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RESEARCH ARTICLE

Fire Hawk Optimizer Adjusted Tri-Stage (1+PI)-PI-TID Cascade Controller for Automatic Generation Control of PSI

MOSES AWAL¹, MICHAEL ROBSON ATIM², JIMMY NABENDE WANZALA¹,
JOHNES OBUNGOLOCH³, AND MOHAMED BARAKAT^{4,5}

¹Physics Department, Mbarara University of Science and Technology, Mbarara, Uganda

²Physics Department, Busitema University, Tororo, Uganda

³Biomedical Sciences and Engineering Department, Mbarara University of Science and Technology, Mbarara, Uganda

⁴CEE Department, Faculty of Engineering, Canadian International College (CIC), Giza 12566, Egypt

⁵CCE Department, College of Engineering, Almaaqaal University, Basrah 61014, Iraq

Corresponding author: Jimmy Nabende Wanzala (wanzalajimmy@gmail.com)

ABSTRACT This study aims to enhance the performance of automatic generation control (AGC) in power systems interconnection (PSI) by employing the fire hawk optimizer (FHO), a green algorithm, to optimize a novel tri-stage cascade controllers (CCs) configuration: (1+PI)-PI-PID and (1+PI)-PI-TID CCs. The FHO draws inspiration from the foraging behaviors of whistling kites, black kites, and brown falcons, known for their unique prey-catching method involving fire propagation. Evaluation of the proposed FHO: (1+PI)-PI-T/PID scheme is conducted using the integral time multiplied absolute error (ITAE) criteria. The versatility of this technique is demonstrated across four PSI test models, including a two-area non-reheat thermal PSI (NRTPSI) and a multi-unit multi-area (MUMA) system incorporating reheat, hydro, and gas units. Challenges are addressed by initially testing NRTPSI with and without governor dead band (GDB) nonlinearity, showing the superior performance of the proposed method. Next, the HVDC link in MUMA is employed under different scenarios. To assess the robustness of the FHO: (1+PI)-PI-T/PID CCs, real-world AGC issues, such as sudden load perturbations and nonlinearities like generation rate constraint, GDB, boiler dynamics, and communication time delay in MUMA, are employed. Also, sensitivity analysis involving a range variation of $\pm 40\%$ in PSI model parameters is conducted for validation. The proposed scheme also undergoes evaluation under random step-load perturbations. The results demonstrate significant improvements in the performance of ITAE by 84.3%, 10.7%, 42.1%, and 16.7% for scenario 1 across all four tested models. The FHO: (1+PI)-PI-TID CC significantly improves system performance compared to existing controllers like the HHO: PD-PI CC, FHO: TID, FHO: PID, and the proposed FHO: (1+PI)-PI-PID CCs. This shows that this approach is effective at improving AGC capabilities and can be used in real life. Update each group's position using their respective equations.

INDEX TERMS One plus proportional integral-proportional integral-tilt integral derivative, cascade controller, fire hawk optimizer, automatic generation control, multi-unit multi-area (MUMA), PS nonlinearities, random step load.

NOMENCLATURE

i Related to numbers 1, 2, ..., n.
 P_L Operating load (MW).
 Δf_i Frequency deviation (Hz).

ΔP_{Li} Step load change.
 ΔP_{tie} Power deviation in tie-line (p.u.)
 TC Time constant.
 ST Settling time (S).
 B_i Bias frequency (p.u.MW/Hz).

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K_H	Contributing factors for hydro unit.
K_G	Contributing factors for gas unit.
K_{DC}	HVDC gain (Hz/p.u.).
i	Subscript related to area ($i = 1, 2$).
f	Operating frequency (Hz).
P_R	Rated Power for each area (MW).
T_{DC}	HVDC TS (S).
b_g	Gas turbine constant of positioner (S).
c_g	Gas turbine valve positioner (S).
Y_C	Lag time of gas turbine (S).
GDB	Governor dead band.
GRC	Generation rate constraints.
CTD	Communication time delay.
SLP	Sudden load perturbation.
ACE	Area Control Error.
BD	Boiler Dynamics.
CC	Cascade Controller.
FHO	Fire Hawk Optimizer.
PID	Proportional-Integral-Derivative.
PI	Proportional-Integral.
PSI	Power System Interconnection.
PS	Power System.
RLP	Random Load Perturbation.
TID	Tilt Integral Derivative.
R_i	Regulation speed (Hz/p.u.).
T_{ri}	Reheat TS (S).
K_{Ri}	Reheat coefficient of steam turbine.
K_{PSi}	Power system gain (Hz/p.u.).
T_{ti}	TS of steam turbine (S).
T_{gi}	TS of speed governor (S).
T_{I2}	Synchronizing coefficient (p.u.).
T_{RSi}	Reset time of hydro turbine (s).
T_{GHi}	TC hydro turbine (S).
T_{Wi}	Nominal initial time of water in penstock (S).
T_{RHi}	Hydro turbine speed governor droop TS (S).
T_{Psi}	TC of power system (S).
K_T	Contributing factors for thermal unit.
X_C	Lead time of gas turbine (S).
T_{CRi}	Time delay of Gas turbine combustion (S).
T_{CDi}	Gas turbine compressor discharge volume TS (S).
T_{fi}	Gas turbine fuel time constant (S).
TS	Time settled.
PSI	Power system interconnection.
FO	Fractional order.
RLP	Random step load.
AGC	Automatic generation control.
$NRTPSI$	Non-Reheat Thermal Power System Interconnection.
TID	Tilt integral derivative.
$MUMA$	Multi-unit multi-area.
$HVDC$	High voltage direct current.
$ITAE$	Integral Time multiplied by Absolute Error.
$ITSE$	Integral Time Squared Error.
ISE	Integral of Squared Error.

IAE	Integral of Absolute Error.
LFC	Load Frequency Control.
$MUMA$	Multi-Unit Multi-Area.

I. INTRODUCTION

The interconnection of numerous diverse generating units through tie-lines, necessitated by the escalating global demand for electricity, presents a significant challenge in electric power systems. Managing these intricate power system interconnections (PSI) amidst increasing size and complexity, alongside sudden indoor and outdoor disturbances, presents a formidable task. Fluctuations in consumer demand can induce frequency variations, impacting tie-line power and frequency stability [1]. Substantial fluctuations may strain equipment and jeopardize overall system stability [2]. Effective load frequency control (LFC) is crucial to ensure power generation matches demand, safeguarding the stability and reliability of PSI [3]. In PSI scenarios, each area typically requires a controller to coordinate power generation. LFC's main goal is to deal with sudden changes in load while considering modeling flaws and nonlinearities, reducing tie-line power differences and frequency changes, and improving transient response [4]. Inadequate LFC design can trigger undesirable oscillations in generation, area frequency, and tie-line power flows, undermining system performance and risking instability and desynchronization. Given these challenges, the efficacy of power system LFC hinges on advanced and efficient control methodologies [5].

Traditional and optimal PID controllers are commonly used in LFC to manage tie-line power and frequency fluctuations due to their straightforward structure and effective performance [1], [6]. Previous studies have analyzed the effectiveness of soft computing-based

PID controllers compared to other controller types like I, PI, and conventional PID controllers, as recommended in [7] and [8]. However, PID controllers face challenges with tuning, response, nonlinearity, and delayed performance in the face of sudden load disruptions or parametric changes, making them less ideal for integration with current power grids and renewable energy sources [9], [10], [11].

