Load frequency control of a three-area power system based on the optimal tuning of a fractional-order proportional–integral–derivative controller with multi-objective gray wolf optimization

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ABSTRACT

In an interconnected electrical power system, load frequency control is the most important ancillary service that is essential for maintaining electrical system reliability at an adequate level. Herein, a multi-objective gray wolf optimization (MOGWO) algorithm was introduced to maintain balance between the exploitation and exploration stages and provide the best fitness value. During a disturbance in the output of the system, optimization was implemented using the firefly algorithm (FFA) and MOGWO, which were carefully tuned, and the parameters were compared with those of the three-area three-source model of the power system. A fractional-order proportional–integral–derivative (FOPID) controller is a PID controller whose derivative and integral orders are fractions rather than integers. The FOPID controller supports the improved stability of the designed model with controlled deviations in the frequency and grid tie-line power. In this study, the optimal tuning of the parameters of controllers, such as PI, PID, and FOPID, in the power system was done to regulate the frequency in the multi-area multi-source model designed with hydro-thermal-gas generation units. The output performance of the proposed model was estimated based on the simulation results using the MATLAB-SIMULINK tool. The dynamic performance of the system was examined by introducing step-load perturbations of 1% or 2% in one area. Sensitivity analysis revealed that the FFA and MOGWO optimized the FOPID controller parameters obtained under nominal conditions of loading, size, and position of disturbance. The system parameters remained robust and did not require to be reset even with significant changes in the system. The simulation results demonstrated the effectiveness of the FOPID controller in the presence and absence of the FF and MOGWO algorithms. Additionally, the MOGWO algorithm was executed appropriately and led to improved performance in terms of metrics, such as overshoot, undershoot, and settling time.

Keywords: Load Frequency Control; Fractional-Order Proportional–Integral–Derivative Controllers; Fire Fly Algorithm; Multi-Objective Gray Wolf Optimization Algorithms.

INTRODUCTION

Load frequency control (LFC) plays a significant role in electric power system operation by damping the frequency and voltage oscillations originating from load variations or sudden changes in load demands (Ayyappan and Kanimozhi, 2021). In an interconnected power system that consists of several control areas, if the system parameters vary, the grid tie-line power will change, and frequency deviations will occur (Daniar et al., 2016). In a power system with large interconnections, transient conflicts promote disturbances within the system (Selvakumaran et al., 2014). These instabilities result in an imbalance between load and generation, which affects the general operation of the power system (Tasar et al., 2015). To maintain this balance, the governing system of the prime mover assists in controlling the frequency of the system and later schedules the grid tie-line flow

(Fakharian and Rahmani, 2016). The LFC executes an essential part of the power system procedure to resolve the complexities that occur because of load variations. In addition, the LFC comprises a system that governs speed, as the initial controller equalizes with the power generated by the load demand. The frequency tuning of the estimable system is performed by a secondary type of control loop (Vijayakumar and Manigandan, 2016). The LFC maintains the frequency in the desired range even after disturbances. Similarly, the exchange of power among various control areas is controlled by methods comprising the LFC (Anbarasi and Muralidharan, 2016). In recent years, several approaches have been proposed in power systems for better control of the load frequency. This secondary type of frequency control, also known as LFC or automatic generation control (AGC), is responsible for regulating the power system frequency and comprises two major goals (Huynh et al., 2018). These are frequency maintenance at the desired level and control power exchange by the main grid tie lines among several control areas. The major part of the third control level is to re-dispatch units for generation and additional reserves, even after disturbances occur in the server (Topno and Chanana, 2018). With the increased penetration level of the energy sources in the power system and changes in load demand, which mainly improve the uncertainties in the system, variations in frequency are determined. For such an increase in the fluctuation of the active power, apart from the demand for stochasticity, the power system frequency will exhibit high oscillations (Praveena et al., 2019). Hence, upcoming power systems require highly robust and optimal LFC methods to address these issues. Numerous control methods have been recommended for LFC with interconnected power systems (Nayak and Maharana, 2019). Among the methods

