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Implementation of Modified Whale Optimization Algorithm in Two-Degree-of-Freedom Fractional Order–Fuzzy-Proportional-Integral-Derivative Controller for Automatic Generation Control in a Multi-Area Interconnected Power System

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ABSTRACT

Any mismatch of power demand and power generation in an interconnected electrical power system causes deviances in tie-line power and frequencies. To overcome this issue, an automatic generation control system equipped with intelligent controllers is used in the power system. This study presents a maiden write-up on a two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative (2DOF-FO-FuzzyPID) controller employed in an interconnected system with different nonlinearities. The controller proposed along with conventional controllers has its gains optimally enumerated by the application of modified whale optimization algorithm (MWOA). Besides this, the potency of the MWOA algorithm over WOA algorithm is examined through some popular benchmark functions. The superior transient response yielded by 2DOF-FO-FuzzyPID controller over PID and fractional-order proportional-integral-derivative controllers of the proposed test system is evaluated. Further, the effectiveness of the projected controller is evaluated by taking the system's nonlinearities and abrupt load perturbation, which acknowledges the robustness of the controller. In spite of these attributes, the stability and relative stability of the 2DOF-FO-FuzzyPID controller is determined in the frequency domain.

***Index Terms*—**AGC, 2DOF-FO-FuzzyPID controller, FOPID controller, Frequency domain analysis, modified whale optimization algorithm

I. INTRODUCTION

Due to ever-increasing demand for electricity, electrical power systems are becoming larger and more complex. Fast load changes in such interconnected systems lead to substantial degradation in the performance of system. So, it is essential to maintain equality between total power generation and total power demanded. Any incompatibility between power demanded and power generated results in frequency alteration from the nominal value of the system [1], thereby affecting the stability of system. Automatic generation control (AGC) is incorporated with a primary objective to equalize total generated power to that of the demanded load. Intense deviations beyond the prescribed limit [2] in frequencies and tie-line powers may lead to partial or complete collapse of the system which is taken care of by the load frequency controller (LFC). Load frequency controller is employed as an integral component of AGC in an interconnected electrical power system [3].

To preserve the stability and smooth operation of the system, it is highly essential to keep a zero steady-state error of tie-line powers and between the area frequencies. To address these aforementioned issues, the design and structure of the controller play a key role. For AGC, the most commonly used controller is proportional-integral-derivative (PID) controller which is employed extensively owing to its simple structure and implementation. Elgerd et al. [4] demonstrated the frequency control mechanism employing integral controller only. A critical study on AGC in different kinds of power system employing PID controller and its varieties is given in [5, 6]. Besides PID controller, a two-degree-of-freedom concept is entitled, namely, 2-DOF-PID controller which is employed in [7] for the study of LFC in a two-area system. To upgrade the performance of a PID-based system with a better degree of flexibility, noninteger integrodifferential operator is

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subjected to find a fractional-order PID (FOPID) controller used in [8, 9] and to investigate the issues related to AGC in multi-area system. In [10-13], some researchers used few classical adaptive controllers for the study of LFC. However, to make the system dynamics faster and curtail the area control error sooner under the influence of uncertainties and parameter variations, fuzzy logic controller is embodied with PID controllers [14-16]. Cascaded fuzzy fractional order PI–FOPID (CFFOPI–FOPID) controller, fuzzy-fractional order-integral-derivative (FFOID) controller with ultra-capacitor (UC) energy storage system, and optimal cascade-fuzzy-fractional order-integral-derivative with filter (CF-FOIDF) controller used for two-area thermal and hydro-thermal power have a detailed discussion in Arya [17-19] with the controller parameters evaluated using stochastic imperialist competitive algorithm (ICA). Besides, these researchers are focusing on the widespread model-free controllers that are based on fuzzy neural networks (FNNs) and fuzzy logic system (FLSs) applied in [20-24]. But, in this study, a maiden control strategy is adopted by conglomerating the non-integer operator with a fuzzy PID controller facilitating a 2DOF.

In order to design a controller, various computational techniques such as hybrid-Particle Swarm Optimization (PSO) [25], Genetic Algorithm (GA) [26], Teaching Learning Based Optimization (TLBO) [24], Artificial Bee Colony (ABC) algorithm [16], ICA [5], Arya [17-19], sine cosine algorithm [27], etc. are employed to enumerate the gains and scaling factors. The same computational technique cannot be applicable to all types of problems, so new computational algorithms are developing. Whale optimization algorithm [28] technique is applied to the concerned system to evaluate the gains of PID, FOPID, and 2-DOF-FOPID. To enhance the stability of the proposed system, the WOA is modified and applied for designing the gains of 2-DOF-Fuzzy-FOPID controller with objective function as Integral Time Absolute Error (ITAE).

Here, designing of 2-DOF-Fuzzy-FOPID controller optimized by modified WOA (MWOA) to take on the issues related to AGC in two-area, four-unit interconnected power system is articulated. This study contributes majorly as follows:

1. Modeling of a two-area, four-unit hydro-thermal power system with and without nonlinearities (generation rate constant (GRC) and governor dead band (GDB)) is done in MATLAB/SIMULINK.
2. Proposed model employing PID, FOPID, 2-DOF-FOPID, and 2-DOF-Fuzzy-FOPID controllers is studied where gains are enumerated by subjecting ITAE objective function.
3. Whale optimization algorithm is applied to design PID, FOPID, and 2-DOF-FOPID controllers.
4. Whale optimization algorithm is modified and its efficacy is examined by using some popular benchmark functions.
5. Modified whale optimization algorithm is applied to design the 2-DOF-FO-FuzzyPID controller to elevate the response of frequency and tie-line power deviation.
6. Stability analysis of the proposed model is carried out by frequency domain (Bode plot).
7. By subjecting random step load change to area-1, robustness of 2DOF-Fuzzy-FOPID controller is achieved.

This study is organized into different sections with Section I covering the introduction and literature review, Section II describing the power system (PS) under examination, Section III introducing the proposed controller and the optimization technique to be used, Section IV containing the results of simulation and their analysis, and Section V presents the conclusion and future avenues of the work.

II. SYSTEMS INVESTIGATED

The two-area, four-unit electrical PS consisting of thermal and hydro units with nonlinearity is pictorially given by a basic block diagram as depicted in Fig. 1. The said system composes of multivariable, complex structure as shown by various blocks. The governor speed regulation constants are represented as R_1 and R_2, frequency bias factors are represented as B_1 and B_2, and T_{g1} and T_{g2} represent the governor's time constants. K_{PS} is the PS gain, PS time constant (in seconds) is represented by T_{PS}, variation in load demand (in p.u.) is represented as ΔP_{D1}, frequency deviations (in hertz) in areas 1 and 2 represented as Δf_1 and Δf_2, and ΔP_{tie} is a deviation in tie-line power (in p.u.). Synchronization constant is represented as T_{12}. Participation factor (PF) for all the power plants is considered as 0.5. The GDB for thermal and hydro generators is taken to be $\pm$0.05% and $\pm$0.06%, respectively, and similarly, GRC is taken to be $\pm$3% and $\pm$6% p.u./s, respectively.

