

Mother Algorithm Optimized Controller for Multi-Area Deregulated Power System Modelled with Solar/Wind/EV Sources: A Novel Approach

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INFORMATION

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Mother optimization
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DOI: 10.23967/j.rimni.2026.10.77958

Revista Internacional
Métodos numéricos
para cálculo y diseño en ingeniería

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ABSTRACT

Due to increased system uncertainty, nonlinear dynamics, and market-driven power exchanges, modern deregulated multi-area power systems with high penetration of renewable energy sources (RES) like wind and solar, and electric vehicle (EV) charging stations present serious challenges to automatic generation control (AGC). Degraded frequency regulation and tie-line power control under deregulated environments result from the limited robustness, slow dynamic response, poor handling of stochastic RES/EV variations, and susceptibility to local optimal solutions of both conventional PI/PID controllers and recently reported optimization-based AGC schemes. However, with a view to addressing these issues, this study focuses on reducing area control errors (ACE) during different operational shifts, such as frequency fluctuation (Δf) and tie line variations (ΔP_{tie}). The main objective of this study is to determine the optimal gain settings for the Fractional Order Proportional-Integral-Derivative controller (FOPIDC) using the mother optimization algorithm (MOA). The proposed control strategy looks at how generators 3-AMS behave in a deregulated environment and emphasises the significance of FOPIDC optimization in preserving system stability with the goal of reducing integral time and absolute error (ITAE). Furthermore, the effectiveness of the proposed method is verified by comparing it with the Walrus Optimization Algorithm (WOA). As case studies, the effectiveness of the suggested strategy is also evaluated under Poolco, bilateral agreements, stability, and sensitivity analysis. In terms of generator outputs, tie-line power variations, and frequencies across different locations, comparative data unequivocally demonstrate that the suggested MOA-adjusted FOPIDC performs better than alternative approaches. In case 1, by implementing the MOA optimized controller, the settling time is 8.5 s, and the value of the objective ITAE for the transient responses is 0.0005292. However, these values are less than the values obtained by WOA. Similarly, in case 2, the settling time is 11.5 s, and ITAE is 0.000395 less when compared to WOA and other techniques available in the literature.

OPEN ACCESS

Received: 20/12/2025

Accepted: 11/02/2026

Published: 21/07/2026

DOI

10.23967/j.rimni.2026.10.77958

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1 Introduction

An integrated electrical power network is now the only alternative accessible due to the difficulty of obtaining a remote system. Several utilities in an interconnected electricity system comprise a large system. Changes in the load cause the system to deviate from its typical behaviour. This variance must remain within reasonable limitations to prevent disruptions to the electrical system. The utilities must meet the demand for the system to operate normally. The discrepancy between actual power generation and demand results in frequency fluctuation and tie-line power variance.

Load frequency regulation (LFR), which maintains ΔP_{tie} and ΔF within a predetermined threshold, is an essential prerequisite. In a deregulated setting, the coordination of generating, transmission, and distribution companies is supervised by an independent system operator (ISO). Maintaining frequency is the current power grid's primary priority due to increasing demands and grid expansion [1–3]. Besides, different power system topologies were developed with conventional generation units to handle LFC. Ref. [4] highlighted the significance of Distribution Companies (DISCOs), Transmission Companies (TRANSCOs), and Generation Companies (GENCOs) in their analysis of the deregulated power system environment. To address LFC concerns, several single-area PS models have been presented in [5]. The excitation effects of the generators have been analyzed, and [6] talks about the damping effect that maintains the frequency constant under different loading fluctuations. However, Ref. [7] discusses the use of AGC. Here, LFC is regularly sampled using area control error (ACE) to regulate power flow. The authors in [8–10] discussed the various optimization techniques to design controllers for single and multi-area hybrid power systems.

In Ref. [11], Arya et al. describe the design issues with the fuzzy scheduling-based AGC two-area power system. The use of a PI tuned using a gradient-based algorithm in a four-area PS was examined by the authors of [12], who showed that it was superior to other control strategies at stabilising the voltage, Δf , and ΔP_{tie} under various conditions. A new method based on SMC is recommended. Additionally, a unique Coatis Optimization Algorithm was used to optimize a TID + IDN controller for a 3-AMS to minimize ITAE error [13]. The hybrid sparrow search and mountain gazelle optimizer algorithm was developed to optimize the parameters of the FOPID three-loop controller for LFC [14]. Besides, an improved squirrel search algorithm was proposed to tune the parameters of PID, 2DOF-PID, 3DOF-PID, and 2DOF-PID fraction order controller to address LFC [15].

Besides, in Ref. [16] examined the best way to operate and regulate systems that include FACTS devices and stochastic renewable energy sources to address the difficulties associated with hybrid power systems. To strike a compromise between system reliability and operational efficiency, they used a clever multi-objective optimization technique. In addition, a new multi-objective RIME algorithm for load dispatch under security constraints was suggested, taking hybrid power systems' uncertainties into account. Their research offers a thorough framework for handling the challenges of system security and renewable integration [17]. However, a novel model order reduction method that integrates fuzzy logic control was introduced by [18], which enables more effective control strategies by successfully reducing system complexity while preserving key dynamic properties. With an emphasis on aerospace applications, Ref. [19] used the sinh-cosh algorithm to create a filtered PID controller for aircraft pitch factor handling, improving response times and stability. Their strategy shows how sophisticated optimization methods can be used in crucial control situations. Besides, the optimally tune FOPIDC using Aquila Optimizer was designed to enhance system performance for the minimization of ACE [20]. Meanwhile, the FOPID controller was implemented for power quality enhancement with EV and renewable-associated power systems by optimal selection of parameters with metaheuristic algorithms [21,22].

Besides, the AGC model and control for a three-area system with each generating area consisting of a thermal plant, a diesel power plant, and a solar thermal power plant was developed with an improved version of Sea-horse Optimization (SHO) to optimize modified MPC controller parameters [23]. Meanwhile, a new type of Opposition-based Sea-horse Optimization (OSHO) algorithm was developed to optimize the fractional order integral tilted derivative controller (FIDN-T) that improves performance in terms of settling time, undershoot, and overshoot for RESs with real data forecasting [24]. On the other hand, the novel adaptive Multi-stage Clustering Differential Evolution (AMCDE) algorithm was proposed that integrates fitness-aware clustering with entropy-triggered dynamic niching and incorporates cluster-level convergence signals into mutation and crossover control in Differential Evolution (DE) [25].

Next, a novel Fractional-Order Differential Evolution (FCDE) technique was introduced with fractional derivatives to adaptively balance exploration and exploitation throughout the optimization process [26]. A novel approach to address LFC in a two-area PS was developed with the spider wasp optimizer (SWO) optimized cascaded control strategy combining a fractional-order proportional–integral (FOPI) controller and a proportional–derivative with filter (PDN) controller, FOPI (1 + PDN) [27]. To address LFC, a marine predators algorithm (MPA) was developed to optimize the unique P-P-FOPID cascade controller for LFC, combining a proportional controller with a fractional-order PID [28]. LFC conventional data is collected from [29].

1.1 Research Gap

Limited resilience, poor adaptability to stochastic RES/EV dynamics, slow convergence, early entrapment in local optima, and poor performance under bilateral and Poolco market structures are all problems with conventional PI/PID and even newly published optimization-based controllers. These drawbacks drive the need for a strong optimization framework and a more adaptable control system. In order to overcome these difficulties, an MOA-tuned Fractional Order PID controller is suggested in this current study. While bio-inspired PID controllers offer better adaptivity and nonlinear handling at the expense of mathematical rigour and practical implementation, FOPID offers strong theoretical assurances and moderate industrial acceptability but limited adaptability. The need for hybrid control frameworks that combine the adaptive intelligence of bio-inspired control techniques with the robustness of FOPID is highlighted by this gap.

1.2 Novelty and Contribution

However, from Table 1 it is clear that most of the previous published works mainly focused on 2 Area with conventional and renewable energy without EV charging stations with traditional LFC. This study addresses the issue of LFC in 3-AMS with optimized FOPIDC. The prime contribution is the application of the MOA to the best possible controller parameter tuning in a hybrid system. This innovative method's output is evaluated under various system operating settings, demonstrating how well it enhances controller performance. The challenge of enhancing PS performance containing a variety of energy sources, including thermal, hydro, gas, wind, EV and solar, is specifically taken into consideration in the proposed work. The performance of the developed controller is assessed by a comparative analysis with WOA optimized FOPID. The prime contributions are as follows:

- Design of MOA-tuned FOPIDC to obtain optimally selected gain values and fractional orders to minimize ITAE and to address the LFC issue of a deregulated 3-AMS.
- Modelling of advanced AGC for 3-AMS with integration of thermal, hydro, gas, renewable, and EV charging stations in the MATLAB/Simulink environment.

- Performance investigation is carried out with bilateral, poolco agreements, and stability, sensitivity analysis as case studies to showcase the robustness of the proposed method.
- Comparison validation of the results with WOA is executed to determine the ability of the proposed method in addressing LFC problem in a deregulated power system.