reported, proportional–integral (PI) controllers are most commonly used for industrial purposes. The PI controller has a constant gain, which is designed with the desired conditions for operation and usage, and is also simple; however, the possibilities of frequency oscillations are high (Ayyappan and Kanimozhi, 2021). The design is such that this controller shows the least dynamic performance against parameter changes in the system and nonlinear conditions, such as rate constraint generation. A proportional–integral–derivative (PID) controller has a static controller for parameters that have an active power system, and the pattern differs with respect to the expansion (Kumar and Subag, 2017). Thus, a fixed parametric PI or PID controller is required to achieve optimal performance. Fuzzy logic has been proposed by several researchers to resolve these challenging, uncertain, and dynamic circumstances. PID controllers combine proportional, integral, and derivative components to obtain standard equations. Despite its simplicity and wide usage, this type of controller has disadvantages (Rajesh and Dash, 2019). Fractional-order PID (FOPID) controllers for LFC can be designed similar to PID controllers but with the advantage of having five parameters to be determined, thus providing two additional degrees of freedom for more precise tuning of dynamic features (Lamba et al., 2019). The foremost task of the LFC is to keep the frequency constant against randomly varying active power loads, also referred to as unknown external disturbances. Another task of the LFC is to regulate the grid tie-line power exchange error (Alhelou et al., 2018). Considering the importance of knowledge regarding multi-area power systems, the proposed approach is based on the tuning of PID controllers through simulations. The proposed control system can influence positivity in a complete dynamic response and provide improved controllability despite sudden system

modifications compared with the control system using the classical decoupling approach. A PID-fuzzy-PID hybrid controller tuned by the multi-objective gray wolf optimization (MGWO) technique was suggested as a control method and was found to be robust during random load application; the recommended controller was tested in a multi-source interconnected system and demonstrated flexibility in LFC (Kumar and Suhag, 2017).

POWER SYSTEM MODEL FOR LFC

The model of the load frequency response in a single-area power system with interconnected sources of energy comprises thermal-hydro-gas. In all three areas of the power system, the generation units include thermal-hydro-gas sources, as shown in Figure 1. The three-area model comprises a system with a diesel generator, governor, turbine, and reheater. A power system with several control areas is connected via grid tie lines to enhance efficiency and consistency, which makes the power system complex and nonlinear in nature.