III. PROPOSED OPTIMAL CONTROLLERS

A. Proportional-Integral-Derivative Controller

Proportional-integral-derivative controllers are utilized hugely in industries, owing to its simple structure comprising three modes of action namely proportional (P) mode, integral (I) mode, and derivative (D) mode. Block diagram of PID is presented in Fig. 2. If appropriate control action is taken, there will be proper response aiding in the reduction of errors in process output. The output of PID controller of area 1 in time domain is described mathematically as:

$$u_1(t) = G\_P_1 e_1(t) + G\_I_1 \int_0^t e_1(t)\,dt + G\_D_1 \frac{de_1(t)}{dt} \tag{1}$$

Here, G_P_1, G_I_1, and G_D_1 are the controller's P, I, and D gains, respectively, of area 1.

B. Fractional-Order Proportional-Integral-Derivative Controller

Conventional PID controller lacks satisfactory performance when used in complex power systems. In order to tackle issues associated with AGC with improved performances, optimally designed FOPID controller by Sandhya [29] and Subhadra [30] is preferred. Here, another two parameters, namely, fractional derivative order (μ) and fractional integral order (λ), are incorporated in addition to the PID controller gains. The approach (as shown in Fig. 3) leads to a change in the point-based control scheme to plane-based scheme, i.e., the FOPID controller can operate anywhere in the whole area of the plane defined by the values of λ and μ, whereas PID operates at predefined points. With this type of flexibility, it is quite easy to stabilize both linear and nonlinear systems. The structure of FOPID controller is shown in Fig. 4. In fractional order controller, fractional derivative order (μ) and fractional integral order (λ) are taken as nonintegers. The fractional calculus for differentiation and integration in the form of an operator is given in (2).

$$a^{D_t^w} = \begin{cases} \dfrac{d^w}{dt^w}, w > 0 \\ 1, w = 0 \\ \displaystyle\int_a^t (d\tau)^{-w}, w < 0 \end{cases} \tag{2}$$

Caputo form of (2) is described in (3).

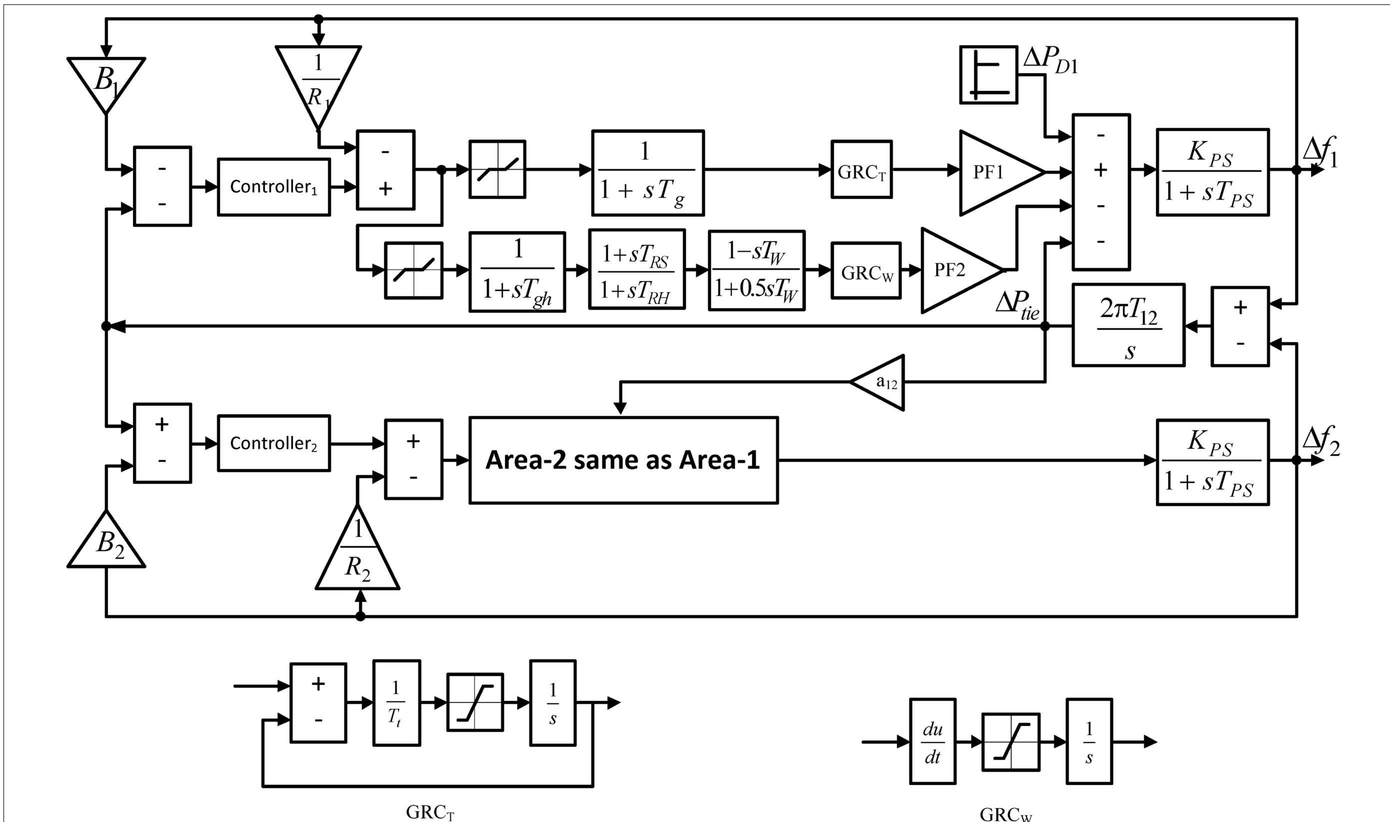


Fig. 1. Transfer function block diagram of the two-area hydro-thermal system considering nonlinearities.

$$ {}_aD_t^w f(t) = \begin{cases} \frac{1}{\Gamma(m-w)}\int_a^t \frac{f^{(m)}(\tau)}{(t-\tau)^{w+1-m}}\,d\tau; \; m-1<w<m \\ \frac{d^m}{dt^m}f(t); \; w=m \end{cases} \tag{3} $$

Here, Γ is the gamma function and m is a first integer such that $w < m$. Laplace transform of the (3) in noninteger derivative form with zero initial condition is:

$$ L\left({}_0D_t^w f(t)\right) = s^w F(s) - [{}_0D_t^{w-1} f(t)]_{t=0} \tag{4} $$

Likewise, Laplace of (3) in noninteger integral form is:

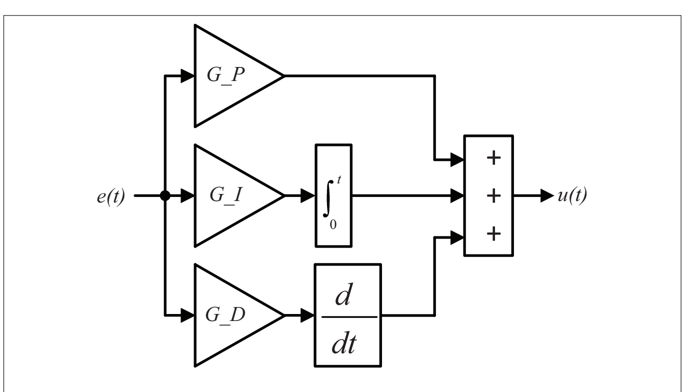


Fig. 2. Structure of PID controller. PID, proportional-integral-derivative.