Several studies have highlighted the superior performance of well-defined cascaded control (CC) schemes over conventional single controllers, with the CC concept known for swift disturbance rejection [7]. Advanced metaheuristic algorithms have been developed for LFC in both traditional and modern power systems, demonstrating superior performance compared to conventional control strategies. Commonly applied in power systems are two-area two-unit and two-area multi-unit systems. Examples of such schemes include TLBO [2], Equilibrium Optimizer (EO) algorithm [12], differential evolution (DE) [13], Golden Jackal Optimizer (GJO) [14], grey wolf optimizer [15], water cycle algorithm [1], flow direction algorithm (FDA) [16], squid game optimizer (SGO) [9], and Harris Hawks optimizer [17]. Novel optimization

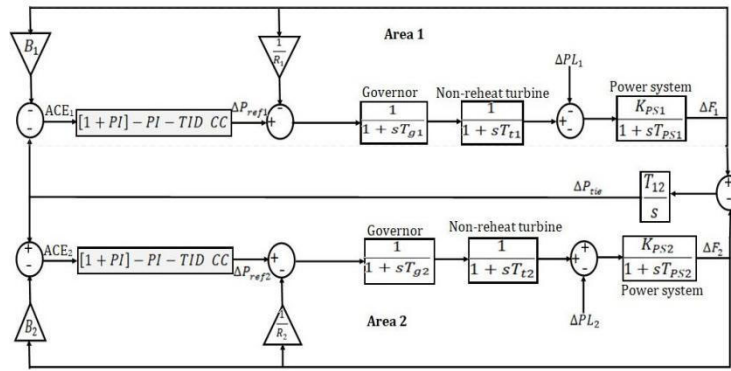


FIGURE 1. Two-area NRTPSI.

methodologies are devised for LFC management, including the LUS-TLBO algorithm detailed in [18] and the dragonfly search algorithm [8]. When juxtaposed against conventional control strategies, these algorithms demonstrate superior performance, underscoring their efficacy in addressing the LFC challenge. Consequently, considerable scholarly attention has focused on novel metaheuristic algorithms based on cascading various control methodologies to address the imperative for effective and efficient controller synthesis.

Noteworthy proposals for LFC in diverse PSI include the DSA-tuned (1+PD)-PID [8], the sine-cosine algorithm (SCA)-tuned PD-PID with a double derivative filter [19], the bat algorithm-optimized PD-PID [20], and the Harris Hawks optimizer-based PD-PI CC [17]. Adaptive DE-based multistage PDF plus (1+PI) is presented in [21] and [22]. The algorithms of hybrid stochastic fractal search and pattern search, flower pollination, and modified GWO techniques are optimized PI-PD CC in [23], [24], and [25], respectively. According to [26], authors proposed a novel frequency regulation approach involving the utilization of a fractional-order (FO) controller, such as FOPID, for the LFC component in conjunction with a superconducting energy storage system. Also, the WCA-based tilt derivative-tilt integral (TD-TI) CC is employed in [27], which improves the system dynamic response. For the LFC of the multi-area renewable-integrated hybrid power system, [28] suggested a novel FOPID- (1 + TD) controller. Overall, the use of FO controllers can lead to improved control system performance, stability, and robustness in a wide range of applications compared to traditional integer-order controllers. On the other hand, incorporating the extra fractional parameter dictates an efficient tuning method for cautious parameter selection [29].

Furthermore, in an effort to solve the intricate problems related to LFC, [30] presents a tri-stage (1+PI)-PI-PID CC optimized utilizing the enhanced artificial bee colony-particle swarm optimization (IABC-PSO) algorithm for LFC in PSI, and [31] suggests 2DOF-PID-TD, a unique hybrid control architecture. In a deregulated setting, authors in [32] suggested a branched combination of fuzzy FOPI (FFOPI) plus PID with filter (FFOPI + PIDN) for a two-area power system.

[12] looks at the new type-2 fuzzy integral-derivative plus proportional (T2FIDPP) controller for LFC of a deregulated two-area hybrid power system that has several generating units. In [33], a new design of intelligent multi-stage fuzzy-assisted PID with filter minus (1+PI), i.e., FPIDF-(1+PI) CC, is developed to improve the conduct of AGC of PSI. They employed a new quasi-opposition-based equilibrium optimizer algorithm to identify the optimal controller settings, with the goal of minimizing the integral of squared error. The tri-stage CCs improve the overall dynamic system response because they can better reject disturbances. Although a 3-stage controller in AGC offers significant advantages in terms of stability, performance, and flexibility, it also presents challenges related to complexity, tuning, and cost. Careful consideration is required to balance these factors for optimal system performance [30].

In order to improve the LFC performance, this study introduces a novel tri-stage CCs framework denoted as (1+PI)-PI-PID and (1+PI)-PI-TID. TID controllers can provide better performance in challenging scenarios, especially where time delays are significant. Although the (1+PI)-PI-TID CC attains better results than (1+PI)-PI-PID, the (1+PI)-PI-TID CC is more complex than (1+PI)-PI-PID, as the TID may involve more complex tuning strategies compared to standard PID [34]. Notably, a distinguishing feature of this scheme compared to its predecessors is the integration of the dual-stage CCs output alongside the frequency deviation (Δf) and tie line power deviation ΔP_{tie} signals. Therefore, this research presents the fire hawk optimizer (FHO), a novel metaheuristic algorithm that draws inspiration from the hunting behaviors of fire hawks, such as brown falcons, black kites, and whistling kites. These birds are known for their unique method of using fire to catch prey, hence earning them the moniker “fire hawks”. The FHO algorithm, unlike particle swarm optimization (PSO), has a fast convergence rate, a better ability to optimize the objective function, reduced computational times, improved exploration and exploitation capabilities, lower complexity, and the ability to focus on local peaks instead of global optima, making it easier to find the best solution. Therefore,

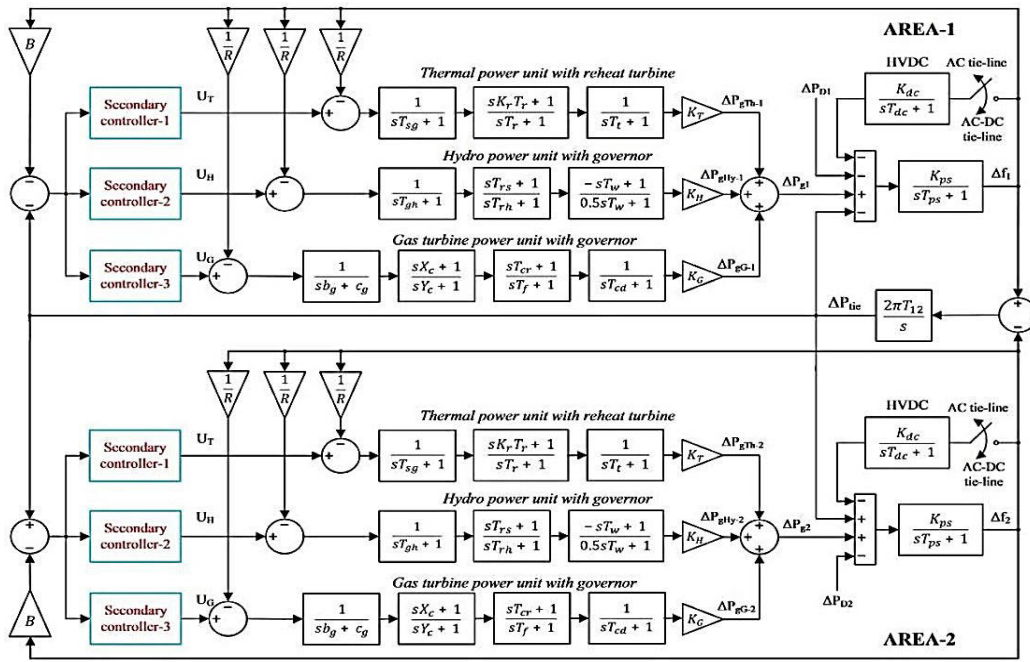


FIGURE 2. Transfer function model of MUMA.