Table 1: State of art of literature

S. No.	Reference Number	Traditional LFC/De-regulated LFC	Controller	Type of Area	Renewable Energy (RE)/Conventional (C)/EV	Metaheuristic Algorithm Considered
1	13	Deregulated	TID + IDN	3	RE+C	Coatis optimization
2	15	Traditional	2DOF-PID-FOI	2	RE+C	Improved squirrel
3	20	Deregulated	FOPID	2	RE+C	Aquila optimization
4	23	Traditional	Modified MPC	3	RE+C	Sea-Horse optimization
5	27	Traditional	FOPI (1+PDN)	2	RE+C	Spider wasp optimizer
6	Proposed	Deregulated	FOPID	3	RE+C+EV	Mother optimization

The following are the remaining papers: [Section 2](#) details the 3-AMS's construction. The created FOPIDC optimized MOA for LFC problem in 3-AMS deregulated environment was described in [Section 3](#). Next, in [Section 4](#), a detailed analysis of simulation findings under various case scenarios was discussed. Additionally, the designed controller's stability and convergence characteristics were also presented. The work is finally concluded in [Section 5](#).

2 Construction of Deregulated 3-AMS

The Mathematical model of a 3-AMS taken into consideration for AGC in a restructured scenario is shown in [Fig. 1](#). However, 3-AMS is the base for analyzing AGC in a deregulated zone. The complete 3-AMS with different generation units is depicted in the diagram. Three generators like thermal, wind and hydro plants, were considered in Area 1 & 3. Similarly, thermal, hydro and a gas turbine plant are located in Area 2. While in all areas, solar and EV charging stations were considered as an additional supply. Besides, to ensure that the system Δf and ΔP_{tie} are within the intended bounds, the FOPID controller is integrated into each region. There are three distinct DISCOs in each control area.

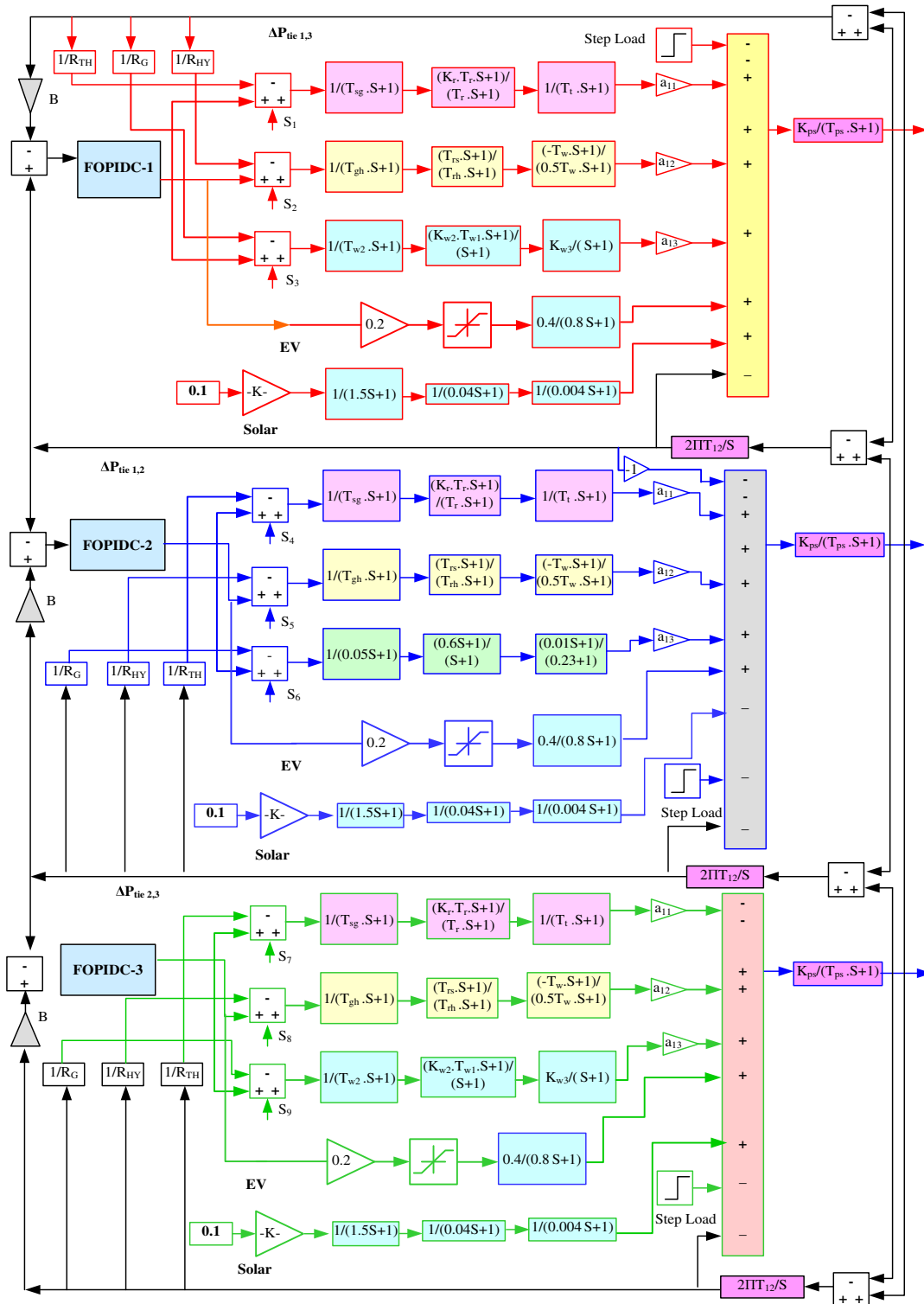


Figure 1: (Continued)

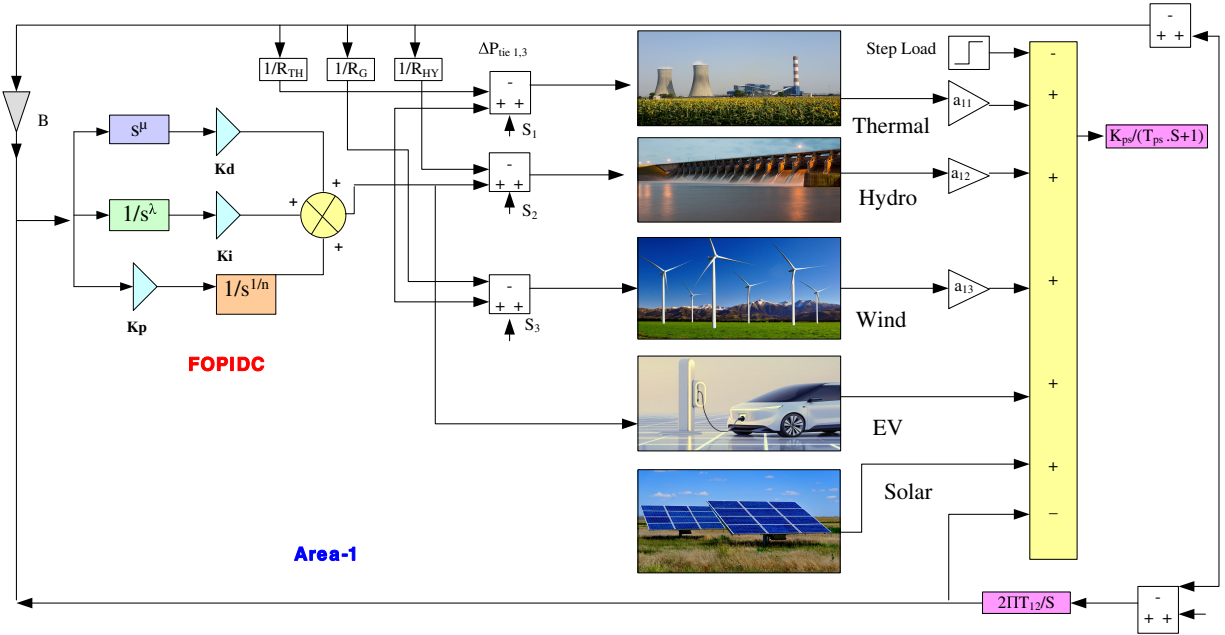


Figure 1: AMS transfer function

Nine GENCOs and nine DISCOs build the interconnected system in a deregulated scenario. A “poolco-based transaction” occurs when a contract for the power is signed between GENCOs and DISCOs within the same control area. A “bilateral transaction”, on the other hand, takes place between GENCOs and DISCOs from two distinct regions. The power contract between DISCOs and GENCOs is specified using the DISCO Participation Matrix (*DPM*). The number of distributed companies in the system is represented by the total columns in *DPM*, while the total rows correspond to the total number of GENCOs. In a *DPM*, the total of all the values in any given column is always 1. Area (1) has GENCOs 1–3 and DISCOs 1–3, Area (2) contains GENCOs 4–6 and DISCOs 4–6, and Area (3) contains GENCOs 7–9 and DISCOs 7–9. The matching *DPM* is therefore expressed in Eq. (1).