$$ L\left({}_0D_t^{-w} f(t)\right) = s^{-w} F(s) \tag{5} $$

Equation (5) gives the solution for FO function, using Oustaloup approximation method [30] with "N" representing the number of poles and zeros. The approximation is done within a frequency band $[\omega_l, \omega_h]$ with a scaling of "K."

$$ s^w = K\prod_{n=1}^{N}\left(\frac{1+\frac{s}{\omega_{zn}}}{1+\frac{s}{\omega_{pn}}}\right); \; w>0 \tag{6} $$

To reduce ripple contents in gain and phase of the solution, the corner frequencies are given in (7)–(11).

$$ \omega_{z,1} = \omega_l\sqrt{n} \tag{7} $$

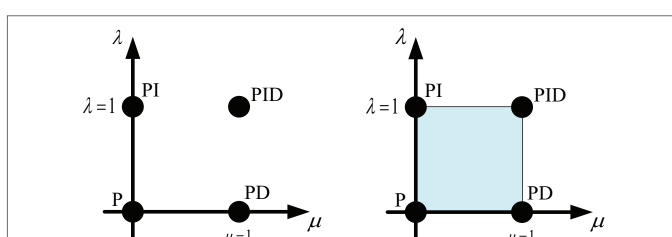


Fig. 3. Graphical representation of FOPID controllers on $\lambda-\mu$ plane from point to plane. FOPID, fractional-order proportional-integral-derivative.

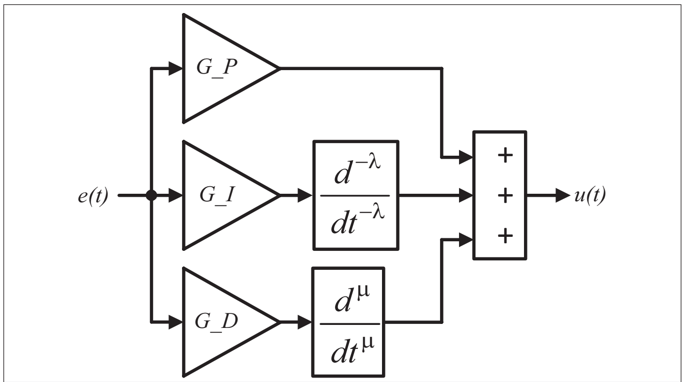


Fig. 4. Structure of FOPID controller. FOPID, fractional-order proportional-integral-derivative.

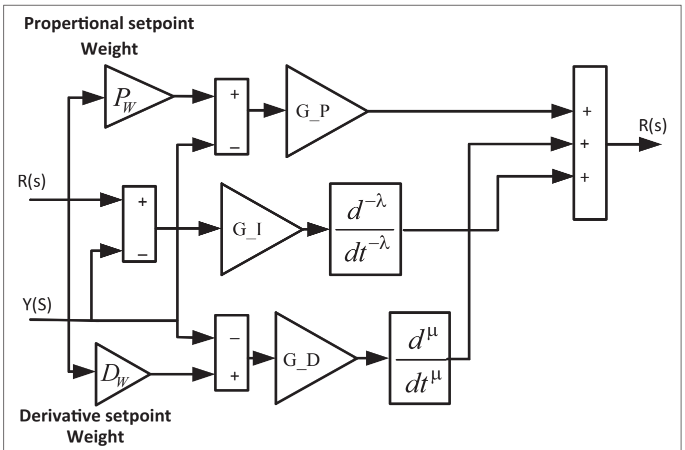


Fig. 5. Structure of 2DOF-FOPID controller. 2DOF-FOPID, two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative.

$$\omega_{p,n} = \omega_{z,n}\varepsilon \tag{8}$$

$$\omega_{z,n+1} = \omega_{p,n}\sqrt{\eta} \tag{9}$$

where,

$$\eta = \left(\frac{\omega_n}{\omega_l}\right)^{\frac{1-w}{N}} \tag{10}$$

$$\varepsilon = \left(\frac{\omega_h}{\omega_l}\right)^{\frac{w}{N}} \tag{11}$$

For the above expression, if $|w > 1|$, then the expression in (5) becomes rational. In order to avoid this problem, the complex frequency's power is decomposed as given below:

$$s^w = s^n s^\sigma \tag{12}$$

where,

$$n \in z \text{ and } w = n + \sigma \tag{13}$$

The term s^σ is approximated here. Corner frequencies are chosen between 0.01 rad/s and 100 rad/s as done in the study [30]. Equation (14) gives the control signal in time domain. The output of the FOPID controller implemented here is expressed in time domain (where μ is fractional derivative order and λ is the fractional integral order):

$$u_1(t) = G\_P_1.e_1(t) + G\_I_1\frac{d^{-\lambda 1}}{dt^{-\lambda 1}}e_1(t) + G\_D_1\frac{d^{\mu 1}}{dt^{\mu 1}}e_1(t) \tag{14}$$

The Laplace transform of (14) in s-domain is expressed as

$$H(s) = \frac{U(s)}{E(s)} = G\_P_1 + \frac{G\_I_1}{s^\lambda} + G\_D_1 s^\mu \tag{15}$$

C. Two-Degree-of-Freedom Fractional Order Proportional-Integral-Derivative Controller

Two-degree-of-freedom-based controller is now quite popular due to its superior control capability in smooth tracking of the set-point variable and improved noise rejection as stated by Vilanova et al. [31].

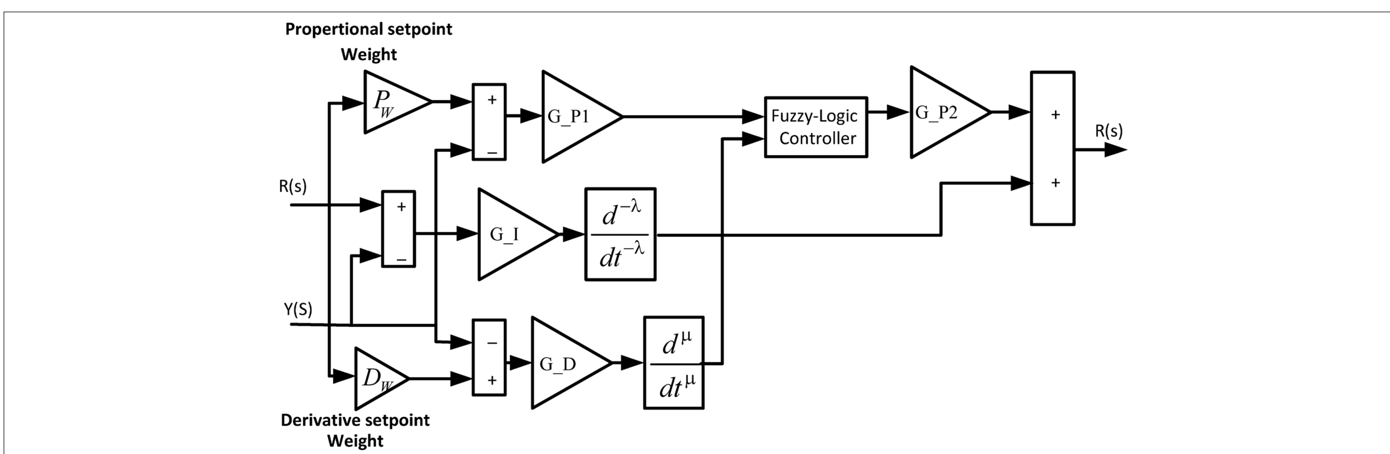


Fig. 6. Structure of 2DOF-FO-FuzzyPID controller. 2DOF-FOPID, two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative.