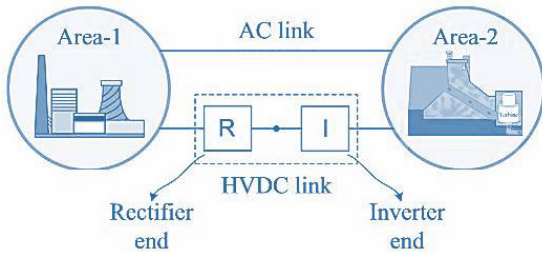


FIGURE 3. Diagrammatic representation of a merged two-area PSI integrating parallel AC-DC lines.

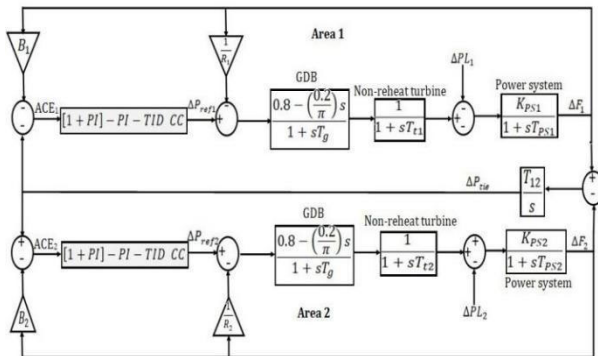


FIGURE 4. NRTPSI with GDB.

this study introduces the FHO technique for the first time, aiming to fine-tune a novel (1+PI)-PI-TID CC system for AGC of a multi-area PSI.

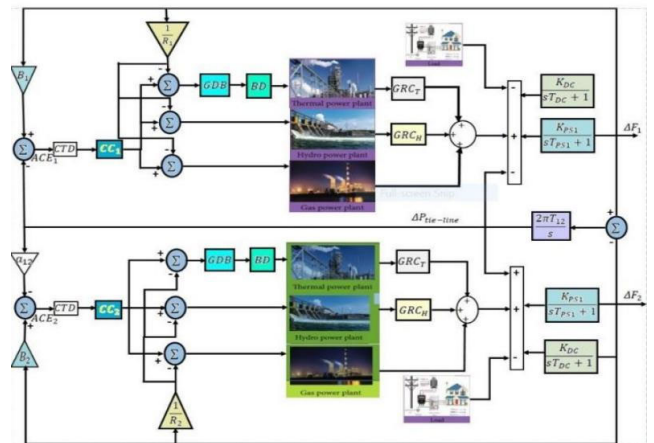


FIGURE 5. Block diagram of MUMA with nonlinearities.

A. KEY RESEARCH GAPS AND MOTIVATION

The dynamic nature of PSs requires advanced control strategies to effectively manage LFC. Although previous studies have highlighted both the successes and limitations of traditional LFC controller designs, such as PID and fuzzy logic controllers, particularly in their ability to adapt to time-varying nonlinearities, there are many lacks in literature, such as:

- Comprehensive analysis: Few investigations adequately consider real-world limitations, such as nonlinearities considering CTD, parameter uncertainties, and random step-load perturbations, which are critical for assessing the robustness of LFC strategies.

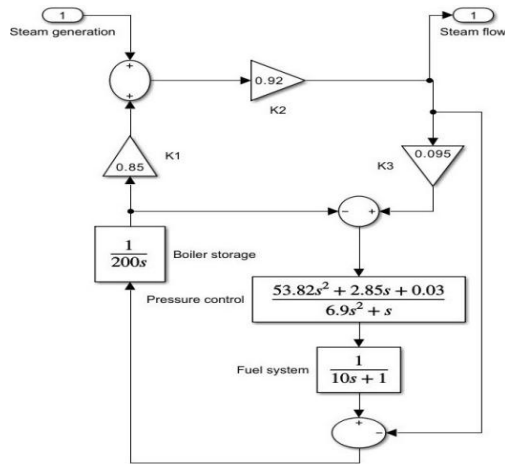


FIGURE 6. Modelling of BD nonlinearity.

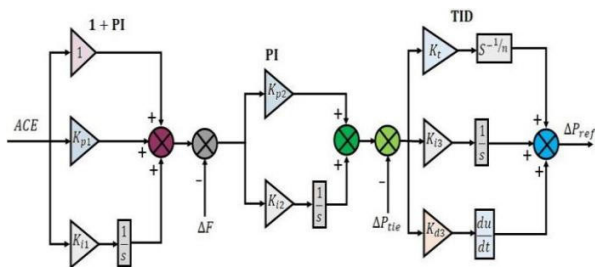


FIGURE 7. Structure of (1+PI)-PI-TID CC.

- Emerging optimization techniques: The application of novel optimization algorithms, such as the FHO, in addressing LFC challenges remains largely unexplored, presenting an opportunity for enhanced controller performance.
- Performance metrics: Current research insufficiently addresses the need for robust performance metrics in multi-area power systems, which are essential for evaluating the effectiveness of LFC controllers under diverse operational conditions.
- Smoothing of signals: There is a need for research focusing on methods to achieve smoother signal outputs in LFC systems to be adequate for smart grids.

This research introduces two novel tri-stage controllers: (1+PI)-PI-TID and (1+PI)-PI-PID, which aim to enhance system performance through the integration of critical signals; ACE , Δf , and ΔP_{tie} , and the application of FO dynamics. By utilizing a tilting block represented by $s^{-1/n}$, these controllers improve transient response, disturbance rejection, and overall system robustness. The proposed FHO: (1+PI)-PI-TID controller will be evaluated against the FHO: (1+PI)-PI-PID controller under identical conditions to demonstrate the advantages of fractional-order control. However, there is a pressing need to examine the resilience of LFC approaches to real-world limitations, such as nonlinearities and parameter

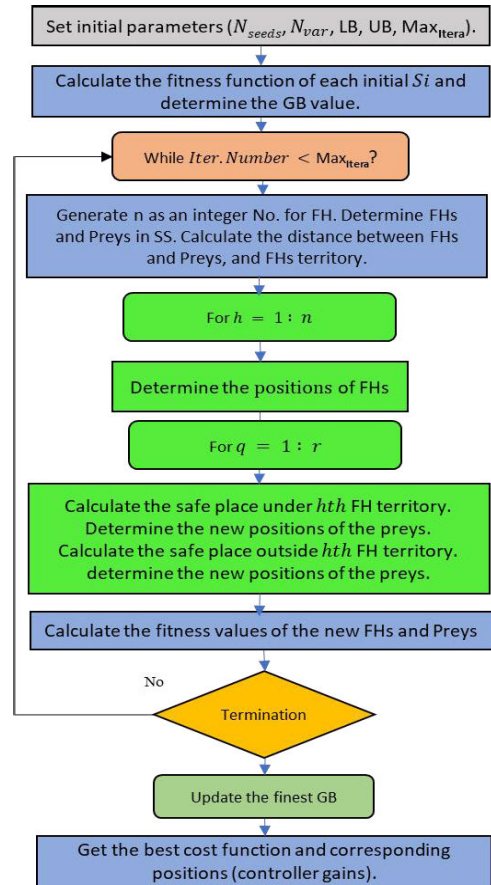


FIGURE 8. FHO flowchart.

uncertainties, which have not been adequately addressed in existing literature.

B. CONTRIBUTIONS OF THIS STUDY

The contributions of this study are outlined as follows, distinguishing it from existing research in related areas:

- 1) Proposing a robust scheme, such as a novel FHO-based (1+PI)-PI-PID and (1+PI)-PI-TID CCs, to tackle LFC challenges in PSI across diverse models.
- 2) Evaluating the dynamic performance of the suggested FHO: (1+PI)-PI-TID CC in comparison to other published control schemes.
- 3) Assessing the robustness of the proposed method in a MUMA both with and without an HVDC link
- 4) Analyzing hybrid power systems incorporating various nonlinearities like CTD, GRC, B, and GDB to create a realistic and robust system model.
- 5) Evaluating the controller's performance through sensitivity analysis using random step load (RSL) perturbations.
- 6) Assessing the robustness and stability of the proposed controller under significant variations in power system parameters, ensuring reliable performance across a wide range of operating scenarios in hybrid power systems.