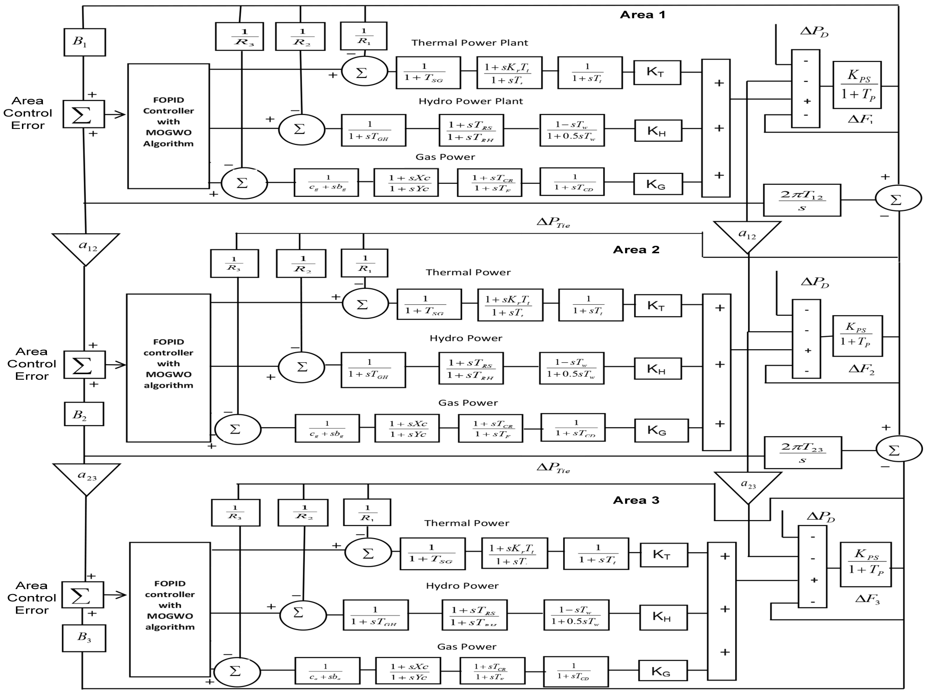

Figure 1 Three-Area Power System Model with a Multi-Source System

A power system with many interconnected areas must operate at a minimum frequency for better synchronization. Power control and exchange with various generating units to maintain the frequency and power flow of grid tie lines among several areas of control in its minimal values are the major objectives of controlling the load frequency, and the FOPID controller easily attains the iso-damping property, offering better performance outcomes of the higher-order system. In addition, it is more stable and robust than PID. Furthermore, this controller can achieve enhanced responses for a system with maximum phase. The FOPID controller consists of only two additional parameters: (λ), which represents the order of the integral part, and (μ), which represents the order of the derivative part. In addition to these two parameters, the FOPID controller includes the conventional PID controller parameters, namely K_P, K_I, and K_D. The concept of the fractional order involves differential equations that use fractional calculus. The FOPID controller has a transfer function represented by Eq. (1).

$$U(s) = K_P + \frac{K_I}{S^{\lambda}} + K_D S^{\mu} \tag{1}$$

Here, K_P, K_I, and K_D are gain parameters of PID. λ and μ are the orders of integrator and differentiator, respectively.

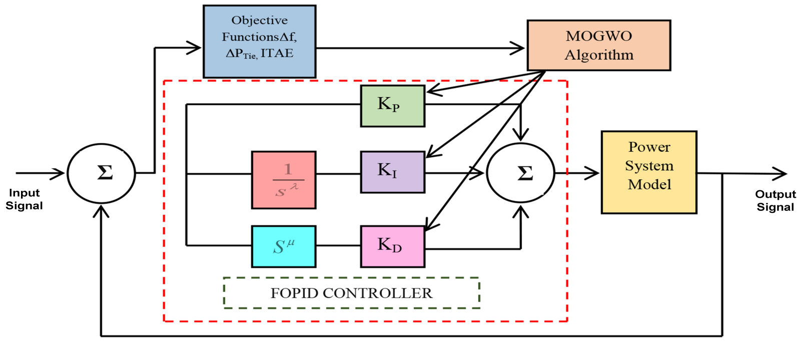

Figure 2 System Model using the FOPID and MOGWO Algorithm

Better results can be expected by fine-tuning all five parameters of the FOPID controller, including the integral of time-multiplied absolute error (ITAE) and the integral of squared error (ISE). Among the three types of controllers considered, the proposed FOPID controller with the MOGWO, shown in Figure 2, yielded better results than the other two controllers. The objective function of the ITAE is calculated using Eq. (2).

$$J = ITAE\int_0^t \left(\left|\Delta f_1(t)\right| + \left|\Delta f_2(t)\right| + \left|\Delta f_3(t)\right| + \left|\Delta P_{Tie1}\right| + \left|\Delta P_{Tie2}\right|\right).dt \tag{2}$$

Similarly, other objective functions of the ISE values were determined based on the algorithms considered in this study. The ISE objective function is estimated using Eq. (3).

$$J = ISE\int_0^t \left|e^2(t)\right|.dt \tag{3}$$

In the equation above, Δf_1, Δf_2, and Δf_3 are the frequency deviations of the system; ΔP_{Tie} is an incremental alteration in the power grid tie line, and t indicates the simulation time range.