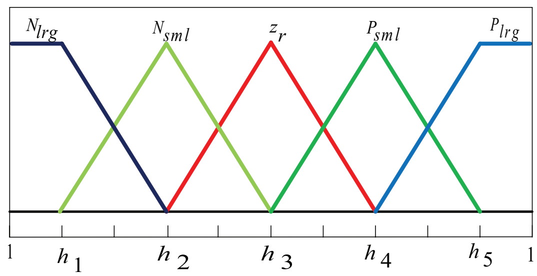


Fig. 7. Structure of membership function.

In the context of control system, DOF means the total number of closed-loop transfer functions which can be independently tuned. In conventional 1-DOF controllers, the process of tuning is carried out on the basis of load disturbance, without specifying the set point, and therefore lacks flexibility in controller design. Unlike the 1-DOF, 2-DOF controller gives the output on the basis of the mismatch between the system's output and reference signals. It calculates biased weighted difference in the signals under study for PID controller, based on the proportional and integral set point weights. Fig. 5 shows the block diagram of a 2DOF-FOPID controller. It comprises a proportional set point weights (P_W), a derivative set point weight (D_W), controller gains (G_P, G_I & G_D), the derivative order (μ), and fractional integral (λ). Here, MWOA is employed as the optimization technique to tune up optimally all these parameters. Many studies reveal that 2-DOFPID controller enhances the dynamic performance of systems in complex control environment in a much better way. In addition to this, the use of fractional order calculus in place of conventional integer order controller design enhances the performance of many folds.

TABLE I. RULE BASE FOR THE FUZZY LOGIC-BASED CONTROLLER

e(*t*)	*e'*(*t*)				
	N_{lrg}	N_{sml}	Zr	P_{sml}	P_{lrg}
N_{lrg}	N_{lrg}	N_{lrg}	N_{sml}	N_{sml}	Zr
N_{sml}	N_{lrg}	N_{sml}	N_{sml}	Zr	P_{sml}
Zr	N_{sml}	N_{sml}	Zr	P_{sml}	P_{sml}
P_{sml}	N_{sml}	Zr	P_{sml}	P_{sml}	P_{sml}
P_{lrg}	Zr	P_{sml}	P_{sml}	P_{lrg}	P_{lrg}

D. Two-Degree-of-Freedom Fractional Order Fuzzy-Proportion al-Integral-Derivative Controller

In this study, by harnessing the advantages of fuzzy logic controller (FLC) with 2DOF-fractional order PID controller, a 2DOF-FO-FuzzyPID controller is developed for the use in AGC of equal multi-area interconnected with linear/nonlinear PS.

The structure of 2DOF-FO-FuzzyPID controllers is shown in Fig. 6. Figure 7 shows the membership functions (MFs) selected for both the input and the output. Defuzzification based on center of gravity method is implemented to get the crisp output. Rule base employed for this work is given in Table I. Fuzzy logic controller has the ability of online updating the controller parameters to efficiently handle all the changes in operating point. Factors affecting the performance of FLC are selection of proper (i) MFs for input and output variables, (ii) input and output scaling factors or gains, and (iii) rule base. In this article, the set point weights, gains, the derivative, and integrator orders are optimally designed through WOA and MWOA algorithms. The 16 numbers of 2DOF-FO-FuzzyPID controller parameters are obtained by running MWOA to carry out the complete system dynamic performance of the PSs under scrutiny.

E. Whale Optimization Algorithm

Whale optimization algorithm technique was suggested by Mirjalili and Lewis in 2016 [32] by mimicking the bubble-net hunting strategy of humpback whales. Various stages of WOA are described as follows:

1) Initialization: For this stage, a probable solution matrix of size [NPxD] is created randomly within the set search space using (16). Performance of each probable solution is evaluated and the best performer among the population is considered as the global best.

$$x = x_{min} + \left(x_{max} - x_{min}\right) X rand\left(NP, D\right) \quad (16)$$

where x_{max} and x_{min} are the maximum and minimum values of the design variables.