TABLE 1. The main difference of the studied models.

Test model	Scale	Characteristic s	Scenarios	Competitors
Test model 1 NRTPSI	Two- areas	Linear	1. 10% SLP in area 1. 2. 20% SLP in area 1. 3. 10% and 20% SLPs in area 1 and area 2, respectively.	IGWO: PID[60], HHO: PD-PI [10] ISFS: PID[53], DSA: (1+PD)- PID[8], and FHO: (1+PI)-PI- PID[30].
Test model 2 NRTPSI	Two- areas	GDB nonlinearity	1. Convergence characteristics curve under 1% SLP at area 1. 2. 3 % SLP at area 1.	SCA [56] and PSO [61], [62] ISFS: PID [36], HBFO-PSO: PI [3], CPSO: PI [63], HHO: PID [10], and FHO: (1+PI)-PI-PID [30]
Test model 3 MUMA	Two- areas	Linear with HVDC link	1. 1% SLP in area-1. 2. 1-5% SLP in area 1. 3. Comparison AC-DC and AC tie- line.	TLBO: PID [2], IPA: TID[64], HHO: PD-PI [10], TD-TI CC [27], and FHO: (1+PI)-PI-PID [30]
Test model 4 MUMA	Two- areas	GRC, GDB, TD, and BD nonlinearities	1. 1% SLP in area 1. 2. Applied random step load. 3. Sensitivity analysis under changes some parameters.	HHO: PD-PI [10], FHO: (1+PI)-PI- PID[30], FHO: PID, and FHO: TID

TABLE 2. Tuned FHO parameters for (1+PI)-PI-TID controller in LFC.

Symbol	Parameter	Recommended Value	Explanation
N	Population size	40	The total number of individuals (both fire hawks and prey) in the search space. A size of 40 offers a good trade-off between solution diversity and computational cost for medium-complexity systems like LFC with nonlinearities.
Max_{iter}	Maximum No of iterations	50–100	The number of generations or loops the algorithm runs. Higher values allow more refined searching but increase runtime. 50–100 is usually sufficient for convergence in LFC tuning tasks.
N_{FH}	Number of fire Hawks	15 ($\approx 37.5\%$)	Fire hawks are elite individuals responsible for intensifying the search around promising areas. Allocating $\sim 37.5\%$ helps balance exploration (by prey) and exploitation (by fire hawks).
A	Attack coefficient	0.8	Controls how aggressively fire hawks move toward prey. A higher value (close to 1) ensures strong exploitation near good solutions. Helps refine gains for transient response.
β	Flight control factor	1.2	Determines how far individuals can fly during exploration. Value >1 encourages broader search in early iterations, avoiding local minima, crucial for nonlinear systems.
P_{esc}	Escape probability	0.2	Defines the likelihood that prey will escape and reposition. This helps maintain diversity in the population and prevents premature convergence to suboptimal solutions.

II. MATERIALS AND METHODS

A. LINEAR TEST MODELS

1) TWO AREA NON-REHEAT THERMAL PSI (NRTPSI)

The system model is represented in transfer function form, encompassing the governor, turbine, and load-inertia components. Feedback from the speed regulation constant and frequency bias factors influence the frequency output. The system includes two frequency variations ΔF_i , ΔF_1 , for area 1 and ΔF_2 , for area 2, and tie-line power change ΔP_{tie} . The step load form is used to present the power demand. The power demand increment for area 1 is ΔP_{l1} , and for area 2, it is ΔP_{l2} . The AGC components of the two-area PSI are shown in Fig. 1, as in [35], [36], and [37].

The transfer functions (TF) in the s-domain for these elements are:

Governor model: The governor TF is as in equation 1 and T_{gi} represents the governor time constant (TC).

$$G_G(s) = \frac{1}{1 + T_{gi}s} \quad (1)$$

where i is subscript to 1 and 2 for area 1 and 2.

Turbine model: Water's potential energy is converted by the turbine into kinetic energy, which generators then use to create electrical energy. The turbine TF is given by

$$G_T(s) = \frac{1}{1 + T_{ti}s} \quad (2)$$

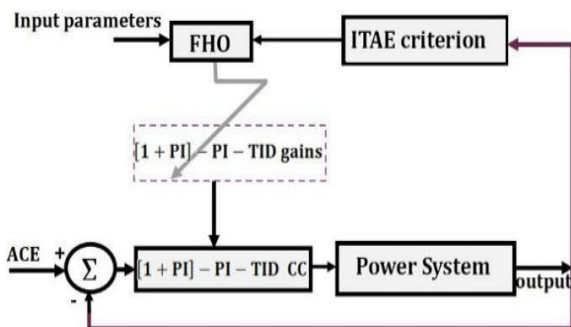
TABLE 3. FHO optimized (1+PI)-PI-TID CC gains under test model 1 at 10% SLP (scenario 1).

Algorithm	Controller parameters			n
	K_p/K_T	K_I	K_D	
IGWO: PID [60]	3.7974	4.9900	1.2403	n/a
FHO: PID	3.1123	5.0000	0.8502	n/a
ISFS: PID [53]	1.6293	2.0000	0.5882	n/a
HHO: PD-PI [17]				n/a
PD Controller	5.0000	—	4.1768	
PI Controller	1.8010	5.0000	—	
DSA: (1+PD)-PID [8]				n/a
1+PD Controller	3.0000	—	1.2130	
PID Controller	1.2830	3.0000	0.0050	
FHO: (1+PI)-PI-PID [30]				n/a
1+PI Controller	2.1414	0.0000	—	
PI Controller	5.0000	4.7905	—	
TID Controller	0.6302	5.0000	0.1725	
FHO: (1+PI)-PI-TID				
1+PI Controller	5.0000	0.0162	—	
PI Controller	5.0000	0.0000	—	
TID Controller	2.3194	5.00000	0.3580	6.3748

TABLE 4. Evaluation and comparison of (1+PI)-PI-TID CC performance at 10% SLP (scenario 1).

Algorithm	$\mathcal{L}$		ST (0.002 band) (s)			Undershoot(-ve)		
	ITAE	ITSE $\times 10^{-5}$	ΔF_1	ΔF_2	ΔP	ΔF_1	ΔF_2 $\times 10^{-3}$	ΔP $\times 10^{-4}$
FHO: (1+PI)-PI-TID	0.0011	0.1593	0.323	0.000	0.000	0.0160	1.235	5.062
FHO: (1+PI)-PI-PID [30]	0.0070	3.5830	1.314	0.715	0.000	0.0330	3.881	18.74
HHO: PD-PI [17]	0.0079	1.7260	0.700	0.840	0.000	0.0280	4.888	16.23
DSA: (1+PD)-PID [6]	0.0110	n/a	0.350	1.170	0.740	0.0361	8.600	32.00
FHO: PID	0.0443	64.030	2.000	2.000	1.695	0.0640	26.00	94.55
IGWO: PID [60]	0.0473	53.325	1.170	2.280	1.862	0.0510	19.00	73.93
ISFS: PID [53]	n/a	n/a	2.150	3.660	3.010	0.0820	42.00	160.0
% Improvement (1+PI)-PI-TID	84.3%	90.8%	7.7%	100%	-	42.9%	68.2%	68.8%

"n/a" denotes that the result is not applicable/available, and bold faces indicate the best results.

**FIGURE 9.** FHO-based (1+PI)-PI-TID CC.

Power system: Equation 3 yields the power system's TF.

$$G_{ps}(s) = \frac{K_{PSi}}{1 + T_{PSi}s} \quad (3)$$

$$K_{PSi} = \frac{1}{D} \quad (4)$$

$$T_{PSi} = \frac{2H}{fD} \quad (5)$$

$$D = \frac{\text{Nominal Load}(P_l)}{\text{Nominal Frequency}(f)} \quad (6)$$

where f is the nominal frequency, H is inertia constant, and P_l is the load connected to PS.