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} & cpf_{15} & cpf_{16} & cpf_{17} & cpf_{18} & cpf_{19} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} & cpf_{25} & cpf_{26} & cpf_{27} & cpf_{28} & cpf_{29} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} & cpf_{35} & cpf_{36} & cpf_{37} & cpf_{38} & cpf_{39} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} & cpf_{45} & cpf_{46} & cpf_{47} & cpf_{48} & cpf_{49} \\ cpf_{51} & cpf_{52} & cpf_{53} & cpf_{54} & cpf_{55} & cpf_{56} & cpf_{57} & cpf_{58} & cpf_{59} \\ cpf_{61} & cpf_{62} & cpf_{63} & cpf_{64} & cpf_{65} & cpf_{66} & cpf_{67} & cpf_{68} & cpf_{69} \\ cpf_{71} & cpf_{72} & cpf_{73} & cpf_{74} & cpf_{75} & cpf_{76} & cpf_{77} & cpf_{78} & cpf_{79} \\ cpf_{81} & cpf_{82} & cpf_{83} & cpf_{84} & cpf_{85} & cpf_{86} & cpf_{87} & cpf_{88} & cpf_{89} \\ cpf_{91} & cpf_{92} & cpf_{93} & cpf_{94} & cpf_{95} & cpf_{96} & cpf_{97} & cpf_{98} & cpf_{99} \end{bmatrix} \quad (1)$$

here, cpf_{ij} referred to as the “contract participation factor”, in p.u., as seen in Fig. 2 [13]. The cpf of each generator determines the generator’s response. The system’s tie-line power deviation between two

regions is represented by ΔP_{12} , ΔP_{23} , and ΔP_{31} , while the frequency deviation in Areas 1 and 2 is represented by ΔF_1 , ΔF_2 , and ΔF_3 , respectively.

$$cpf_{ij} = \frac{jth\ DISCO\ power\ demand\ from\ jth\ GENCO}{jth\ DISCO's\ total\ power\ demand} \quad (2)$$

Eqs. (3)–(5) can be used to calculate the tie line power of Areas 1, 2 and 3 based on the cpf values.

$$\Delta P_{12} = \sum_{i=1}^3 \sum_{j=4}^6 cpf_{ij} \Delta P_{Lj} - \sum_{i=4}^6 \sum_{j=1}^3 cpf_{ij} \Delta P_{Lj} \quad (3)$$

$$\Delta P_{23} = \sum_{i=4}^6 \sum_{j=7}^9 cpf_{ij} \Delta P_{Lj} - \sum_{i=7}^9 \sum_{j=4}^6 cpf_{ij} \Delta P_{Lj} \quad (4)$$

$$\Delta P_{31} = \sum_{i=7}^9 \sum_{j=1}^3 cpf_{ij} \Delta P_{Lj} - \sum_{i=1}^3 \sum_{j=7}^9 cpf_{ij} \Delta P_{Lj} \quad (5)$$

Eqs. (6)–(8) give the ΔP_{tie} across the tieline between Areas 1, 2 and 3.

$$\Delta P_{12} = \frac{2\pi T_{12}}{s} (\Delta F_1(s) - \Delta F_2(s)) \quad (6)$$

$$\Delta P_{23} = \frac{2\pi T_{23}}{s} (\Delta F_2(s) - \Delta F_3(s)) \quad (7)$$

$$\Delta P_{31} = \frac{2\pi T_{31}}{s} (\Delta F_3(s) - \Delta F_1(s)) \quad (8)$$

At steady-state, there should be no difference between the tie-line's real power and zero. This error, which can be represented as Eq. (9), is used to assess ACE as:

$$ACE_i = Bi\Delta F_{ierror} + \Delta P_{ierror} \quad (9)$$

The objective function is given by Eq. (10):

$$J = ITAE = \int_0^t (|\Delta F_1| + |\Delta F_2| + |\Delta F_3| + |\Delta P_{tie(1-2)}| + |\Delta P_{tie(2-3)}| + |\Delta P_{tie(3-1)}|) .t.dt \quad (10)$$

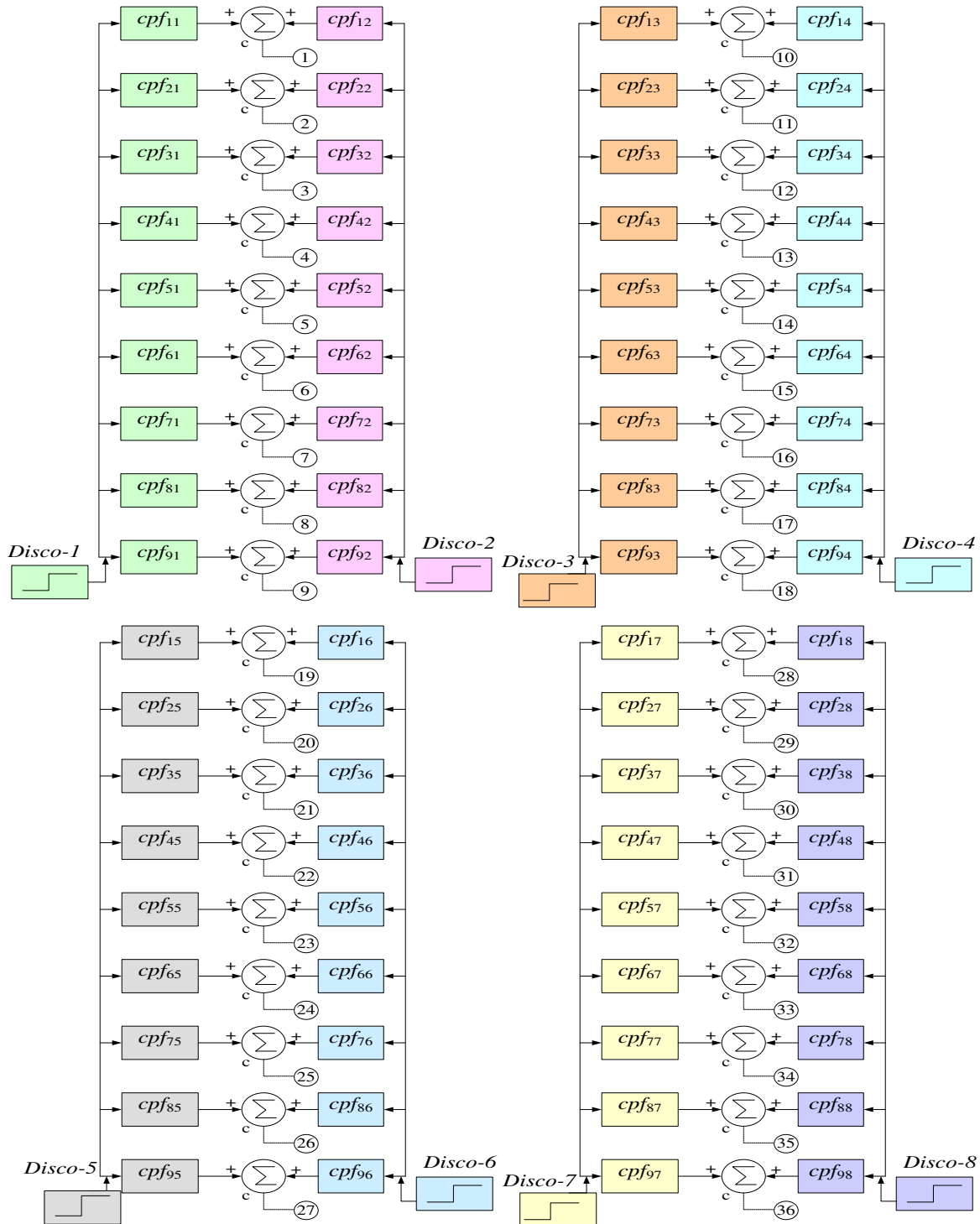


Figure 2: (Continued)

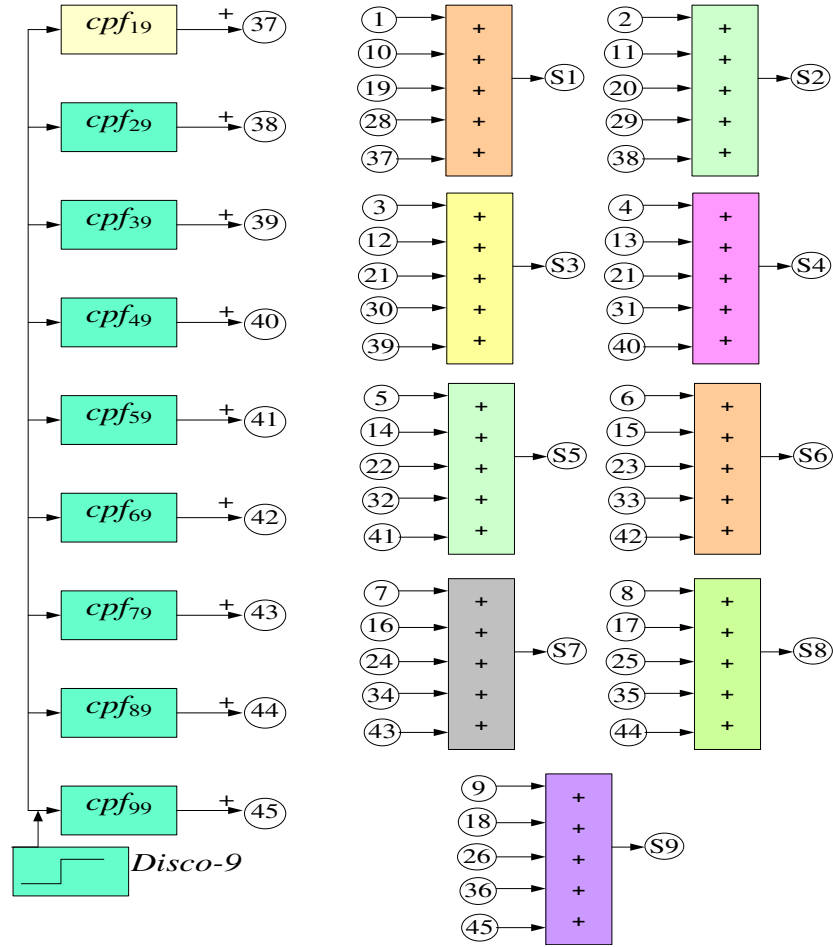


Figure 2: CPF of DISCOs with GENCOs

3 Proposed Mother Optimization Algorithm Tuned FOPIDC

In this study, the MOA optimized FOPIDC is used to address the issue of load frequency control (LFC) in 3-AMS. The application of the MOA is for the best possible controller parameter tuning in a hybrid test system. The proposed MOA and design of FOPIDC are discussed in the subsections in detail:

3.1 FOPID Controller

Several AGC regulators have been created and used in earlier research. However, because fractional order controllers have the advantage of noise cancellation in addition to the lower computation time than traditional controllers, they have received a lot of attention lately. The FOPIDC design is depicted in Fig. 3 and includes five parameters: fractional integrator order (μ), fractional derivative order (λ), derivative term (K_d), proportional term (K_p), and integral term (K_i). A differential equation representing the FOPIDC output is provided by Eq. (11) with transfer function $Gc(t)$.

$$Gc(t) = \frac{Y(s)}{U(s)} = K_p + K_i \frac{1}{s^\lambda} + K_d s^\mu \quad (11)$$

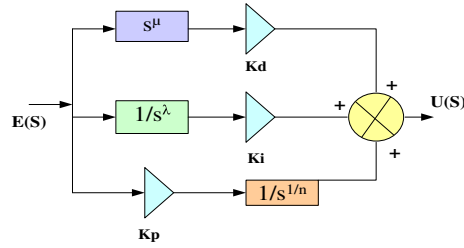


Figure 3: FOPID controller

The FOPIDC gain values are the considered problem control variables. Therefore, to indicate the problem variables, each member in MOA is represented in vector form as follows:

$$R = [K_p, K_i, K_d, \lambda, \mu] \quad (12)$$

The limitations are shown as

$$R_{i\min} \leq R_i \leq R_{i\max}; i = 1, 2, \dots, n \quad (13)$$

The objective function is to minimization of ITAE obtained by the fitness (F).

$$\begin{aligned} \text{MaxF} &= \frac{1}{1 + (\text{Obj})} \\ \text{Obj} &= \text{ITAE} \end{aligned} \quad (14)$$

Design variables are inherently limited. As a result, when trying to find the best answer, the given imperatives shouldn't be disregarded. In light of this, the following design restrictions are present in the current optimization problem: Reduce ITAE Subject to:

$$\begin{aligned} K_p^{\min} &\leq K_p \leq K_p^{\max} \\ K_d^{\min} &\leq K_d \leq K_d^{\max} \\ K_i^{\min} &\leq K_i \leq K_i^{\max} \\ \lambda^{\min} &\leq \lambda \leq \lambda^{\max} \\ \mu^{\min} &\leq \mu \leq \mu^{\max} \end{aligned} \quad (15)$$

The FOPID controller's minimal and maximum controllable variable ranges are denoted by the terms *Min* and *Max* in Eq. (15). In order to determine the best controller design variables on a large scale, this study also chooses the limits for the differentiator and integrator coefficient ($\lambda, \mu = 0$ to 1), while the proportional, integral, and derivative gains ($K_p, K_i, K_d = 0$ to 2). The Oustaloup Recursive Approximation is used to implement the fractional-order operators (s^λ) and (s^μ) of the FOPIDC. To obtain a suitable balance between computational complexity and accuracy, a fifth-order approximation is used. The dominating dynamics of the AGC system are adequately covered by the approximation, which is performed throughout a frequency range of 10^{-3} to 10^3 rad/s. A sample time of 0.01 s is used for the simulations.

3.2 Mother Optimization Algorithm

The mother plays a key role in raising her children. She imparts life education and talents to her kids, who grew up with their capabilities by following her instructions. This process of interaction is mainly in three steps: (i) educating, (ii) advising, and (iii) upbringing.

MOA is an iterative population-based technique that resolves engineering problems. Candidate solutions are represented in vector form. At the beginning of the optimization procedure, the population is initialized using Eq. (16).

$$X_i: x_{ij} = lb_j + r. (ub_j - lb_j), \quad i = 1, 2 \dots N, j = 1, 2 \dots m \quad (16)$$

where N denotes the number of members; X represents the population matrix of MOA; m represents the number of control variables; X_i, x_{ij} give the solution of i^{th} applicant and variable function with r of a random number (0, 1). lb_j and ub_j are the lower and upper bounds of the j^{th} decision variable's. The objective function (obj) is given in vector form as in Eq. (17) with F, F_i are the obj value vectors and i^{th} candidate solution.

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N \times 1} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N \times 1} \quad (17)$$

Phase 1: Education (exploration phase). In the MOA design, the mother is seen as the best member of the population, and the way she raises her kids is modeled to mimic the educational stage. Eq. (18) is used here to create a new position for every candidate. According to Eq. (19), the updated position is considered as the suitable position of the member if the obj value increases.

$$X^{P1}_{ij} = x_{ij} + rand. (M_j - (2) .rand..x_{ij}), \quad (18)$$

$$X_i = \begin{cases} X^{P1}_i, & F^{P1}_i \leq F_i, \\ X_i, & \text{else} \end{cases} \quad (19)$$

here, x_{ij} is the j^{th} dimension of the i^{th} population member's location, and M_j is the j^{th} dimension of the mother's position. The function $rand$ is value the interval of [0, 1], and the random function $rand(2)$ uniformly generates a random value in the interval between {1, 2}. X_i, X^{P1}_i is the updated position determined for the i^{th} member based on phase-1 of the MOA, X^{P1}_{ij} is its j^{th} dimension, and F^{P1}_i is its obj value.

Phase 2: Advice (exploration phase). Counselling and preventing misbehaviour are two of a mother's major everyday jobs during parenting. The 2nd- phase of the update is developed by considering the mother's suggestions. Using Eq. (20), the obj value is compared to get the set of worst behaviour, BB_i , for every candidate. To simulate keeping the youngster away from misbehaviour, a new position is first constructed for each member using Eq. (21). This new position then replaces the associated member's prior position, according to Eq. (22), if it increases the obj value.

$$BB_i = X_k, F_k > F_i \wedge k \in \{1, 2 \dots N\}, i = 1, 2 \dots N, \quad (20)$$

$$X^{P2}_{ij} = x_{ij} + rand. (x_{ij} - rand(2) ..SBB_{ij}), \quad (21)$$

$$X_i = \begin{cases} X^{P2}_i, & F^{P2}_i \leq F_i; \\ X_i, & \text{else}, \end{cases} \quad (22)$$

SBB_i is the chosen poor behavior for the i^{th} population member, $SBB_{i,j}$ is its j^{th} dimension, and F^{P2}_i is its *obj* value. The random function $rand(2)$ creates a random value in the set $\{1, 2\}$. X^{P2} is the new position computed for the i^{th} population member based on the 2nd phase of MOA.

Phase 3: Upbringing (exploitation phase). Mothers encourage their children to become more proficient in the educational process in different ways. First, each member of the population is given a new position based on the modelling of children's personality development using Eq. (23) in order to replicate the raising phase. According to Eq. (24), the appropriate member's prior location is swapped out for the new one if the *obj* value improves in the new position.

$$X^{P3}_{i,j} = x_{i,j} + (1 - 2 \cdot rand) \cdot \frac{ub_j - lb_j}{t}, \quad (23)$$

$$X_i = \begin{cases} X^{P3}_i, & F^{P3}_i \leq F_i; \\ X_i, & \text{else,} \end{cases} \quad (24)$$

here, X^{P3} is the new location for the i^{th} member depending on 3rd-phase of the planned MOA, t is the current iteration counter, j indicates j^{th} dimension, and F^{P3}_i is its *obj* value. The quality of the solutions produced by the population members is gauged by the values of the objective function. The *obj* best and worst values can be used to determine the population's best and worst members, respectively. The best population member must also be changed in accordance with each iteration's changes to the population members' placements. In the ITAE, as the objective function, the deregulated multi-area system closed-loop AGC performance is evaluated at each iteration. The optimal FOPIDC control parameter value is chosen from among the candidate solutions that give the lowest ITAE. Ultimately, the optimal population member resolves the issue at the conclusion of the algorithm's iterations.

An MOA-tuned FOPIDC that guarantees quick dynamic response, lower ACE, and enhanced robustness is produced by continuing the optimization process until convergence conditions are satisfied. The MOA is a balanced exploration–exploitation mechanism compared to other algorithms, but it has its own limitation like computational burden for multi-objective problems. A population of 25 agents and a maximum of 100 iterations are used when executing the MOA. On a typical desktop machine (Intel i7 processor, 16 GB RAM), each optimization run takes an average of 25–30 s.

Pseudo-code of MOA:

Provide the data of the problem

Set N, T

Randomly generate the population Eq. (16)

For $t = 1:T$

Update the position of the mother

For $i = 1:N$

Phase1: Educating

Evaluate new position from Eq. (18)

Update position of i^{th} member from Eq. (19)

Phase2: Advice

Identify bad behaviour set from i^{th} population member from Eq. (20)

Pseudo-code of MOA (Continued):

Select randomly a bad behavior member from the BBi to advice

Evaluate new position from Eq. (21)

Update position of i^{th} member from Eq. (22)

Phase3: upbringing

Evaluate new position from Eq. (23)

Update position of i^{th} member from Eq. (24)

End

keep best solution obtained till now

End

Output the best global solution

End

4 Results and Discussions

MATLAB is used to implement the 3-AMS under discussion, as seen in Fig. 1, for LFC analysis. The optimum settings of the FOPID controller are obtained using the suggested MOA optimization technique. For the comparative analysis, WOA-tuned FOPIDC has been used to analyze the controller's temporal response. Various agreements for the power between GENCOs and DISCOs is examined in the context of the deregulated electricity sector. The impact of Poolco and the bilateral agreement has been taken into consideration when analyzing a number of cases. The performance of LFC is assessed through the various case studies, which are then covered in the parts that follow.