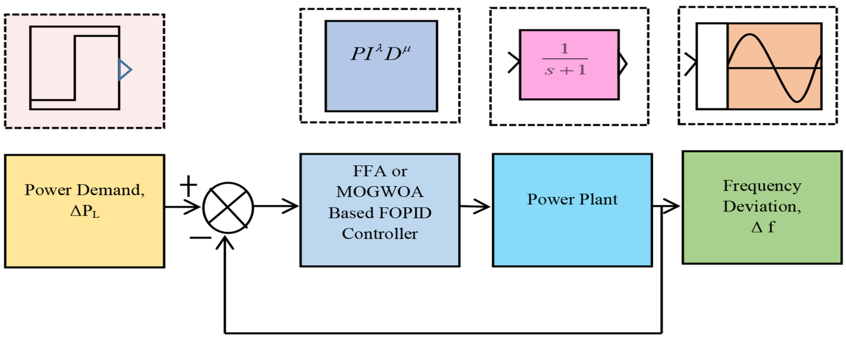

Figure 3 General Overview of the Firefly and MOGWO Algorithms

These metaheuristic algorithms are often nature-inspired and have become the most widely used algorithms for optimization. When the performance of the FOPID-based MOGWO algorithm is compared with that of the firefly algorithm (FFA)-FOPID, it is observed that the proposed algorithm yields better results. Figure 3 presents a general overview of the algorithm, where the MOGWO algorithm shares similar features and comparative advantages with the GWO optimization algorithm.

SIMULATION RESULTS

This section presents the performance results of the proposed multiple-area and multiple-source models using the modified algorithm of GWO and FFA. The power system model was developed using the MATLAB/Simulink simulation software. The objective functions of both the ITAE and ISE are simulated in the Simulink block, and the data for the controller are obtained. The dynamic performance of the system was studied using a 2% step-load perturbation in one area. The frequency and tie-line power changes due to load perturbation were measured, and the stability of the system was recovered using the proposed controller, which mainly focused on the settling time, peak overshoot, and undershoot.

Table 1 Settling time of controllers in Multi Area Multi Source (MAMS) system without an optimization algorithm

Controller	Settling Time in Seconds				
	Δf_1	Δf_2	Δf_3	ΔP_{tie1}	ΔP_{tie2}
PI	7.39	7.24	6.85	6.5	7.1
PID	6.45	6.5	5.86	4.85	5.2
FOPID	5.3	3.8	4.6	4.2	4.7

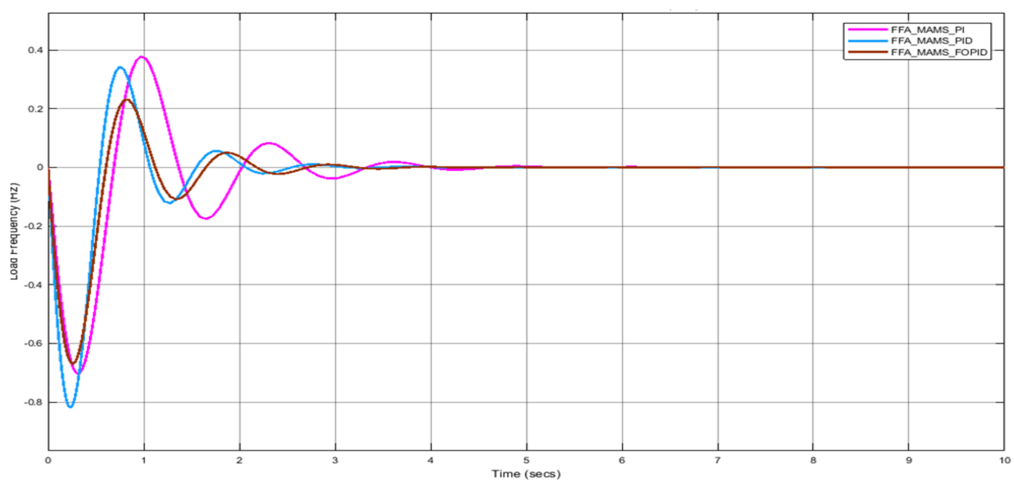

Figure 4 Multi-Area Multi-Source using the FFA

Similarly, the settling time is attained by the FOPID in less time than by the other controllers. The results in Table 1 were obtained in the multi-area multi-source system without optimization with a load variation of 2% in the power system. A power system with multi-area and multiple sources was simulated using the FFA algorithm. In this case, the performance variations were better than those of a single-area power system.