Frequency bias factor: The frequency bias factor (B), which is the entirety of the frequency-sensitive load change (D) and speed regulation (R), is denoted by [38].

$$B = \frac{1}{R} + D \quad (7)$$

The effect of combining tie-line power error and frequency fluctuation is attributed to the ACE [23] and [24]. The ACEs, ΔF_i , and ΔP_{tie} are inputs to the proposed (1+PI)-PI-TID CC

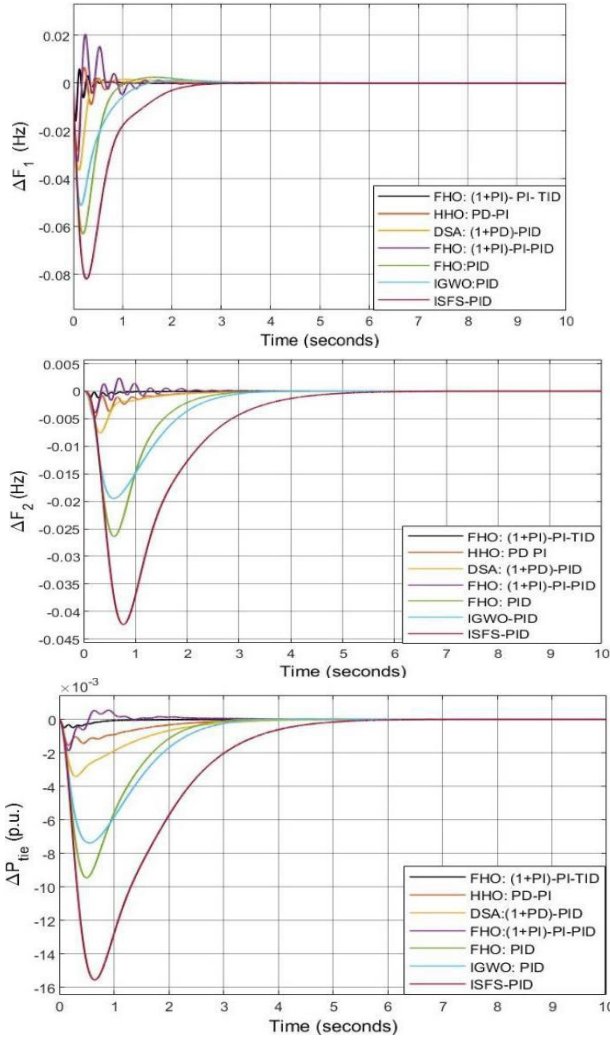


FIGURE 10. Contrast dynamic responses under test model 1 at scenario 1.

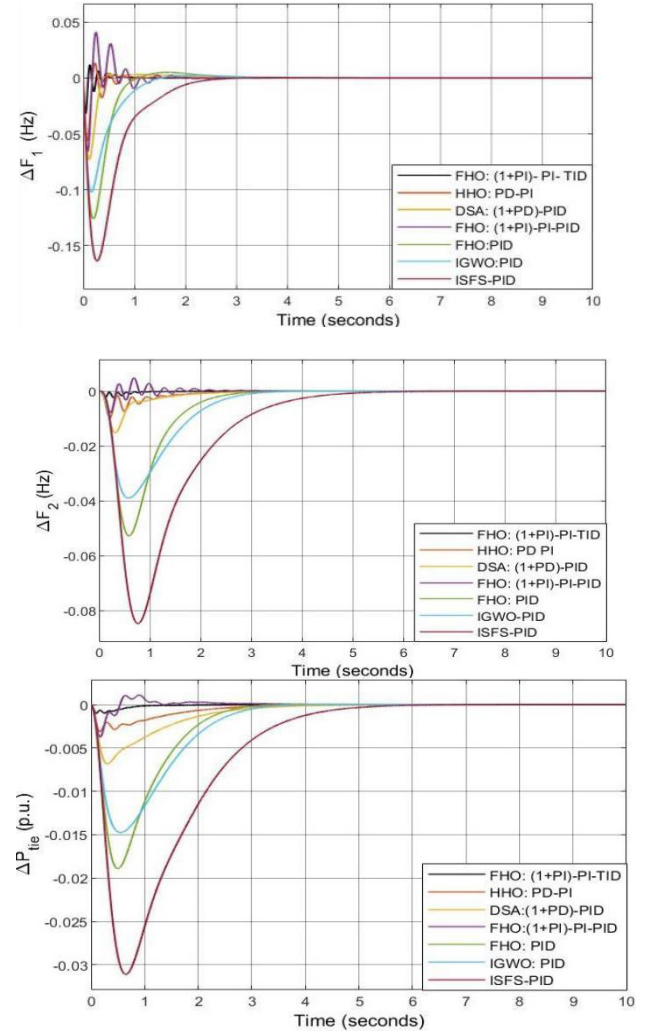


FIGURE 11. Contrast dynamic responses under test model 1 at scenario 2.

corresponding to each area. The area-specific ACEs

$$\begin{aligned} ACE_1 &= \Delta P_{tie} + B_1 \Delta F_1 \\ ACE_2 &= \Delta P_{tie} + B_2 \Delta F_2 \end{aligned} \quad (8)$$

where B is the frequency bias factor [38]. In the event of a load disturbance on the power system, ACEs are employed as a regulating signal to reduce ΔP_{tie} and ΔF_1 to zero at the steady state.

2) MUMA WITH HVDC AND AC TIE-LINES

An extra inquiry was supported by integrating the HVDC link to the MUMA power system. Separate secondary controllers in each section regulate the rate of generation from the thermal, hydro, and gas units, as seen in Fig. 2, and Fig. 3 models a two-area power plant as in [8], connected by AC-DC parallel lines. When the switch is turned on, the system uses an HVDC link in parallel with the existing AC link, and when the switch is turned off, only an AC tie-line is utilized to connect the two areas. With a gain of K_{DC} and a time constant

of T_{DC} , a first-order transfer function model provides the description of a DC link as.

$$\Delta P_{tie,DC} = \frac{K_{DC}}{1 + T_{DC}S} \quad (9)$$

In the LFC region, HVDC links are starting to be widely employed for power exchange across control areas in parallel with the current high-voltage AC links. Research shows that HVDC links operating in tandem with conventional AC links offer not only affordable and environmentally friendly benefits but also ensure higher-quality electric power delivery [41]. Moreover, it strengthens the system's resistance to minor disruptions [42].

B. NONLINEAR TEST MODELS

To make the multi-unit multi-area PSI more realistic, a number of physical nonlinearities are added to the linear PSI test models. Initially, the GDB nonlinearity is integrated into the NRTPSI as test model 2 to evaluate the proposed algorithm's effectiveness in handling power system