Case I: POOLCO Agreement

In this case, every GENCO in the three regions is taking an equal role in AGC. Particularly in Area 1, a load disturbance of 0.033 per unit (p.u.) is created, and the three DISCOs that operate there share this load perturbation equally. Crucially, the GENCOs are not consuming any load from the remaining DISCOs in the various control areas.

$$DPM = \begin{bmatrix} 0.333 & 0.333 & 0.333 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.333 & 0.333 & 0.333 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.333 & 0.333 & 0.333 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (25)$$

Notably, in the DPM provided by Eq. (25), the nonappearance of contractual agreements between a GENCOs and a DISCO of two distinct control areas is indicated by the presence of null values in the respective cells. The power produced by GENCOs must, in steady-state conditions, equal the load that DISCOs in their respective regions require. Figs. 4 and 5 show the power that flows across three tie-lines and the Δf across various areas.

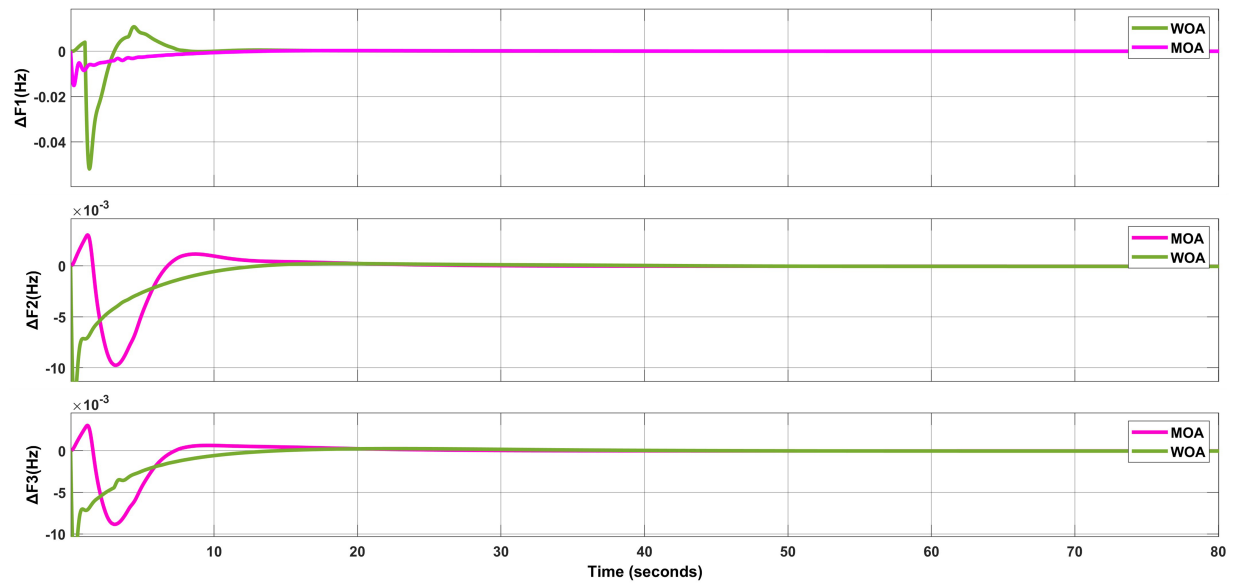


Figure 4: Frequency deviation comparison of case 1

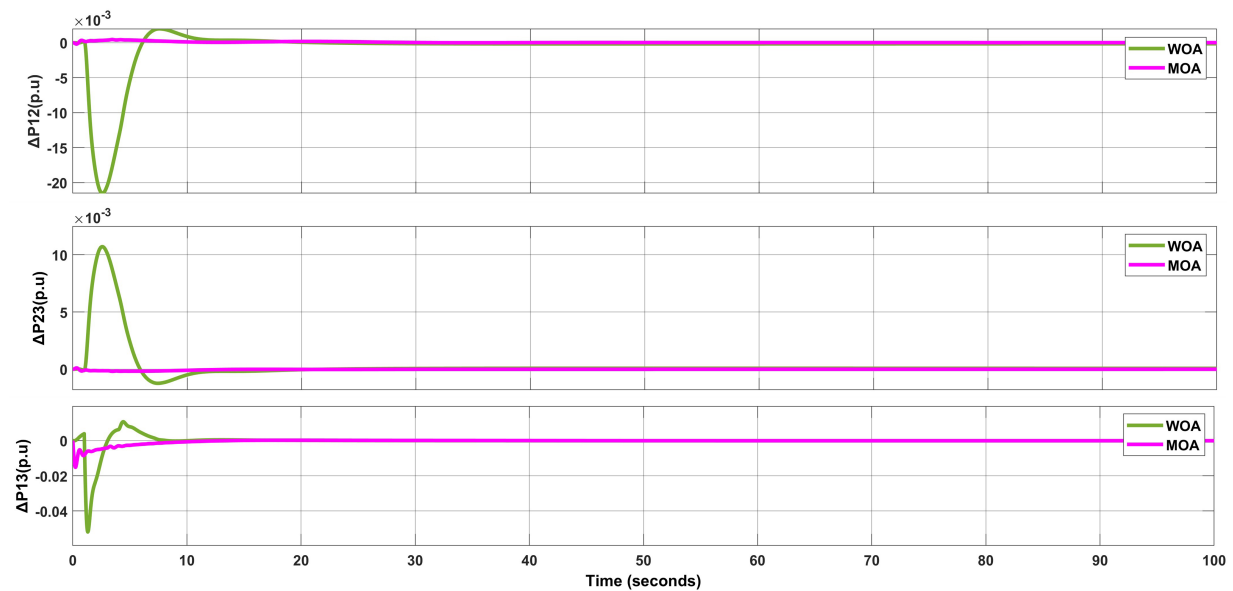


Figure 5: Tie line powers comparison of case 1

Table 2 provides the time domain specifications, such as undershoots with a value of -0.0617 , -10×10^{-3} , -8×10^{-3} and overshoot of 0.005 , 2.5×10^{-3} , 2.8×10^{-3} and settling time of 8.5 s, 14 , 15.5 s for the proposed approach and compared with that of WOA for POOLCO case study for frequency. Besides, Table 3 lists the optimized gain values of the FOPIDC adjusted using various optimization algorithms with ITAE values.

Table 2: Time domain specifications for Case-1 (Poolco)

Optimization	Specification	Undershoot	Overshoot	Settling time
WOA	ΔF_1	-0.051	0.010	9.2
	ΔF_2	-12×10^{-3}	0.001×10^{-3}	15
	ΔF_3	-11×10^{-3}	0.002×10^{-3}	16.2
	ΔP_{12}	-22×10^{-3}	2×10^{-3}	18
	ΔP_{23}	-1.5×10^{-3}	11×10^{-3}	16
	ΔP_{31}	-0.05	0.011	10
MOA	ΔF_1	-0.0617	0.005	8.5
	ΔF_2	-10×10^{-3}	2.5×10^{-3}	14
	ΔF_3	-8×10^{-3}	2.8×10^{-3}	15.5
	ΔP_{12}	-0.0008×10^{-3}	0.001×10^{-3}	12
	ΔP_{23}	-0.0006×10^{-3}	0.0001×10^{-3}	13
	ΔP_{31}	-0.012	0.0007	8

Table 3: Optimized control parameters for Case-1 (Poolco)

Optimization	ITAE	Parameter	FOPIDC-1	FOPIDC-2	FOPIDC-3
WOA	0.0005579	K_p	1.41212	1.1925	0.8236
		K_i	1.3972	1.054	0.8407
		K_d	1.0295	0.5745	0.5407
		λ	0.6925	0.6925	0.6775
		μ	0.8445	0.8621	0.8554
MOA	0.0005292	K_p	1.5	1.247	0.9989
		K_i	1.4852	1.199	0.8606
		K_d	1.1536	0.6715	0.5868
		λ	0.71216	0.78216	0.7821
		μ	0.8110	0.8214	0.8335

The enhanced performance of the suggested MOA optimized FOPIDC responds to the dynamic changes in tie line powers and frequency more quickly and smoothly than the other controllers. The suggested controller successfully reduces the Ups and downs in the area frequency deviation (Δf) and tie-line power deviation (ΔP_{tie}) transient responses. The power generating output for case study I is shown in Fig. 6. It's also important to note that the MOA-selected FOPIDC performs better than the WOA. Furthermore, Fig. 7 illustrates the convergence characteristics of WOA with the suggested controller, confirming the inadequacy of the optimization methods in terms of efficiency and speed.

