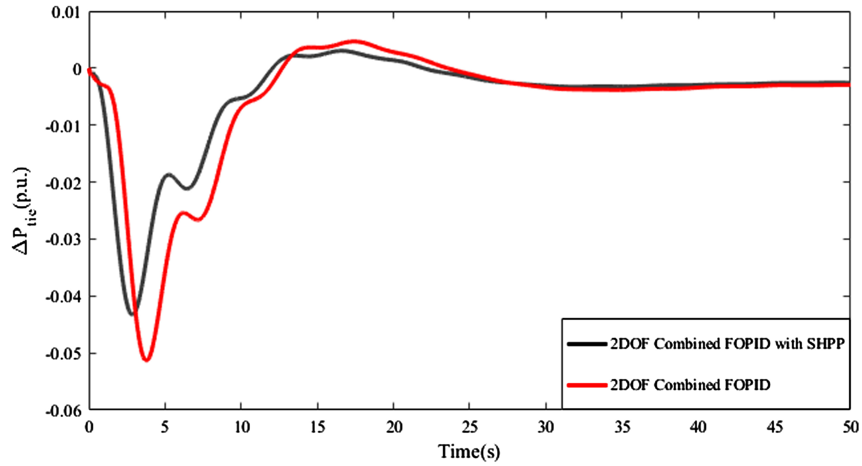

Fig. 12. Contribution of SHPP and WTG. SHPP, small hydropower plant.

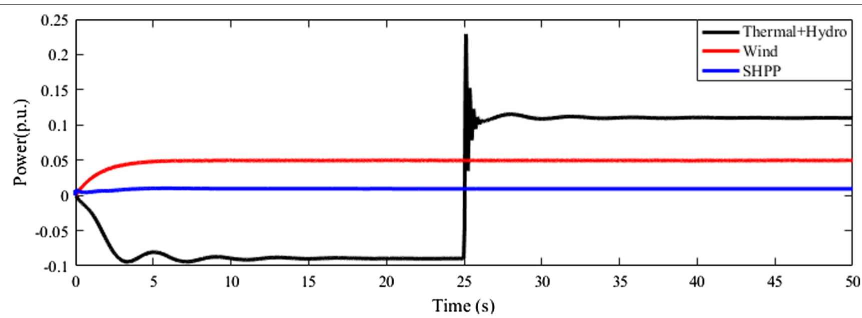

Fig. 13. Dynamic response of power RES in isolated mode.

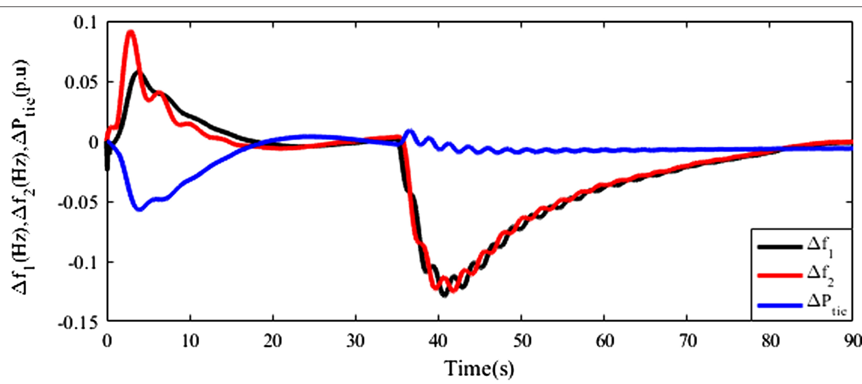

Fig. 14. Tie-line power deviations (p.u.).

VI. ROBUSTNESS AND SENSITIVITY ANALYSIS

The suggested 2DOF-combined FOPID PID controller and CSA algorithm have been demonstrated as effective and stable techniques for achieving superior performance in a two-area hydrothermal system, with deviations of frequency and tie-line power being observed. However, in order to ensure the robustness of these techniques, it is necessary to test them under various system conditions. This section includes a brief comparative analysis between CSA-based controllers in order to verify their robustness. The system parameters (Appendix A) were varied widely to confirm the system's robustness. A fluctuating load of varying magnitudes, as shown in Fig. 14, was applied, and the resulting tie-line power deviations using the proposed techniques were observed. The robustness of the system was evaluated based on mean and standard deviation values, which are presented in Table IV. The proposed 2DOF-combined approach was found to be more robust and sensitive, with lower mean and standard deviation values, indicating its superiority over the other techniques tested.