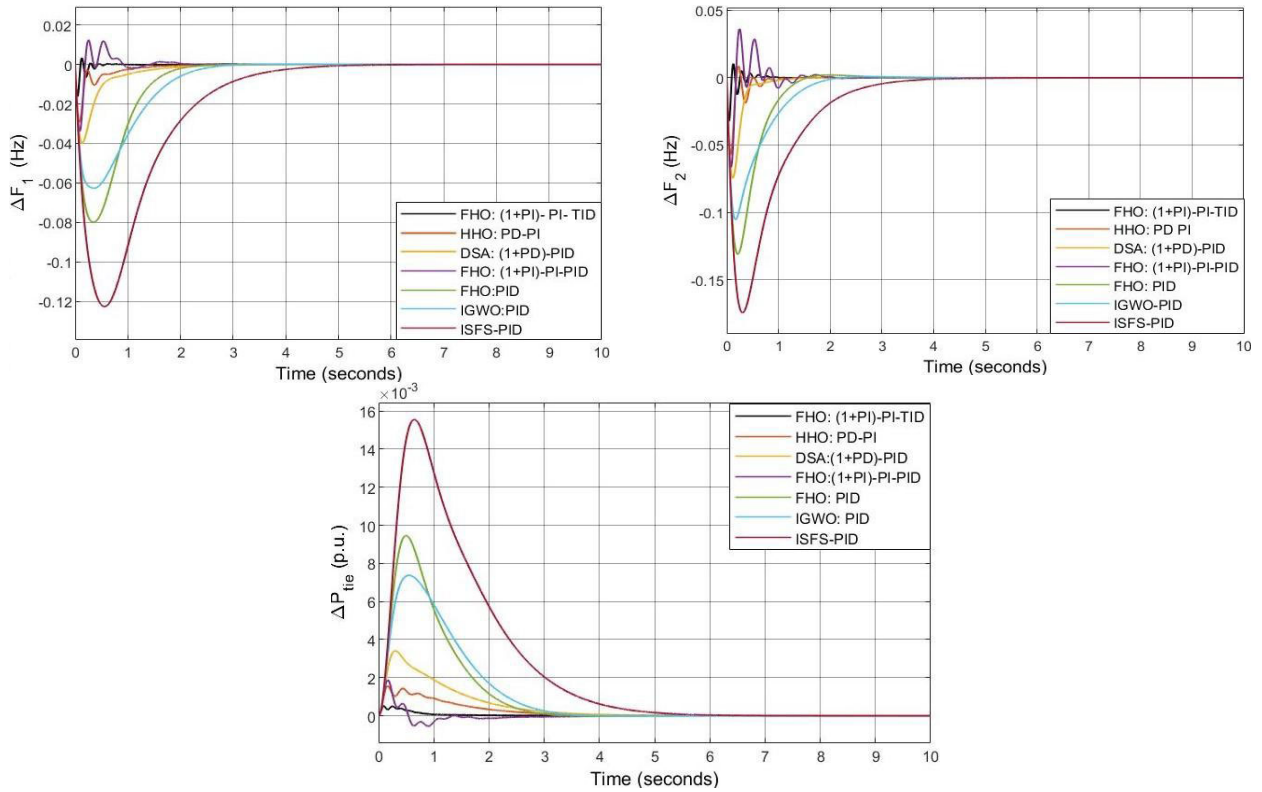


FIGURE 12. Contrast dynamic responses under test model 1 at scenario 3.

nonlinearities, as depicted in Fig. 4. Subsequently, the nonlinearities of GRC, GDB, CTD, and BD are incorporated into MUMA, as illustrated in Fig. 5. A significant nonlinear element, known as GRC, was introduced to restrict the rate of generation change. Literature suggests that a GRC value of 3% per minute is the standard benchmark for thermal plants. Therefore, for the thermal system, GRC is defined as $|\Delta P_g| \leq 0.0005 \text{ p.u.MW/s}$ to prevent excessive generation. The thermal unit's saturation block is limited to ± 0.0005 to manage generation levels effectively. For hydro power plants, a GRC of 270% per minute for increasing generation and 360% per minute for decreasing generation was considered. This translates to $|\Delta P_g(s)| \leq 0.06 \text{ p.u.MW/s}$ for decreasing generation and $|\Delta P_g(s)| \leq 0.045 \text{ p.u.MW/s}$ for increasing generation. The system model incorporates a saturation block in the hydro turbine, constrained between -0.06 and 0.045 , as described in [43] and [44]. The GDB nonlinearity is expressed as in Zhang et al. [45], [46] as;

$$G_d(s) = \frac{0.8 - \frac{0.2}{\pi}s}{1 + T_g s} \quad (10)$$

Similarly, a boiler dynamic is introduced into the thermal reheat system as a nonlinearity, with their schematic nature depicted in Fig. 6 [9], [47]. To enhance the system's realism, a communication time delay (CTD) was incorporated after the controller design. This study adopts a time delay parameter τ_d value of 0.25 seconds, as documented in [36] and [48],

and is given as;

$$e^{-s\tau_d} = \frac{1 - \frac{\tau_d}{2}s}{1 + \frac{\tau_d}{2}s} \quad (11)$$

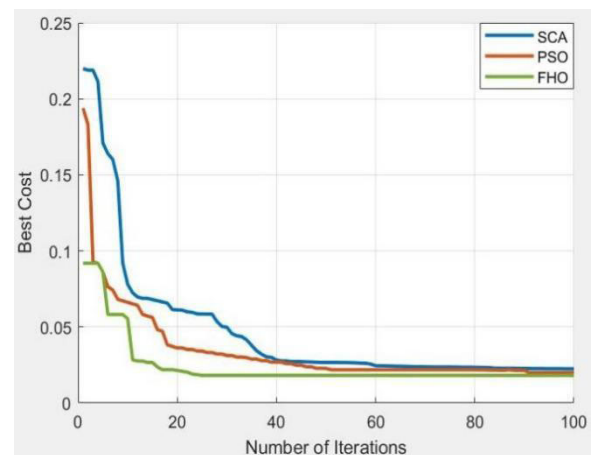


FIGURE 13. The convergence characteristic curves of SCA, PSO, and the proposed FHO under scenario 1.

C. THE PROPOSED (1+PI)-PI-TID CC STRUCTURE

For the first instance, LFC introduces a novel cascade combination of PI, TID, and (1+PI) controllers as a tri-stage controller, known as the (1+PI)-PI-TID, as structured in

TABLE 5. ITAE values for FHO, SCA, and PSO at scenario 1.

Algorithm	Minimum	Maximum	Average	St. deviation
FHO	0.018138879	0.091907081	0.0479	0.0264
PSO	0.020000510	0.193907081	0.0924	0.0409
SCA	0.022419532	0.219867041	0.1314	0.0703

TABLE 6. FHO optimized (1+PI)-PI-TID CC gains for test model 2 at the scenario 2.

Algorithm	Area_1			n	Area_2			n
	K_P K_D	K_I			K_P K_D	K_I		
ISFS: PID [53]	0.3898	1.0113	0.7695	—	0.3898	1.0113	0.7695	—
HBFO-PSO: PI [3]	0.4253	0.3260	—	—	-0.4253	0.3260	—	—
CPSO: PI [63]	-0.5762	0.1962	—	—	-0.5762	0.1962	—	—
HHO: PID [17]	1.1794	3.5816	0.7982	—	-0.0459	0.0230	1.8218	—
FHO: TID	1.2464	2.0000	0.7883	5.4991	0.9051	0.2135	1.4684	6.2940
(1+PI)-PI-PID CC								
1+PI Controller	1.1089	0.0000	—	—	0.9177	1.9970	—	—
PI Controller	2.0000	0.0000	—	—	0.2608	0.4259	—	—
PID Controller	0.1894	0.7779	0.1388	—	0.0000	0.0491	1.2677	—
(1+PI)-PI-TID CC								
1+PI Controller	0.2757	1.9992	—	—	0.9489	0.0000	—	—
PI Controller	1.0219	8.0486e-6	—	—	0.2622	0.2980	—	—
TID Controller	0.9918	1.8532	0.4153	2.8416	1.0357	0.0452	1.2588	81.4470

TABLE 7. Evaluation and comparison of (1+PI)-PI-TID CC performance at 1% SLP with GDB.