Table 2 Settling time of controllers in MAMS with the FFA

Controller	Settling Time in Seconds				
	Δf_1	Δf_2	Δf_3	ΔP_{tie1}	ΔP_{tie2}
PI_FFA	5.3	6.2	4.35	5.2	6.3
PID_FFA	3.8	3.62	3.5	3.5	5.3
FOPID_FFA	4.5	4.3	3.4	3.2	5.6

The proposed FOPID controller exhibited the shortest settling time among the three controllers considered. Figure 4 shows a graphical view of the controllers compared with

the algorithm of the FFA was applied, and the results are presented in Table 2. The simulation results explained the different outputs acquired for multiple areas and sources in the model system. The overall performance of the FOPID controller was better than that of the PI and PID controllers, as shown in Figure 5.

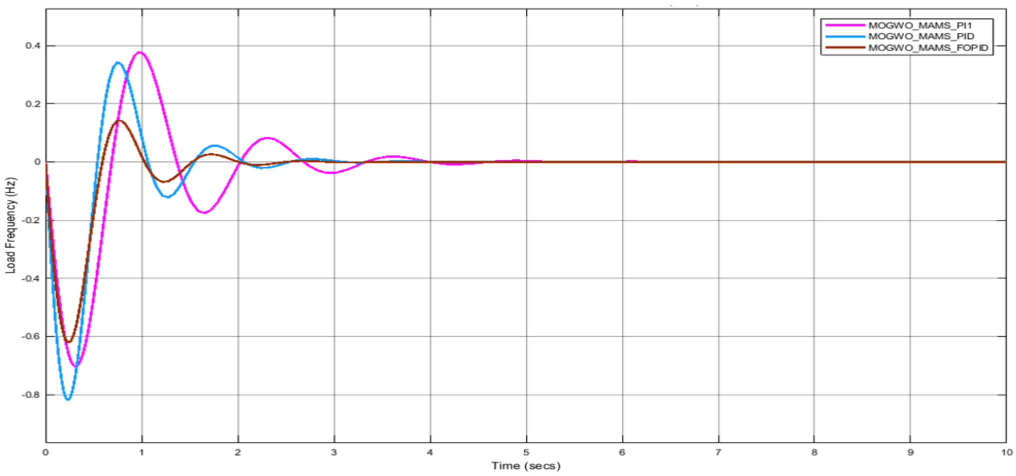

Figure 5 Multi-Area Multi-Source using MOGWO

From Table 3, the settling time of the proposed FOPID-based MOGWO algorithm is substantially shorter than that of the other controllers.

Table 3 Settling time of controllers in MAMS with MOGWO

Controller	Settling Time in Seconds				
	Δf_1	Δf_2	Δf_3	ΔP_{tie1}	ΔP_{tie2}
PI_MOGWO	6.1	5.8	3.9	4.9	6.1
PID_MOGWO	6.2	6.42	3.57	4.05	5.8
FOPID_MOGWO	3.2	2.8	3.3	2.8	3.2

The performance results showed that the change in outputs obtained from the simulation was better for the FOPID controller, whereas the other two displayed significantly lower performance than FOPID. The incremental changes in the frequency and grid tie-line power values of the controllers with and without the FFA, as well as the MOGWO algorithm, are shown in Table 4. From this Table, deviations in the individual area frequencies (Δf_1, Δf_2, and Δf_3) were obtained**.** The grid tie-line power alterations, such as ΔP_{tie1} and $\Delta P_{tie2,}$ increase based on the type of controller used, along with the algorithm implemented. The PI, PID, and FOPID controllers exhibit gain values with respect to the number of areas and sources considered.