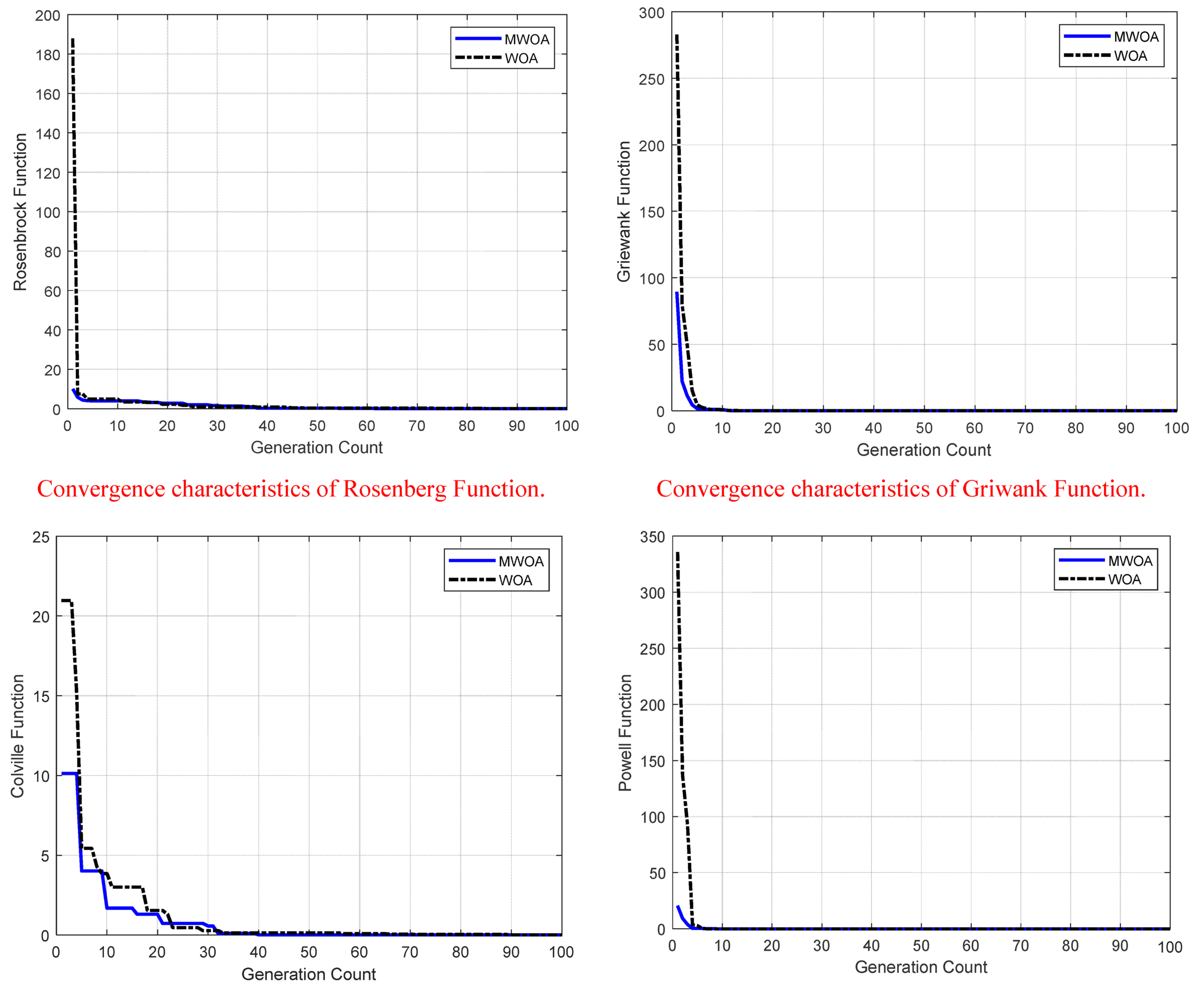
TABLE II. BENCHMARK FUNCTIONS CONSIDERED IN THIS STUDY

Functions	Function's expression	Dimension	Range
Rosenberg (F1)	$f(x) = \sum_{i=1}^{d-1}\left[100\left(x_{i+1} - x_i^2\right)^2 + \left(x_i - 1\right)^2\right]$	5	[−5 to 10]
Griwank (F2)	$f(x) = \sum_{i=1}^{d}\frac{x_i^2}{4000} - \prod_{i=1}^{d}\cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$	30	[−600 to 600]
Colville (F3)	$f(x) = 100\left(x_1^2 - x_2\right)^2 + \left(x_1 - 1\right)^2 + \left(x_3 - 1\right)^2 + 90\left(x_3^2 - x_4\right)^2$	4	[−10 to 10]
Powell (F4)	$f(x) = \sum_{i=1}^{\frac{d}{4}}\left[\left(x_{4i-3} + 10x_{4i-2}\right)^2 + 5\left(x_{4i-1} - x_{4i}\right)^2 + \left(x_{4i-2} - 2x_{4i-1}\right)^4 + 10\left(x_{4i-3} - x_{4i}\right)^4\right]$	10	[−4 to 5]

TABLE III. PERFORMANCE ANALYSIS OF MWOA AND WOA ALGORITHMS

Algorithm	Function	Optimum Value	Minimum	Maximum	Mean	Standard Deviation	Computational Time (sec)
MWOA	F1	0	7.4991×10^{-07}	3.6054×10^{-05}	9.0242e-06	7.9570e-06	0.2281
WOA			$1.1754 \times 10-^{-04}$	0.0024	5.4612×10^{-04}	5.5072×10^{-04}	0.1379
MWOA	F2	0	0	0	0	0	5.8256
WOA			0	0	0	0	4.8319
MWOA	F3	0	7.9323×10^{-08}	9.4985×10^{-07}	2.9301×10^{-07}	2.1124×10^{-07}	0.1654
WOA			4.6717×10^{-06}	1.8369×10^{-04}	5.4438×10^{-05}	4.8297×10^{-05}	0.0927
MWOA	F4	0	0	1.0850×10^{-34}	3.6166×10^{-36}	1.9809×10^{-35}	0.1013
WOA			0	5.9652×10^{-16}	1.9884×10^{-17}	1.0891×10^{-16}	0.0558

MWOA, modified whale optimization algorithm.



Convergence characteristics of Rosenberg Function.

Convergence characteristics of Griwank Function.

Convergence characteristics of Colville Function.

Convergence characteristics of Powell Function.

Fig. 8. Convergence characteristics of different benchmark functions.

2) Prey encircling: Humpback whales easily identify the location of prey and encircle them. This algorithm assumes the best-performing solution as the target prey and updates the other probable solutions (location of other whales) using the following equations:

$$x_{new} = x_{best} - m \times n \tag{17}$$

$$n = \left| t \times x_{best} - x \right| \tag{18}$$

where the coefficient vectors "m" and "t" are expressed as:

$$m = 2pr - p \tag{19}$$

$$t = 2r \tag{20}$$

In (19), "p" is decreased linearly from "2" to "0" using (21) as the iteration progresses and "r" is a number randomly generated in the range [0, 1].

$$p = 2 - 2 \times \frac{iter}{iter_{max}} \tag{21}$$

TABLE IV. OPTIMALLY DESIGNED CONTROLLERS' GAINS (SYSTEM WITHOUT NONLINEARITIES)

Gains of various proposed Controllers									
WOA PID Controller [28]									
		Area-1					Area-2		
G_P_1		G_I_1	G_D_1			G_P_2	G_I_2		G_D_2
5.0001		4.9968	1.0457			0.0101	3.6985		3.5401
WOA FOPID Controller [28]									
		Area-1					Area-2		
G_P_1	G_I_1	G_D_1	λ_{1}	μ_{1}	G_P_2	G_I_2	G_D_2	λ_{2}	μ_{2}
0.8406	5.0001	4.3586	0.8645	0.7107	1.7408	0.0101	4.8556	0.5525	0.9428
WOA 2DOF-FOPID Controller [28]									
Area-1							Area-2		
G_P_1	G_I_1	G_D_1	λ_{1}	μ_{1}	G_P_2	G_I_2	G_D_2	λ_{2}	μ_{2}
1.8536	5.0000	1.4911	0.8004	0.9742	1.3215	3.6021	3.8474	0.1100	1.0000
		Set point weights					Set point weights		
P_{W1}			D_{W1}			P_{W2}			D_{W2}
3.5913			4.5898			4.4623			4.1096
WOA 2DOF-FO-FuzzyPID Controller									
		Area-1					Area-2		
G_P_1	G_I_1	G_D_1	λ_{1}	μ_{1}	G_P_3	G_I_2	G_D_2	λ_{2}	μ_{2}
2.1421	5.0000	1.6708	0.9228	0.9888	1.3803	5.0000	0.2087	0.0273	0.9796
P_{W1}		D_{W1}	G_P_2			P_{W1}	D_{W1}		G_P_4
4.9529		0.1000	3.7879			0.2087	0.9796		3.7879
MWOA 2DOF-FO-FuzzyPID Controller									
		Area-1					Area-2		
G_P_1	G_I_1	G_D_1	λ_{1}	μ_{1}	G_P_3	G_I_2	G_D_2	λ_{2}	μ_{2}
4.9592	4.8340	1.4478	0.9320	1.0000	4.1331	0.1000	1.3952	0.3674	0.9666
P_{W1}		D_{W1}	G_P_2			P_{W1}	D_{W1}		G_P_4
1.7608		0.1000	3.6723			4.2406	0.3379		5.0000

MWOA, modified whale optimization algorithm; 2DOF-FOPID, two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative; FOPID, fractional-order proportional-integral-derivative.