VII. CONCLUSION

This research proposes a novel approach to enhancing AGC in a thermal hydropower system through a 2DOF-combined FOPID controller. The gain parameters of the controller are evaluated using CSA,

TABLE IV. STATISTICAL STUDY OF SENSITIVE ANALYSIS OF THE SYSTEM BY ALTERING THE SYSTEM PARAMETERS

Controller	Statistical Parameter	Overshoot			Undershoot (Ush)			Settling time (Ts)		
		Δf_1 (Hz)	Δf_2 (Hz)	ΔP_{tie} (p.u.)	Δf_1 (Hz)	Δf_2 (Hz)	ΔP_{tie} (p.u.)	Δf_1 (Hz)	Δf_2 (Hz)	ΔP_{tie} (p.u.)
2DOF-combined FOPID	Mean value	0.0003	0.0005	0.0002	−0.0025	−0.0015	−0.0003	2.6096	3.4899	5.6999
	Nominal value	0.0003	0.0004	0.0002	−0.0025	−0.0016	−0.0003	2.8034	2.6621	4.9080
	Standard deviation	0.0001	0.0001	0.0001	0.0004	0.0004	0.0001	0.0003	0.0004	1.2640
2DOF-FOPID	Mean value	0.0011	0.0013	0.0006	−0.0050	−0.0052	−0.0009	8.5269	8.5000	13.5276
	Nominal value	0.0011	0.0012	0.0006	−0.0049	−0.0052	−0.0009	0.0008	0.0015	5.7101
	Standard deviation	0.0003	0.0004	0.0002	0.0007	0.0013	0.0002	0.0015	0.0006	1.3142
2DOF-PID	Mean value	0.0030	0.0097	6.4494	−0.0010	−0.0053	−5.9347	0.0014	0.0016	5.6528
	Nominal value	0.0028	0.0097	4.7974	−0.0009	−0.0052	6.7426	8.6222	8.6222	14.7402
	Standard deviation	0.0011	0.0027	1.7683	0.0013	0.0014	1.5833	0.0022	0.0032	2.3821
FOPID	Mean value	0.0039	0.0103	10.0845	−0.0046	−0.0120	−9.4423	0.0012	0.0023	15.0402
	Nominal value	0.0013	0.0033	2.5035	−0.0015	−0.0103	−2.7417	0.0004	0.0008	3.2294
	Standard deviation	0.0017	0.0028	2.2264	0.0013	0.0031	1.8384	0.7250	0.7642	4.7446
PID	Mean value	0.0055	0.0128	11.1567	−0.0063	−0.0142	−11.5268	0.0015	0.0032	12.7354
	Nominal value	0.0040	0.0102	8.9517	−0.0048	−0.0120	−8.9517	0.0012	0.0023	16.3106
	Standard deviation	0.0056	−0.0127	11.6079	0.0065	0.0168	11.6079	0.8506	1.3389	13.3365

DOF, degree of freedom; FOPID, fractional order PID.

known for its exceptional abilities in exploration and exploitation balance.

- Simulation results show that the proposed controller outperforms other controllers in terms of overshoot, undershoot, and settling times under different operational conditions with fluctuating renewable energy generation and load disturbances.
- To further validate its capability, volatile wind generation is introduced in both areas, with 10% SLP injected in area-1. The proposed combined controller is demonstrated to be superior in damping frequency and tie-line power oscillations.
- Additionally, nonlinear PID-based SHPP is implemented in area-2 to assist with the frequency and tie-line power deviations with the proposed 2DOF-combined FOPID controller.
- The robustness and stability of the proposed controller are evaluated with extensive changes in system parameters and random load changes; the results show stable performance at ±50% parameter variation.

The proposed CSA-optimized 2DOF-combined FOPID controller with SHPP shows fine outcomes in terms of system performance parameters. In this paper, the speed control and voltage regulation of SHPP are based on a classical PID controller. In future research, a detailed study of SHPP using intelligent fuzzy and machine learning techniques can be proposed using enhanced CSA algorithms.

Appendix A: Power system parameters

T_{G1}= 0.08 s; T_{T1}=0.4 s; $K_{P1}=K_{P2}=120$ Hz/p.u. MW; $T_{P1}=T_{P2}=20$ s; $R_1=R_2=2.4$ Hz/p.u. MW; $B_1=B_2=0.425$ p.u. MW/Hz; $T_{12}=0.0707$; $T_w=1$ s; $T_r=10$ s; K_r= 0.33; T_1=48.7 s; $T_2=0.513$ s.

Appendix B: SHPP parameters

$P_{rh}=20$ MW rated/base power; $T_c=0.173$; $T_b=0.06$; $K_A=300$; $T_A=0.01$; $K_F=0.1$; $T_F=0.001$; $T_E=0.01$; $T_P=0.05$; $K_S=1$; $T_G=0.2$; $R_P=0.04$; $R_T=0.4$; $T_R=5$; $T_W=2.67$; $\beta=2.5$; $A_\tau=1$.

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