Algorithm	$\mathcal{L}$		Settling time (0.002 band) T_s (s)			Undershoot(-ve)		
	ITAE	ITSE $\times 10^{-4}$	ΔF_1	ΔF_2	ΔP	ΔF_1	$\Delta F_2 \times 10^{-3}$	$\Delta P \times 10^{-4}$
FHO: (1+PI)-PI-TID	0.01801	0.6800	1.176	0.000	0.000	0.014	1.566	19.60
FHO: (1+PI)-PI-PID	0.02017	0.6222	1.256	1.572	0.803	0.015	3.372	24.13
FHO: TID	0.02100	0.9272	1.272	1.940	0.951	0.017	9.765	27.86
ISFS: PID [36]	n/a	n/a	6.250	6.480	4.400	0.017	11.000	31.6
HHO: PID [17]	0.0212	0.9177	1.440	1.130	0.869	0.016	8.966	26.38
HBFO-PSO: PI [3]	0.3948	40.530	7.760	7.070	4.190	0.032	33.000	84.9
CPSO: PI [63]	0.5829	83.180	7.500	6.520	6.180	0.034	37.000	94.1
% Improvement by (1+PI)-PI-TID	10.7%	—	6.4%	100%	100%	6.7%	53.6%	18.8%

Fig. 7. By integrating these three controllers into a cascading link, disturbance sources are typically swiftly rejected before they can propagate through the system. The tilting factor of $s^{-\left(\frac{1}{h}\right)}$ within the tilt block replaces the integer power in a TID controller, distinguishing it from a PID controller. This unique controller incorporates two additional signals, Δf and $\Delta P_{\text{tie-line}}$, exchanged between neighboring areas, alongside the ACE as the primary input signal. This feature sets it apart from other cascade controller configurations proposed in the field. To the best of the authors' knowledge, no previous research has explored this particular control scheme.

The controller generates the required load reference (ΔP_{ref}), which also serves as the power system input signal, by processing the ACE, Δf , and $\Delta P_{\text{tie-line}}$ signals.

The expression for the s-domain of (1+PI), PI, and TID controllers is as follows:

$$T_{1+PI}(s) = 1 + K_{p1} + \frac{K_{i1}}{s} \quad (12)$$

$$T_{PI}(s) = K_{p2} + \frac{K_{i2}}{s} \quad (13)$$

$$T_{TID}(s) = K_{i3} s^{-\left(\frac{1}{h}\right)} + \frac{K_{i3}}{S} + K_{d3}s \quad (14)$$

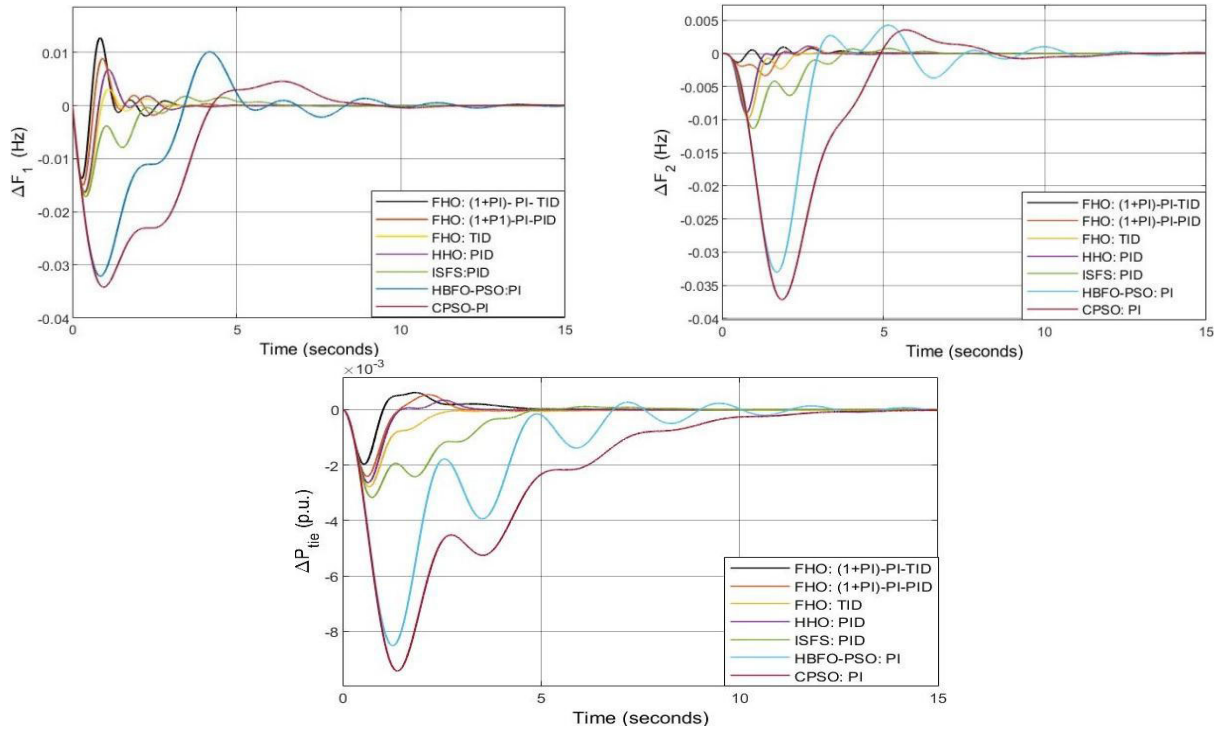


FIGURE 14. Contrast dynamic responses for test model 2 at scenario 2.

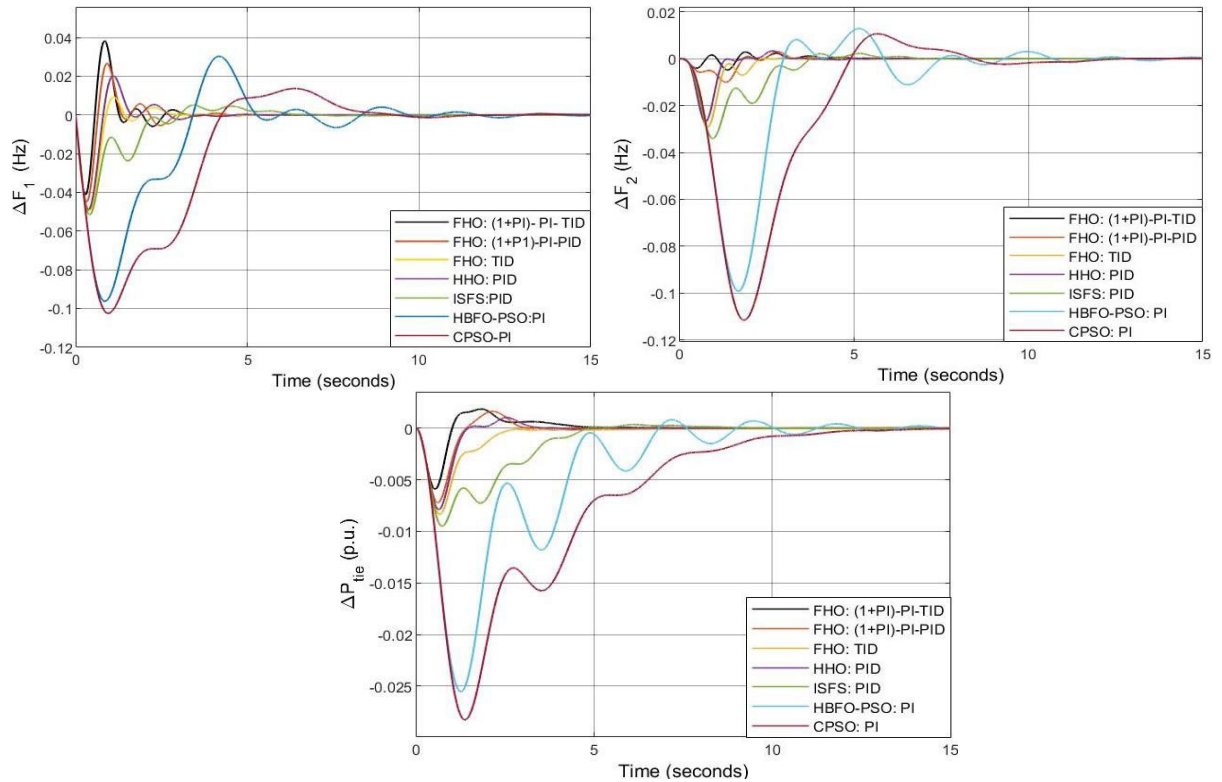


FIGURE 15. Contrast dynamic responses for test model 2 at scenario 3.

where K_{pi} , K_{ii} , K_t , K_d , and n are proportional, integral, tilt, derivative, and fractional parameters, respectively. Therefore,

we have eight degrees of freedom to configure a (1+PI)-PI-TID CC. Optimal performance of this controller necessitates

concurrent optimization of these eight parameters, for which FHO is selected in this study to fulfill this objective.