3) Bubble-net attacking strategy: In addition to prey encircling, the humpback whales also try to attack the prey with bubble-net strategy which is mathematically modeled using the following two methods:
   a) Encircling shrinking mechanism: As the value of "p" decreases using (21), the value of "m" also decreases. If the magnitude of "m" becomes less than 0.5, it is again randomly generated and updated using (17–21).
   b) Spiral updating position: The humpback whales attack the prey following a spiral-shaped shrinking circular path. In order to mathematically model the nature of the attack, a probability of 50 % is allotted to both types of movements followed during the attacking strategies, i.e., shrinking circular and spiral, which can be mathematically described as:

$$x_{new} = \begin{cases} x_{best} - m.n & if\ q < 0.5 \\ n'.e^{cl}.\cos(2\pi l) + x_{best} & if\ q \geq 0.5 \end{cases} \quad (22)$$

   where $n' = |x_{best} - x|$ "c" decides the shape of the spiral path and is taken as in this work, "l" is a number generated randomly in the range [−1, 1].
   c) Prey searching: Position updating is carried out by randomly selecting hunt agent rather than the best agent. Mathematically, the strategy can be described as:

$$x_{new} = x_{rand} - m \times n \quad (23)$$

Where,

$$n = |t \times x_{rand} - x| \quad (24)$$

and $t = 2r$ as mentioned in (20).

F. Modified Whale Optimization Algorithm

Whale optimization algorithm is modified by integrating an additional stage in WOA. The newly added stage involves the replacement of some of its elements with randomly generated new members. The element to be replaced is also decided randomly. In this way, more diversity in the population can be achieved which thereby enhances the algorithm's convergence performance. This also reduces the chance of getting stuck into local optima. Steps involved in the phase are:

The random generation of '*NP*' number of integers are randomly generated within the range [1-D]. These random integers decide which elements are to be replaced. Let the random integers are:

$$r_{int} = [r_{int,1}, r_{int,2}, ..., r_{int,NP}] \quad (25)$$

So, in this stage, $r_{int,1}^{th}$ element of first population, $r_{int,2}^{th}$ element of second population…. $r_{int,NP}^{th}$ element of NP^{th} population is replaced by numbers generated randomly within [0–5] which is the specified range of the variables. Consider the randomly generated numbers are:

$$r_{mut} = [r_{m,1}, r_{m,2}, ..., r_{m,NP}] \quad (26)$$

These randomly generated numbers are replaced in "X_{new}" at the proper positions as defined in (25). The fitness value of this new population is evaluated after the replacement of these random numbers, compared with the previously updated population and the best-performing elements are stored to take part in next iteration.

To show the supremacy of MWOA over conventional WOA, four popular benchmark functions, namely, Rosenbrock, Griewank, Colcille, and Powell are considered in this study. Mathematical expression, dimension, and the range of search space for these four benchmark functions are depicted in Table II. Both MWOA and conventional WOA techniques are written in MATLAB code (.m file) and run for 30 times by taking both maximum number of iterations and number of population as 100. Various parameters like mean value, minimum value, maximum value, standard deviations, and computation time are presented in Table III and are taken as performance indicators to prove the superiority of the MWOA technique. In Table III, it is quite

TABLE V. OPTIMALLY DESIGNED CONTROLLERS' GAINS. (SYSTEM WITH NONLINEARITIES)

MWOA PID

Area-1			Area-2		
G_P_1	G_I_1	G_D_1	G_P_2	G_I_2	G_D_2
3.2717	0.1391	2.5333	0.0106	0.0104	2.3452

MWOA Fuzzy PID Controller

Area-1				**Area-2**			
G_1	G_2	G_P_1	G_i_1	G_3	G_4	G_P_2	G_i_2
3.4381	4.9996	0.4413	0.0547	0.0103	0.1667	4.3467	0.0104

MWOA 2DOF-FO-FuzzyPID Controller

Area-1					**Area-2**				
G_P_1	G_D_1	G_P_2	G_I_1	μ_1	G_P_3	G_D_2	G_P_4	G_I_2	μ_2
4.995	4.7635	0.2168	0.0232	0.9958	0.6938	3.9678	0.0103	0.0643	0.0102
G_1	G_2	λ_1			G_3	G_4	λ_2		
1.6156	1.9429	0.9897			1.8517	0.0115	0.0108		

evident that minimum, maximum, mean values, and standard deviations of the benchmark functions are less in MWOA when compared to WOA. It is also seen that to converge to optimum values, MWOA takes lesser number of iterations. But the computation time in case of MWOA is a little bit on the higher side because of the inclusion of an additional updation phase. Convergence characteristics of various benchmark functions are presented in Fig. 8. It is quite evident from Table III and Fig. 8 that MWOA technique outperforms conventional WOA technique in all aspects except the computation time.

IV. SIMULATION RESULTS AND ANALYSIS

A. Transient Performance Analysis

The proposed AGC system is modeled in MATLAB and SIMULINK environment. The proposed test model is a two-area, four-unit electrical power system with individual areas having a hydro-generating unit and a thermal unit along with their nonlinearities like GDB and GRC. The values of the different system parameters used in the concerned power system are given in Appendix. Gain parameters of all the discussed controllers are considered in the range [0, 5] and that of the fractional order of differentiation and integration, within the range [0-1]. Here, WOA technique is utilized to design the controllers (PID, FOPID, and 2DOF-FOPID). Further, fuzzy logic is embedded with PID and 2DOF-FOPID controllers to make them as intelligent controller. These modified intelligent controllers (2DOF-FO-FuzzyPID and Fuzzy-PID) are designed by using both WOA and MWOA techniques. The optimization is carried out, endorsing ITAE cost function with a population size and iteration number as 100. Tables IV and V tabulate the optimized gains of the various controllers considering the system without and with nonlinearities, respectively. A step load of 0.1 p.u. is given to the test model to find out the dynamic characteristics without/with system non-linearities.

Dynamic response of frequency and tie-line power without nonlinearities by WOA-based controllers is given in Figs 9–11. In these figures, it is observed that the FO controller has amended the response produced by PID controller. Again, the 2DOF controller assisting FO operator has produced an ameliorated prompt response. Further, the 2DOF-FO-FuzzyPID intelligent controller has curtailed the overshoot and undershoots acutely. So, the fuzzy technique added with FO operator in the presence of independent loop control (2DOF control) technique has enhanced the system response adequately. Simultaneously, in Figs 9-11, it is quite evident that the MWOA–2DOF-FO-FuzzyPID controller has yielded smooth and prompt response by soothing out oscillations. The transient values produced by these controllers are presented in Table VI. Data in Table VI interpret that the 2DOF-FO-FuzzyPID controller is superior to other controllers. Again, the MWOA algorithm has an edge over conventional WOA algorithm.

In the presence of nonlinearities, the dynamic response is portrayed in Figs 12–14. Here, the performance of MWOA-PID, MWOA-fuzzy-PID, and MWOA-2DOF-FO-FuzzyPID controllers has been compared. The time domain analysis shows that the MWOA-2DOF-FO-FuzzyPID controller has produced a better-ameliorated performance. Despite its sluggish response, the controller has a great ability to make the stability of the system intact. The transient values at time t = 0 are tabulated in Table VII. Both from Table VII and Figs 12–14, it is obvious that the MWOA-2DOF-FOPID controller has produced better performance over others due to the presence of fuzzy logic and FO operators.