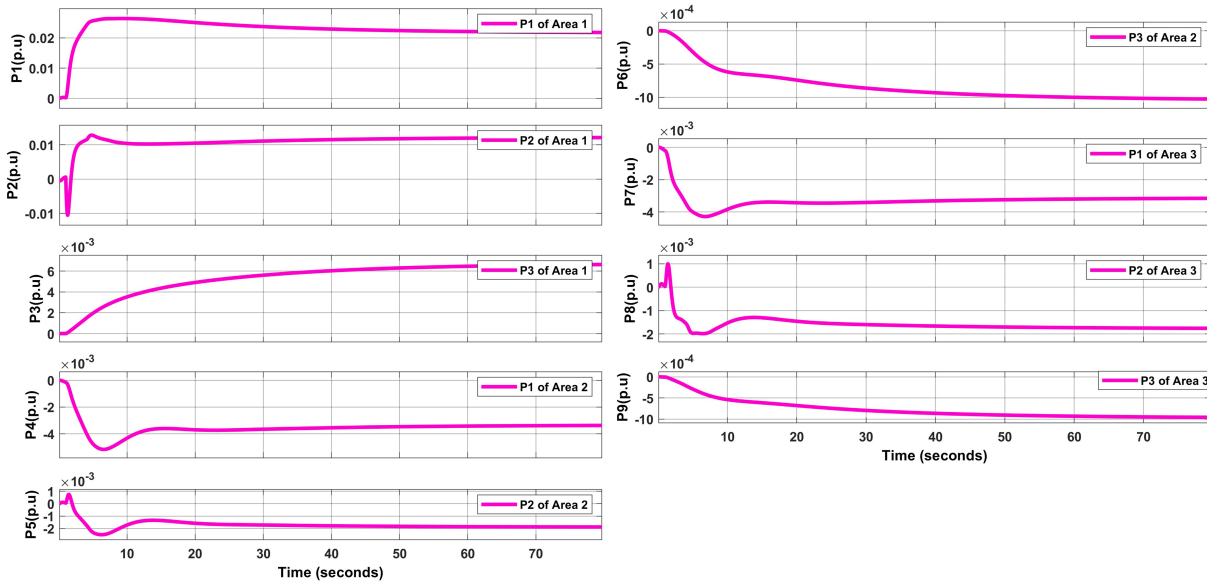


Figure 6: Power generation output of MOA of case 1

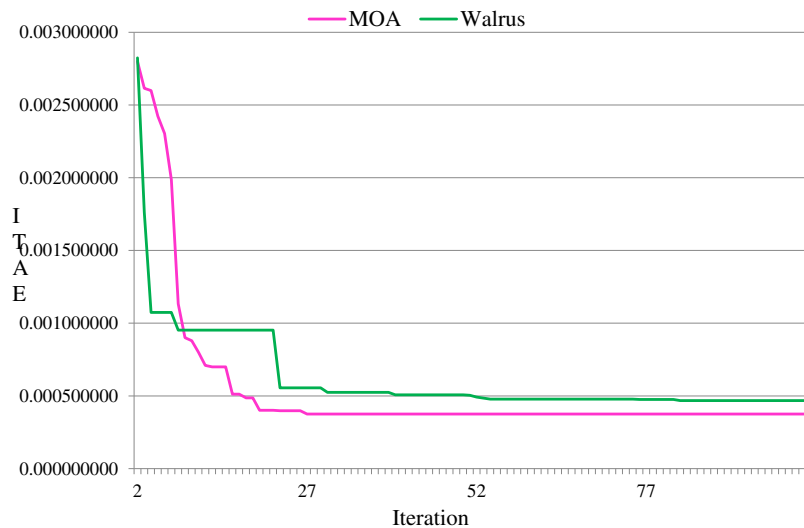


Figure 7: Convergence plot for case 1

Case study II: Bilateral agreement

In this case, DISCO's in any region are free to ask GENCO's in any region for power. Depending on the transaction allotted by the administrator, each GENCO modifies its power production to satisfy the needs of DISCOs. The following is the *DPM* for bilateral transactions.

$$DPM = \begin{bmatrix} 0.1 & 0.1 & 0.2 & 0.1 & 0.1 & 0.1 & 0.2 & 0.2 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.2 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.2 & 0.1 & 0.1 & 0.2 & 0.1 & 0.2 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.2 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.2 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \end{bmatrix} \quad (26)$$

In this case, the three area electricity systems have developed a bilateral agreement. Electrical load is currently changing for all DISCOs in each area; Area 1 with a load change of 0.03 per unit (p.u.), which is reflected in Area 2 in a similar manner. To get into the details of each DISCO; Area-1 DISCO-1 has a requirement of 0.01, DISCO-2 requires 0.01, and DISCO-3 requires 0.01. Conversely, DISCO-4 needs 0.01 in Area 2, DISCO-5 needs 0.01 as well, and DISCO-6 has a significant demand of 0.01. DISCO-7 needs 0.01 in region 3, DISCO8 needs 0.01, and DISCO9 has a significant demand of 0.01. The construction of *DPM* is carried out by the agreements that are taken between the DISCOs and GENCOs. Powers produced by the GENCOs are evaluated.

The time domain characteristics of the response values are compiled in Table 4, which makes it abundantly evident that the suggested controller greatly minimizes both overshoots and undershoots. The undershoot with a value of -0.05 , -7×10^{-3} , -5.6×10^{-3} , and overshoot of 0.01 , 5×10^{-3} , 5×10^{-3} , and settling time of 14.5 s, 16.8, 13.1 s for the proposed approach, and compared with that of WOA for the Bilateral case for frequency. Table 5 lists the optimal values for the controller's settings that were adjusted using four different optimization algorithms with the ITAE performance index, while Table 6 shows the superior performance of proposed method with methods that are available in the literature survey.

Table 4: Time domain specifications for Case-2 (Bilateral)

Optimization	Specification	Undershoot	Overshoot	Settling time
WOA	ΔF_1	-0.01	0.007	15
	ΔF_2	-14.5×10^{-3}	2×10^{-3}	17.2
	ΔF_3	-15.2×10^{-3}	1×10^{-3}	14.2
	ΔP_{12}	-18×10^{-3}	0.007×10^{-3}	79
	ΔP_{23}	-0.1×10^{-3}	9×10^{-3}	75
	ΔP_{31}	-0.04	0.006	35
MOA	ΔF_1	-0.05	0.01	11.5
	ΔF_2	-7×10^{-3}	5×10^{-3}	16.8
	ΔF_3	-5.6×10^{-3}	5×10^{-3}	13.1
	ΔP_{12}	-0.01×10^{-3}	0.003×10^{-3}	9
	ΔP_{23}	-0.005×10^{-3}	0.5×10^{-3}	9.5
	ΔP_{31}	-0.015	0.002	32

Table 5: Optimized control parameters for Case-2 (Bilateral)

Optimization	ITAE	Parameter	FOPIDC-1	FOPIDC-2	FOPIDC-3
WOA	0.0004509	K_p	1.385	0.321	0.328
		K_i	1.366	1.025	1.016
		K_d	0.952	0.577	0.867
		λ	0.824	0.801	0.784
		μ	0.802	0.709	0.807
MOA	0.000395	K_p	1.492	0.3504	0.477
		K_i	1.498	1.230	1.048
		K_d	1.002	0.688	0.982
		λ	0.895	0.815	0.895
		μ	0.816	0.816	0.816

Table 6: Settling time comparison with methods in literature

Case	Ref. [No.]	Controller	Settling time (s)
1	[13]	PSO-TID+IDN	14.17
	[13]	SSA-TID+IDN	11.69
	[13]	COA-TID	12.48
	[13]	COA-IDN	13.64
	Proposed	MOA-FOPIDC	8.5
2	[13]	PSO-TID+IDN	24.95
	[13]	SSA-TID+IDN	12.14
	[13]	COA-TID	11.13
	[13]	COA-IDN	13.53
	Proposed	MOA-FOPIDC	11.5

The ΔP_{tie} and ΔF are exhibited in Figs. 8 and 9. However, it is clear that compared to other controllers, the proposed MOA-tuned FOPIDC, which is used in the current system during bilateral agreements, performs exceptionally well. This is accomplished by lowering the settling times and successfully limiting the amplitudes of up and down. Additionally, as shown in Figs. 8 and 9, the MOA-tuned FOPIDC has produced better results than WOA. The power produced by generators in case study II is displayed in Fig. 10.