Table 4 Deviations in frequency and tie-line power in the MAMS power system

Controller	Δf_1	Δf_2	Δf_3	ΔP_{tie1}	ΔP_{tie2}
PI	-0.1004	-0.0246	-0.0021	-0.0737	-0.0267
PID	-0.1159	-0.0109	0.0086	-0.1136	-0.0023
FOPID	-0.1159	-0.0109	0.0086	-0.1112	0.0113
PI_FFA	-0.0221	-0.1347	-0.0179	0.1304	-0.1526
PID_FFA	-0.0253	-0.1056	-0.0457	0.126	-0.1513
FOPID_FFA	-0.0253	-0.1056	-0.0457	0.0589	-0.0859
PI_MOGWO	-0.005	0.0261	0.005	-0.0361	0.0311
PID_MOGWO	-0.0058	-0.0081	0.0453	-0.043	0.0372
FOPID_MOGWO	-0.0058	-0.0081	0.0453	0.0147	-0.0208

The calculated gains for multiple areas and sources designed for the power system model are listed in Table 5.

Table 5 Gains of the PI, PID, and FOPID controllers with multi-area power system model

Controller	Thermal					Hydro					Gas				
	K_P	K_I	K_D	λ	μ	K_P	K_I	K_D	λ	μ	K_P	K_I	K_D	λ	μ
PI_A1	0.9	0.02	-	-	-	1.9	0.05	-	-	-	2.956	0.189	-	-	-
PI_A2	1.109	1.195	-	-	-	0.754	1.023	-	-	-	2.013	0.234	-	-	-
PI_A3	1.056	0.235	-	-	-	0.551	0.987	-	-	-	1.354	0.01	-	-	-
PID_A1	0.9	0.02	0.02	-	-	1.9	0.05	0.01	-	-	9.554	0.49	0.09	-	-
PID_A2	1.109	1.859	1.279	-	-	0.652	1.678	0.573	-	-	1.146	1.850	0.362	-	-
PID_A3	5.559	0.05	0.546	-	-	2	0.06	0.02	-	-	1	0.03	0.01	-	-
Fopid_A	0.923	0.162	0.031	0.	0.	4.002	2.005	0.054	0.	0.	0.215	0.213	0.021	0.	0.
Fopid_A	1.923	0.162	0.035	0.	0.	-0.902	0.523	-0.042	0.	0.	0.215	0.213	0.021	0.	0.
Fopid_A	1.023	0.032	0.012	0.	0.	0.201	0.062	0.021	0.	0.	5.325	0.784	0.039	0.	0.

From Table 6, it can be observed that, among the three controllers, FOPID had better undershoot and overshoot values with reduced settling time. Improvements were observed when the MOGWO algorithm was implemented along with controllers, which enhanced the performance efficiency of the power system model designed in this study. In Table 7, the values represent the settling time of the frequencies and grid tie-line power between the areas with and without implementation of the FFA and MOGWO algorithms.

Table 6 Overshoot (O_{sh}), undershoot (U_{sh}), and settling time frequency (f_{Ts}) of controllers with algorithms in MAMS