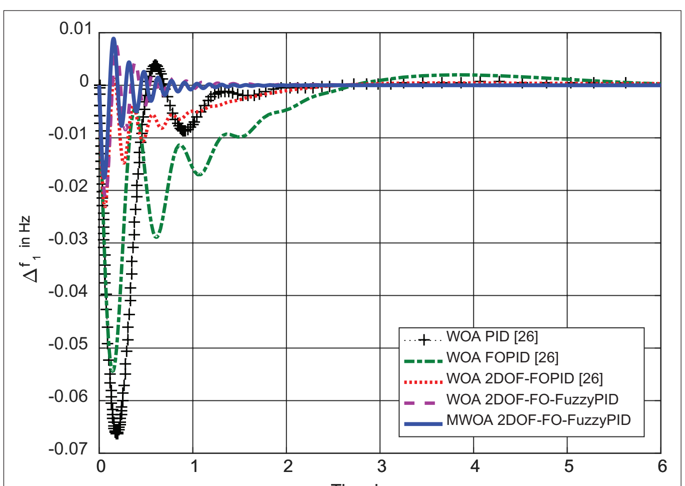


Fig. 9. Frequency deviation of area 1 (system without nonlinearities).

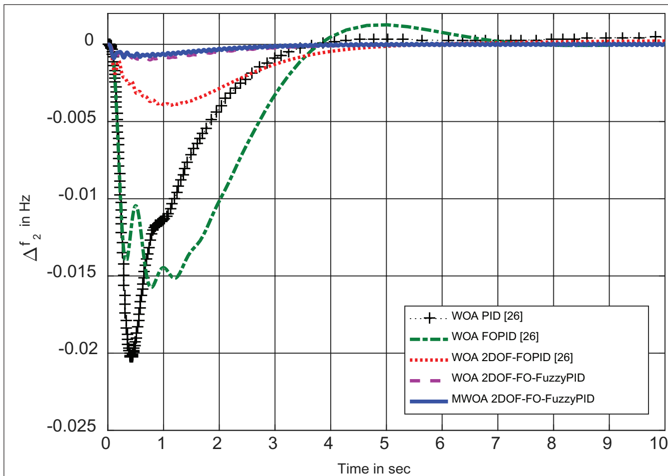


Fig. 10. Frequency deviation of area 2 (system without nonlinearities).

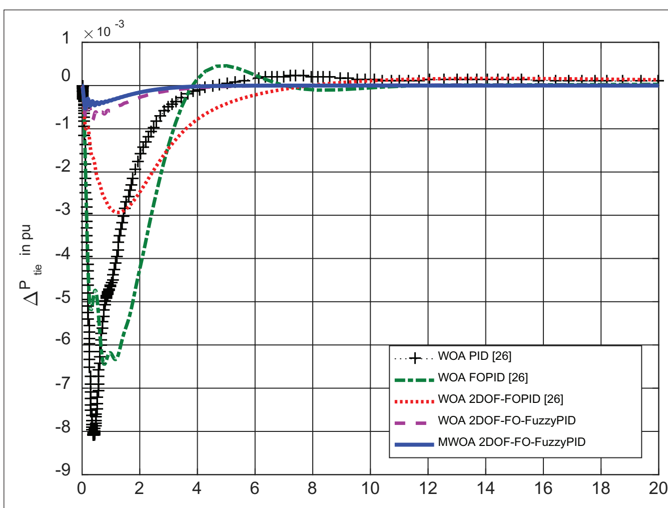


Fig. 11. Tie-line power deviation (system without nonlinearities).

TABLE VI. TRANSIENT PERFORMANCE INDICATOR (SYSTEM WITHOUT NONLINEARITIES)

Frequency/ Tie-Line Power	Transient Parameter	Controllers				
		MWOA 2DOF-FO-FuzzyPID	WOA 2DOF-FO-FuzzyPID	WOA 2DOF-FOPID [28]	WOA FOPID [28]	WOA PID [28]
Δf_1	$U_{sh}\times10^{-3}$ in Hz	**−17.5956**	−20.4345	−23.1869	−54.4452	−66.3760
	$O_{sh}\times10^{-3}$ in Hz	**8.8853**	9.4475	**1.5285**	1.9903	3.7752
Δf_2	$U_{sh}\times10^{-3}$ in Hz	**−0.9139**	−1.0693	−3.9465	−15.7466	−20.2520
	$O_{sh}\times10^{-3}$ in Hz	**0.0252**	0.0593	0.2244	1.2634	0.4579
ΔP_{tie}	$U_{sh}\times10^{-3}$ in P.U.	**−0.5344**	−0.7968	−2.9350	−6.4507	−8.0938
	$O_{sh}\times10^{-3}$ in P.U.	**0.0009**	0.0103	0.1639	0.4568	0.2218

MWOA, modified whale optimization algorithm; 2DOF-FOPID, two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative; FOPID, fractional-order proportional-integral-derivative.
Bold Values Indicates the superior results.

TABLE VII. TRANSIENT PERFORMANCE INDICATOR (SYSTEM WITH NONLINEARITIES)

Frequency/Tie-line Power	Transient Parameter	Controllers		
		PID	Fuzzy PID Controller	2DOF-FO-FuzzyPID Controller
Δf_1	$U_{sh}\times10^{-3}$ in Hz	−313.4735	−298.5029	**−285.5641**
	$O_{sh}\times10^{-3}$ in Hz	164.1380	78.4595	**67.5304**
Δf_2	$U_{sh}\times10^{-3}$ in Hz	−435.7080	−400.4439	**−344.4736**
	$O_{sh}\times10^{-3}$ in Hz	196.0052	75.9816	**20.9778**
ΔP_{tie}	$U_{sh}\times10^{-3}$ in P.U.	−78.2021	−77.9885	**88.2691**
	$O_{sh}\times10^{-3}$ in P.U.	30.2178	8.1526	**5.7252**

PID, proportional-integral-derivative; 2DOF-FOPID, two-degree-of-freedom fractional order–fuzzy-proportional-integral-derivative.

B. Stability Analysis

The stability of the system (with nonlinearity) incorporating MWOA-2DFO-FO-FuzzyPID controller is presented in frequency domain. In this regard, Bode plot (both magnitude and phase plots) analysis is proposed and is shown in Fig. 15. By introspecting the magnitude and phase plots, it is found that the phase margin and gain margin are 70.5° and 37.3 dB, respectively. Positive values of phase and gain margins clearly indicate the system is quite stable using the proposed controller.