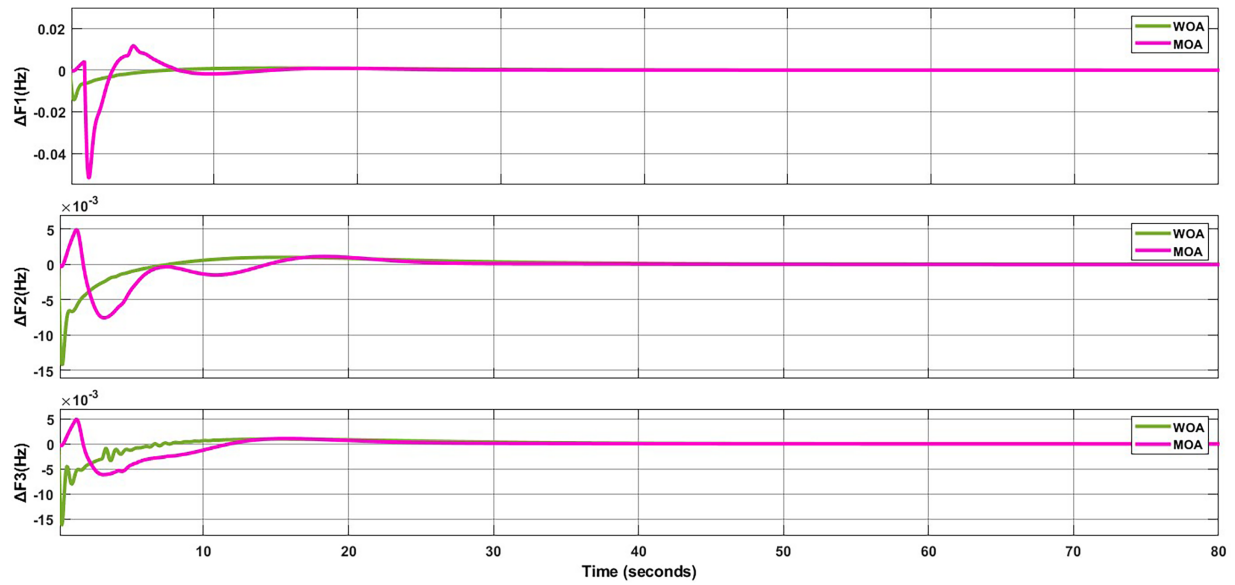


Figure 8: Frequency deviation comparison of case 2

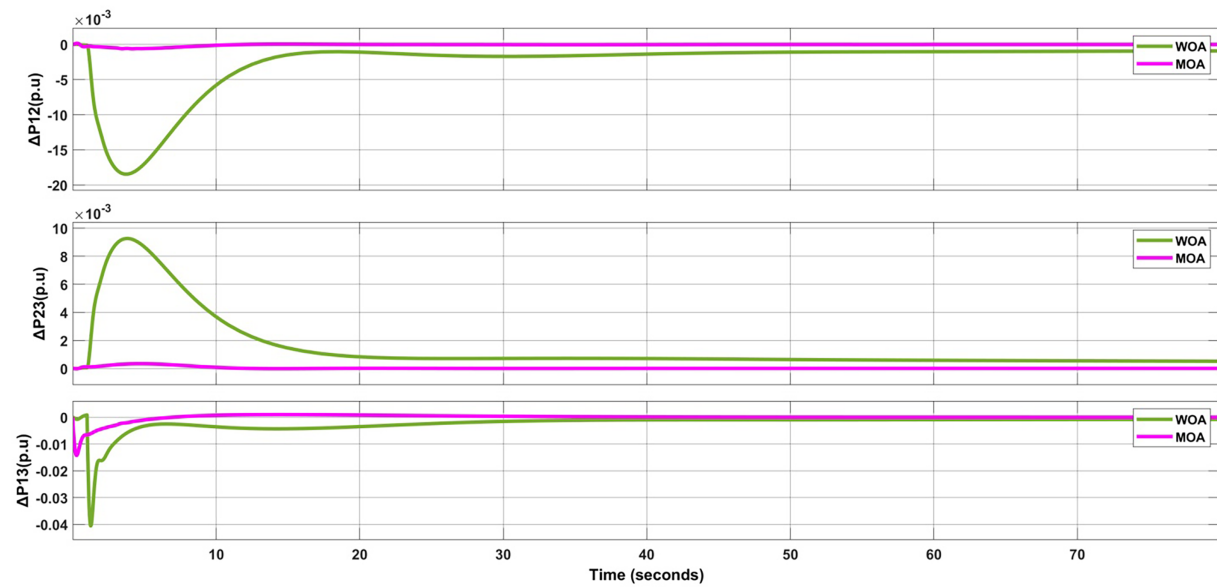


Figure 9: Tie line power comparison of case 2

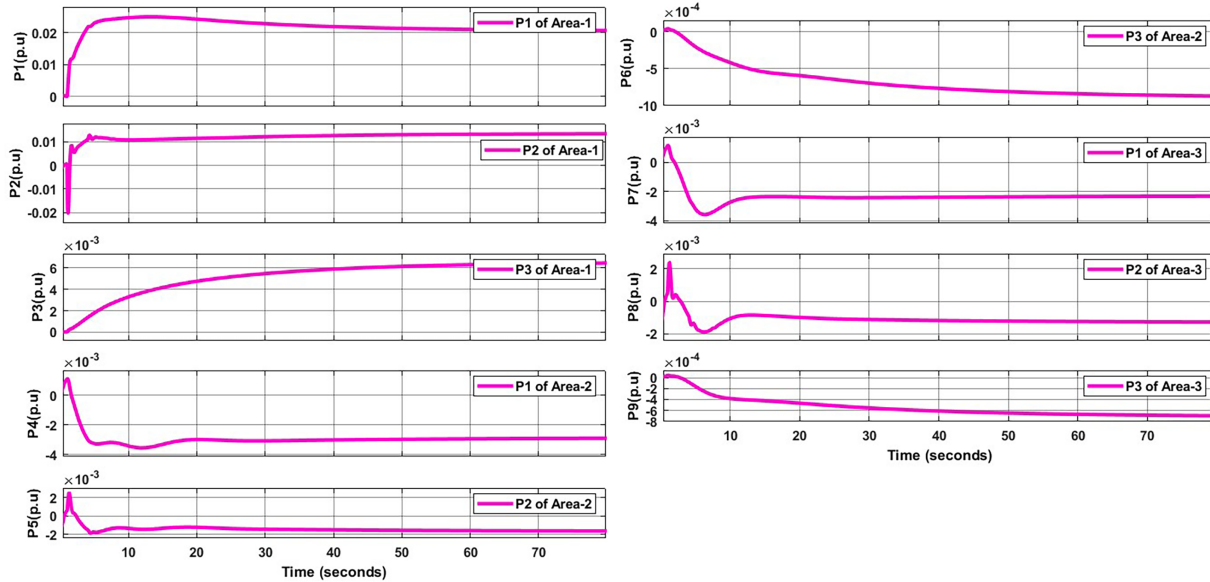


Figure 10: Output powers of MOA of case 2

Furthermore, [Table 7](#) provides the statistical analysis of ITAE carried out for case-1 and case 2, with the best, mean and worst values with standard deviation for 20 runs. The suggested method offers better robustness against market-driven power exchanges, EV-induced uncertainty, and renewable intermittency, as well as increased tuning flexibility and speedier convergence as shown in [Fig. 11](#).

Table 7: Statistical analysis of objective function for case studies for 25 runs

Case number	Best ITAE	Mean ITAE	Worst ITAE	Standard deviation
1	0.0005292	0.0005399	0.0005798	1.47×10^{-5}
2	0.0003950	0.0004101	0.0004502	1.35×10^{-5}

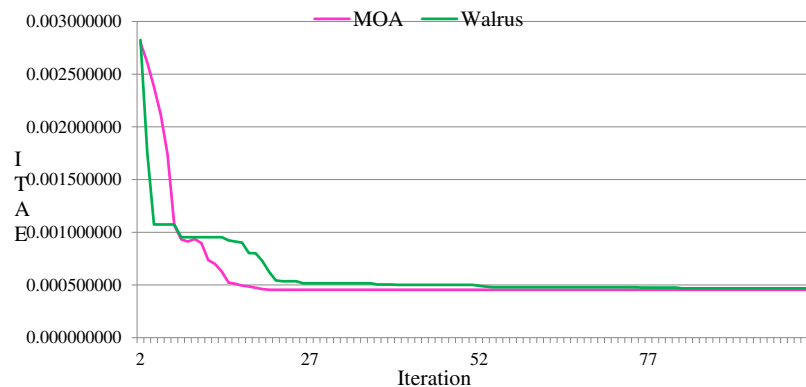


Figure 11: Convergence comparison plot of case 2

Case III: Frequency domain stability analysis

It is possible to do a stability study of the MOA-tuned FOPID controller, as seen in Fig. 12. A key technique for evaluating the stability properties of a system undergoing LFC is the frequency domain stability test, which uses Bode graphs. Analysts can identify important details like gain, resonances, phase margins, etc., by looking at the magnitude and phase responses. The investigation focuses on the effects of LFC interventions with the goal of optimizing these parameters to increase system stability. From the Fig. 12, it is clearly seen that the system is stable with positive gain and phase margins.

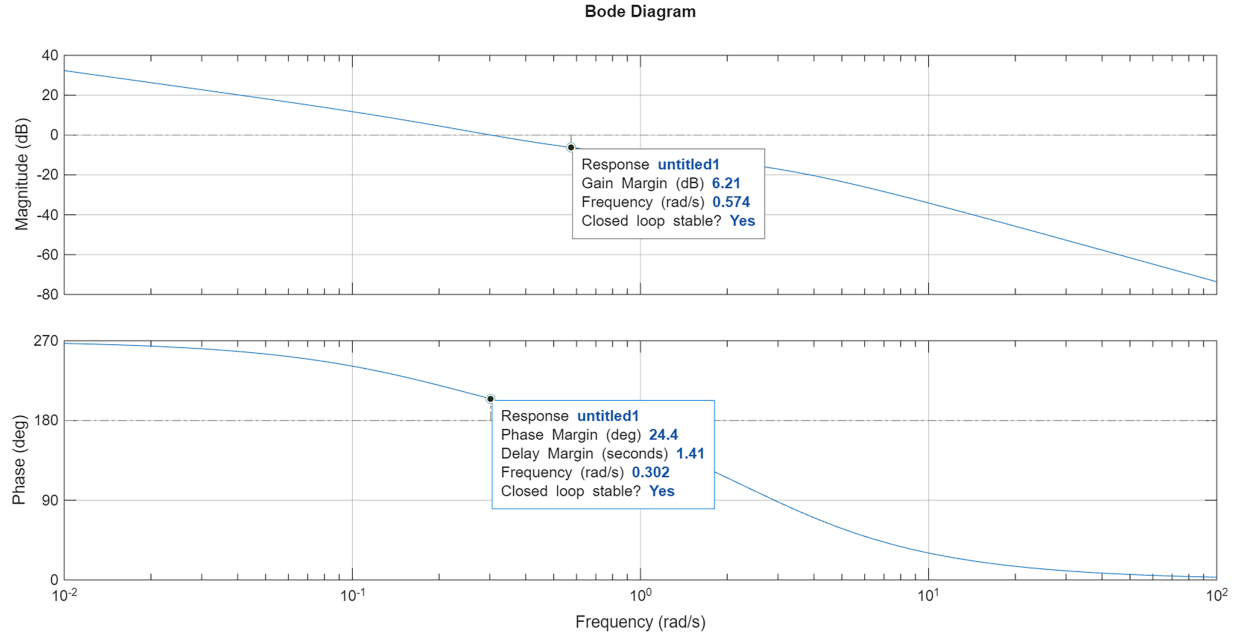


Figure 12: Bode plot for proposed controller

Case IV: Sensitivity analysis

The resilience of the MOA-tuned FOPID controller against parameter uncertainties and nonlinear operating conditions must be examined since an ideal model of a power system cannot be realised in actuality. The governor time constant (T_{gov}), frequency bias factor (β), and speed droop coefficient (R), three crucial system parameters, are separately modified within $\pm 40\%$ of their nominal values given in the Appendix A. Table 8 displays the obtained system performance indices for various operating circumstances together with the related MOA-optimised controller parameters.