Controller	Δf_1			Δf_2			Δf_3			ΔP_{tie1}			ΔP_{tie2}		
	F_{Ts}	O_{sh}	U_{sh}	F_{Ts}	O_{sh}	U_{sh}	F_{Ts}	O_{sh}	U_{sh}	F_{Ts}	O_{sh}	U_{sh}	F_{Ts}	O_{sh}	U_{sh}
PI	-0.091	0.022	-0.3535	-0.0826	0.3123	-0.3214	-0.0091	0.0407	-0.044	0.0092	0.601	-1.1157	-0.0916	0.3528	-0.3648
PI_FFA	-0.1429	-0.1398	-0.6023	-0.12	0.3231	-0.4025	-0.0225	0.041	-0.0521	-0.0012	0.4664	-1.0098	-0.143	0.3644	-0.4529
PI_ MOGWO	0.0124	-0.1942	0.0231	0.0249	0.3319	-0.2506	-0.0016	0.0424	-0.0346	-0.0012	0.3692	-0.8915	0.0269	0.3739	-0.2844
PID	-0.0815	-0.0476	-0.3169	-0.0655	0.2624	-0.1733	-0.0195	0.2745	-0.2615	0.0156	0.5435	-1.2964	-0.0822	0.5254	-0.3942
PID_ FFA	-0.1491	-0.1671	-0.2521	-0.0939	0.2682	-0.2202	-0.544	0.2648	-0.244	-0.0014	0.3877	-1.1989	-0.1487	0.5195	-0.4101
PID_ MOGWO	0.0279	-0.0342	-0.1797	-0.0117	0.27	-0.19	0.0397	0.3022	-0.1321	-0.0023	0.3868	-1.1673	0.0281	0.5582	-0.2774
FOPID	-0.0499	0.0402	-0.4014	-0.0018	0.0194	-0.0064	-0.0474	0.2515	-0.1285	0.0025	0.2259	-0.9825	-0.0458	0.2658	-0.1355
FOPID_ FFA	-0.0989	-0.1292	-0.2361	-0.0035	0.0196	-0.0083	-0.0945	0.2567	-0.0832	-0.0015	-0.0687	-0.7687	-0.0989	0.2708	-0.0877
FOPID_ MOGWO	-0.0358	-0.1136	-0.2331	-0.0023	0.0194	-0.0082	-0.0362	0.2299	-0.0594	0.0042	0.0057	-0.8198	-0.0375	0.3034	-0.0695

Table 7 Settling time of various controllers with an optimization algorithm in the MAMS system

Controller	Settling Time in Seconds				
	Δf_1	Δf_2	Δf_3	ΔP_{tie1}	ΔP_{tie2}
PI	7.39	7.24	6.85	6.5	7.1
PI_FFA	5.3	6.2	4.35	5.2	6.3
PI_MOGWO	6.1	5.8	3.9	4.9	6.1
PID	6.45	6.5	5.86	4.85	5.2
PID_FFA	3.8	3.62	3.5	3.5	5.3
PID_MOGWO	6.2	6.42	3.57	4.05	5.8
FOPID	5.3	3.8	4.6	4.2	4.7
FOPID_FFA	4.5	4.3	3.4	3.2	5.6
FOPID_MOGWO	3.2	2.8	3.3	2.8	3.2

CONCLUSION AND DISCUSSION

In this study, various conventional controllers were considered for better tuning of the load frequency. However, the proposed FOPID controller provided a much better response than the aforementioned controllers. This study introduced a MOGWO-based optimization, in which the stages of both exploitation and exploration were altered, and high importance was given to the fittest wolf to acquire the updated wolf position at the time of iteration. The proposed MOGWO and FF algorithms were compared to improve system optimization. The dynamic performance of the system was studied with a 2% step-load perturbation in one area, and the metrics of overshoot, undershoot, and settling times of the frequency were analyzed with each simulation output. The FOPID controller with the MOGWO exhibited better performance results with a reduced frequency settling time. In addition, an analysis based on the grid tie line of power according to the deviation in frequency was carried out. The ITAE and ISE were obtained from the simulation results using the FFA and MOGWO algorithms with P, PI, PID, and FOPID controllers. The overall comparison of the system provided with the performance metrics for each controller with the implemented algorithms showed a higher efficiency of the designed model. In the future, this power system model will be extended to multiple energy sources and areas with highly efficient optimization algorithms in restructured environments. The damping measures, such as the value of the ITAE index, maximum peak value, peak time, and settling time parameters, were analyzed in the system oscillation mode, and the relative FOPID with MOGWO yields better results. The use of the resilience random variance reduction technique and revolutionary energy balance control approaches can improve the stability of multi-source interconnected systems.

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