C. Robustness Analysis

The proposed 2DOF-FO-FuzzyPID controller is subjected to variation from −20% to +20% in steps of 10% for some of its vital system

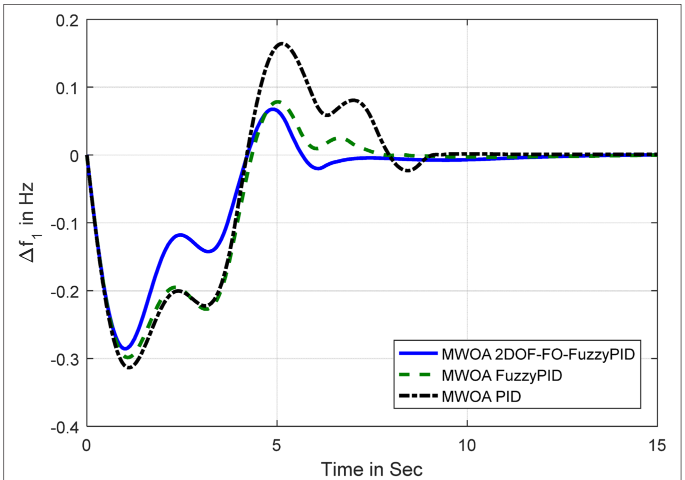


Fig. 12. Frequency deviation of area 1 (system with nonlinearities).

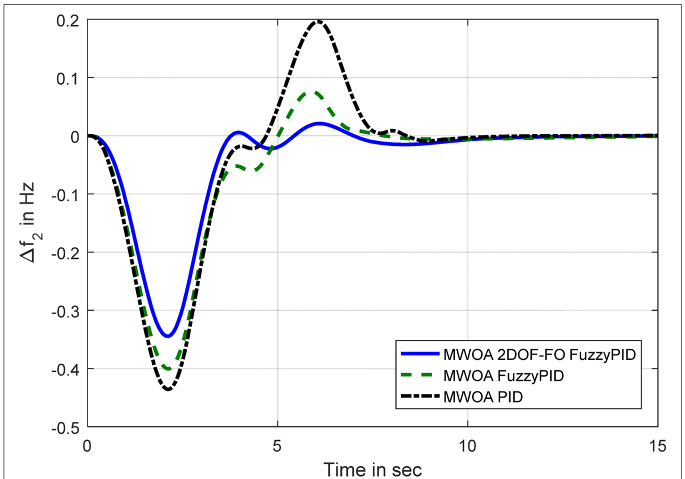


Fig. 13. Frequency deviation of area 2 (system with nonlinearities).

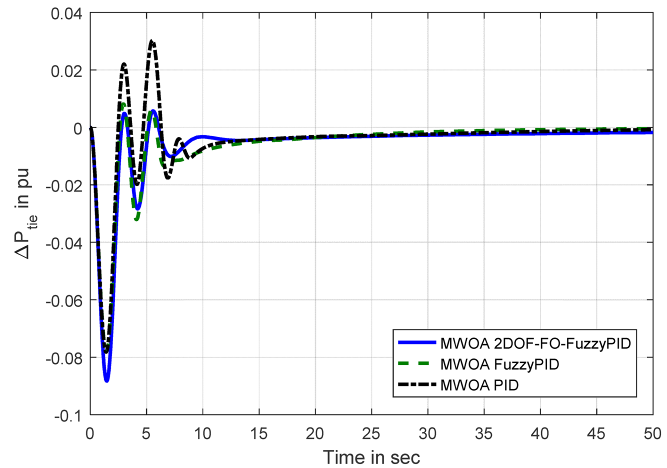


Fig. 14. Tie-line power deviation (system with nonlinearities).

parameters to study the robustness. Table VIII presents the transient performance of the AGC system (without nonlinearities) with variation in systems' parameters.

The values given in Table VIII show all the transient parameters to vary within a small range suggesting the proposed 2DOF-FO-FuzzyPID controller be quite robust against variation in parameters.

V. CONCLUSION

In this piece of work, the role of AGC in a multi-unit two-area interconnected electrical power system, with both the areas employing a thermal and a hydro unit with and without system nonlinearities, is addressed. The employed 2DOF-FO-FuzzyPID controller has produced a prompt response over PID and FOPID controllers. The intelligent control technique assisted by FO operators is quite capable to handle the nonlinearities, parametric change, and sporadic load change occurring in the system. Further, the potential of the MWOA technique over WOA technique is measured by evaluating mean value, minimum value, maximum value, standard deviations,

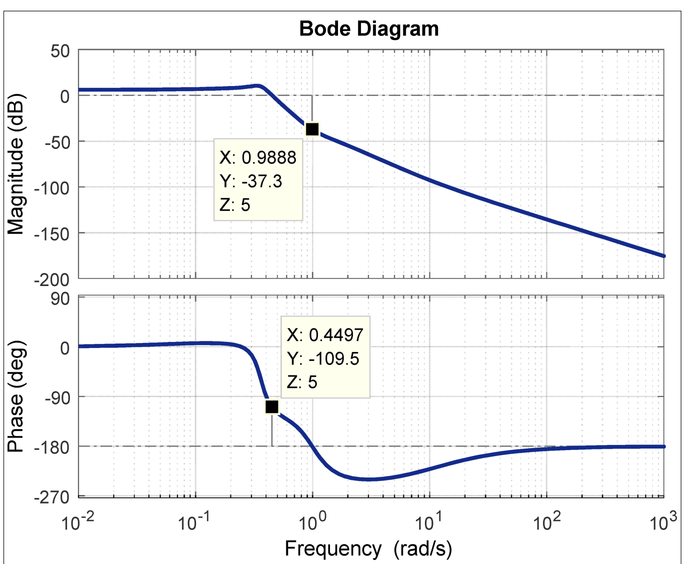


Fig. 15. Bode plot of the system with nonlinearity.

TABLE VIII. TRANSIENT PERFORMANCE INDICATORS DUE TO SYSTEMS PARAMETRIC VARIATION

	Parameter	Percentage Change	$U_{sh}\times10^{-3}$ (in Hz)	$O_{sh}\times10^{-3}$ (in Hz)
Δf_1	**R**	−20%	−17.5927	8.9066
		−10%	−17.5943	8.8923
		+10%	−17.5967	8.8692
		+20%	−17.5976	8.9330
Δf_2	**B**	−20%	−17.6050	8.8498
		−10%	−17.5889	8.9402
		+10%	−17.5893	8.8792
		+20%	−17.5871	8.8052
ΔP_{tie}	$\mathbf{T_{12}}$	−20%	−17.5993	8.7136
		−10%	−17.5985	8.8296
		+10%	−17.5892	8.7555
		+20%	−17.5901	8.8396

and computation time through some benchmark functions which confer to achieve an optimal and robust controller. Further, the system stability with the proposed 2DOF-FO-FuzzyPID controller is good enough which is elucidated by the Bode plot. Analyzing all these aspects, it can be believed that the proposed MWOA-2DOF-FO-FuzzyPID controller is more suitable to implement in a power system to address the AGC problems.

The current work is done with the sole objective of designing a simple yet robust controller for AGC. In the future, the work can be extended to other configurations of traditional, deregulated, and renewable electric power systems. Besides this, the proposed controller may be applied to micro-grids having very intermittent nonlinearities.

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APPENDIX

System parameters: $T_g = 0.08$ sec, $T_t = 0.3$ sec, $B_1 = B_2 = 0.425$ MW/Hz; $T_{12} = 0.0867$; $R_1 = 2.4$ Hz/MW, $K_{ps} = 120$; $T_{ps} = 20$ sec; $T_1 = 48.7$ sec; $T_2 = 0.513$ sec; $T_r = 0.3$ sec; $K_r = 1$; $T_w = 1$ sec., a_{12}=-1, PF_1= PF_2= PF_3= PF_4=1.