A further analysis of Table 9 indicates that despite significant changes in system settings, the performance indicators show only slight fluctuations. Furthermore, Fig. 13 shows the frequency deviation responses of Area-1 for various values of T_{gov} , R , and β , showing that when the suggested controller is used, changes in system dynamics have very little impact on control performance. All things considered, our findings confirm the robustness of the suggested control strategy and its capacity to maintain steady and dependable functioning in the face of large parameter uncertainties and nonlinearities.

Table 8: Sensitivity analysis considering variations in power system parameters in Area-1 with proposed method

Parameter variation	% Change	Settling time (s)		
		ΔF_1	ΔF_2	ΔF_3
Nominal	0	8.5	9.44	10.13
T_{gov}	+40%	9.871	8.792	10.11
	-40%	9.852	8.676	10.09
R	+40%	8.88	9.415	10.244
	-40%	9.123	8.999	9.785
β	+40%	9.498	9.456	10.093
	-40%	9.754	9.444	9.456

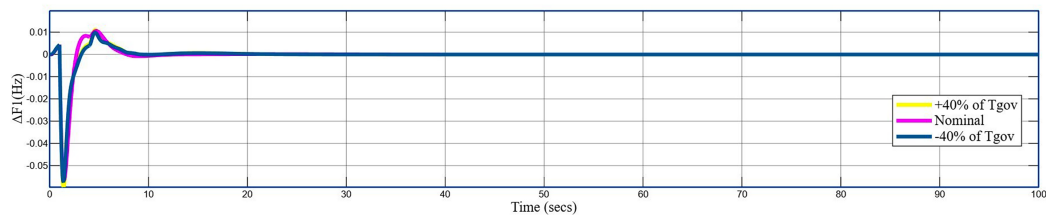
Table 9: Tuned parameters of the proposed controller under system parameter variation

Parameter variation	% Change	Parameter	Area 1	Area 2	Area 3
T_{gov}	+40%	K_p	1.5	1.4344	1.2691
		K_i	1.456	0.53457	0.73184
		K_d	1.0192	0.16403	1.0256
		λ	0.7039	0.8016	0.80334
		μ	0.935	0.938	0.765
	-40%	K_p	1.612	1.513	1.256
		K_i	1.543	1.274	0.789
		K_d	1.452	0.975	1.045
		λ	0.751	0.965	0.459
		μ	0.679	0.675	0.984
R	+40%	K_p	1.3592	0.69458	1.35275
		K_i	1.5	0.80879	0.64952
		K_d	0.52373	1.2201	0.95742
		λ	0.80243	0.80275	0.89274
		μ	0.9547	0.76543	0.87654
	-40%	K_p	1.5	1.5	1.3165
		K_i	1.3971	0.49419	0.67207
		K_d	1.0365	0.37656	0.14275
		λ	0.84946	0.84849	0.83945
		μ	0.75421	0.65428	0.75448
β	+40%	K_p	0.7884	1.11	0.97073
		K_i	1.5	1.3502	0.96172
		K_d	1.3639	0.9898	0.76578
		λ	0.77267	0.77467	0.77267
		μ	0.96082	0.97072	0.87172

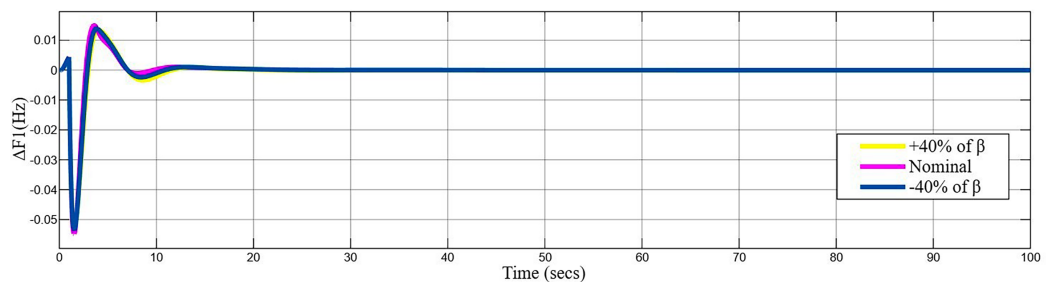
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Table 9 (continued)

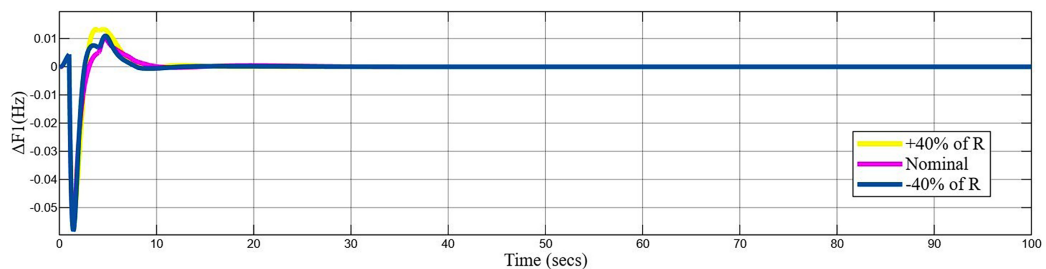
Parameter variation	% Change	Parameter	Area 1	Area 2	Area 3
	-40%	K_p	1.1899	1.3954	0.85018
		K_i	1.1749	0.88977	0.75916
		K_d	1.0152	0.68343	0.83469
		λ	0.88176	0.84567	0.74567
		μ	0.76943	0.79543	0.92347



(a) T_{gov}



(b) R



(c) β

Figure 13: Effect of power system parameter variations on the Area-1 frequency response (sensitivity analysis) of Area-1 with the proposed method

5 Conclusion

To control the frequency disturbances of a system with three distinct control areas, the paper presents a novel MOA for the best choice of FOPIDC gain settings. The study shows that the suggested

algorithm outperforms WOA in a deregulated field. Simulation results show that this method is more efficient than other controllers when used for LFC in a 3-Area PS. With faster settling times for ΔF_1 , ΔF_2 , ΔF_3 and ΔP_{12} , ΔP_{23} , ΔP_{31} —8.5, 14, 15.5, and 12, 13, 8 s, respectively, for Poolco agreement and 11.5, 16.8 13.1 and 9, 9.5, 3.2 s, respectively, for bilateral agreement with MOA optimized FOPID controller—the suggested controller outperforms the proposed controller in terms of time domain performance indices. Besides, when the MOA optimized controller is used in case 1, the objective ITAE for the transient responses is 0.0005292, while 0.000395 for case 2, which is lower than WOA. However, the study finds that the modified controller greatly reduces the system's maximum peak overshoot and undershoot after minor disruptions. Finally, the result analysis of the system highlights the effectiveness of the proposed method. The robustness of the suggested control idea has been evaluated using a stability analysis employing Bode plots in addition to parameter uncertainties and nonlinear operating conditions as a sensitivity analysis. Future work can be carried out with large-scale integrated power systems recently trending like hydrogen energy and other storage, with electric vehicles in the hybrid system, with hybrid optimization techniques including additional uncertainties like delays, cyber physical disturbances.

Acknowledgement: We would like to thank the department of EEE, JNTUH, for providing the necessary facilities to carry out this research work.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Saraswathi Sriramula: writing original draft, investigation, methodology, software, analysis. B. Ravindranath Reddy: review and editing, supervision and validation. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Data will be provided on request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The system parameters are [13,20,29]:

$P_R = 2000$ MW, $P_L = 1000$ MW, $f = 60$ Hz, $T_{G1} = 0.2$ s, $T_{G2} = 0.3$ s, $T_{T1} = 0.5$ s, $T_{T2} = 0.5$ s, $K_1 = 0.30$, $T_R = 10$ s, $T_{RH} = 28.70$ s, $T_{CH} = 0.2$ s, $T_W = 1$ s, $K_{pc} = 0.8$, $K_T = 0.5747$, $K_{Diesel} = 16.5$, $K_D = 0.2873$, $K_W = 0.138$, $T_{Wd1} = 0.041$ s, $T_{Wd2} = 0.6$ s, $K_{Wd1} = 1.25$, $K_{Wd2} = 1.3$, $D_1 = 0.6$, $D_2 = 0.9$, $H_1 = 5$, $H_2 = 5$, $K_{DG} = 16.5$, $T_D = 0.025$ s, $a_{12} = -1$, $K_p = 1/D$, $T_p = 2$ H/Df, $R_{T1} = R_{H1} = R_{G1} = 0.05$ Hz/p.u., $R_{T2} = R_{H2} = R_{G2} = 0.0625$ Hz/p.u., $K_2 = 0.85$, $K_3 = 0.095$, $K_4 = 0.92$, $C_{BD} = 200$, $K_{BD} = 0.03$, $T_{BD} = 26$ s, $T_{RBD} = 69$ s, $T_{DM} = 0$, $T_{FD} = 10$ s.

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