D. PERFORMANCE OBJECTIVE FUNCTION DESIGN FOR LFC

The frequency of the PS is influenced by customer demand fluctuations, leading to deviations in ΔF_i and ΔP_{tie} to diverge from their nominal values. To enhance LFC performance, it is recommended to initially implement modern heuristic optimization-based controller schemes effectively with a suitable objective function [46], [49], [50]. The literature has delved into various performance functions such as integral square error (ISE), integral of time multiplied absolute error (ITAE), integral AE (IAE), and integral time SE (ITSE) to tackle AGC challenges and restore nominal performance [25], [26], [27], [28].

The ITAE criterion has become synonymous with accuracy in AGC research due to its comprehensive quantification of deviations and its capacity to consider them over time [54]. The utilization of the ITAE criterion, as outlined in [29] and [30], will be pivotal in this study for adjusting the scaling parameters of the (1+PI)-PI-TID CC. This criterion, highlighted for its ability to diminish variations over time [54], will be instrumental in reducing incremental variations in $\Delta P_{tie-line}$ and ΔF is the main goal of this research. The objective function, depicted with the symbol $\mathcal{L}$, contains this goal [53], [56].

$$\begin{aligned}\mathcal{L}_1 &= \text{ITAE} = \int_0^{t_{\text{sim}}} t \cdot [\Delta F_1 + \Delta F_2 + \Delta P_{\text{tie-line}}] dt \\ \mathcal{L}_2 &= \text{ITSE} = \int_0^{t_{\text{sim}}} t \cdot [(\Delta F_1)^2 + (\Delta F_2)^2 + (\Delta P_{\text{tie-line}})^2] dt\end{aligned}\quad (15)$$

where ΔF_1 and ΔF_2 are the PS frequency deviations in area 1 and 2, $\Delta P_{\text{tie-line}}$, while t represents the simulation time necessary to ensure steady state conditions. The optimum performance has the lowest value of $\mathcal{L}$.

Minimize $\mathcal{L}$

$$\begin{aligned}\text{Subjected to: } K_p^{\min} &\leq K_p \leq K_p^{\max}, \\ K_t^{\min} &\leq K_t \leq K_t^{\max}, \\ K_i^{\min} &\leq K_i \leq K_i^{\max}, \\ K_d^{\min} &\leq K_d \leq K_d^{\max}, \\ n^{\min} &\leq n \leq n^{\max}.\end{aligned}\quad (16)$$

The superscripts “min” and “max” denote the lower and the upper values of K_p , K_t , K_i , K_d , and n which are the corresponding (1+PI)-PI-TID CC parameters. To find out optimistic controller gains on a large scale, the gains ranges are chosen in the range $[-5, 5]$ for linear NRTPSI and non-linear MUMA test models [17]. In linear MUMS and NRTPSI with GDB, the gains are in the range $[0, 2]$. The n is in the range $[1, 100]$ for all test models. In conclusion, by exploiting the FHO metaheuristic algorithm, an optimal or

near-optimal set of (1+PI)-PI-TID CC parameters is derived within the recommended edges for the smallest value of $\mathcal{L}$.

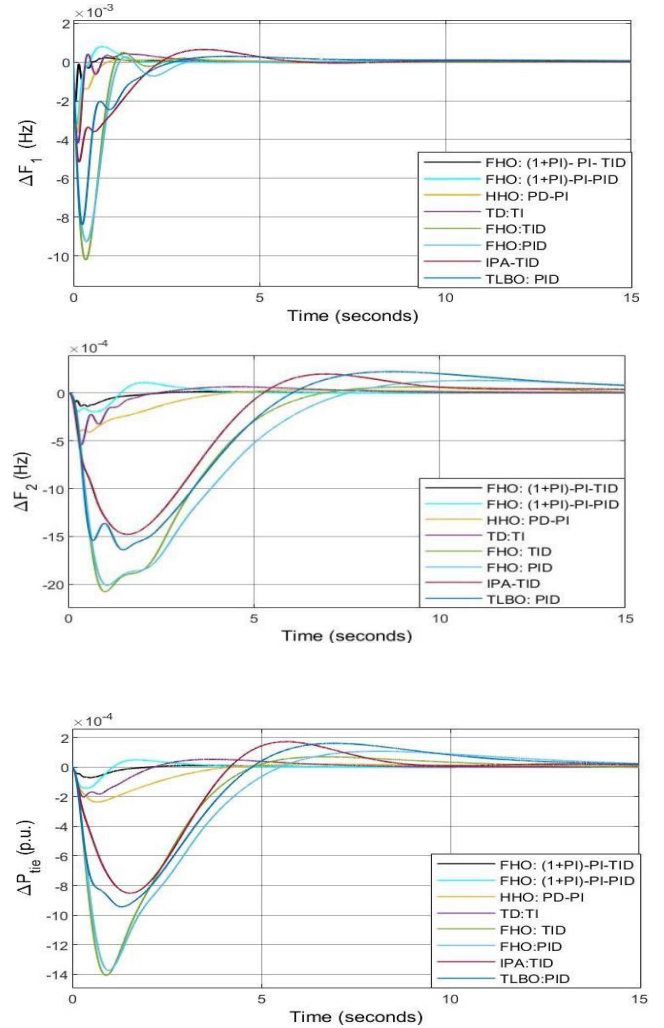


FIGURE 16. Transient responses comparison at 1% SLP in area-1 with HVDC tie-line.

III. FIRE HAWK OPTIMIZER (FHO)

The fire hawk optimizer (FHO) was first put forth by Azizi et al. [57]. The FHO algorithm takes inspiration from the behavior of birds like whistling kites, black kites, and brown falcons that spread fire by carrying flaming sticks in their beaks and claws. This behavior is considered a unique and subversive natural phenomenon. These birds strategically use the flaming sticks to create small fires in unburned areas, which startle and frighten prey such as rats and snakes, causing them to flee in panic. This behavior makes it easier for the hawks to capture the fleeing prey. The FHO algorithm utilizes the concept of fire hawks spreading fire to model an optimization algorithm where the positions of fire hawks (FHs) and prey are determined using a large number of solution candidates (SCs) denoted as (X) as described in [57] and [58]

TABLE 8. The controller gains for test model 3 at scenario 1 (MUMA with HVDC).

Algorithm	Thermal				Hydro				Gas			
	K_p	K_I	K_D	n	K_p	K_I	K_D	n	K_p	K_I	K_D	n
TLBO: PID [2]	5.0658	3.9658	2.4170	—	0.7032	0.0220	0.0264	—	8.7211	7.4729	2.4181	—
FHO: TID	5.0000	2.4152	2.9393	2.0929	4.9999	-4.672	-0.078	2.3449	5.0000	5.0000	-5.000	99.0537
FHO: PID	5.0000	3.2937	2.4633	—	5.0000	-5.000	-4.783	—	5.0000	5.0000	-5.000	—
IPA: TID [64]	5.5726	3.9653	.9621	—	0.7051	0.0354	0.0394	—	8.7211	7.4725	2.4185	2.5405
WCA: TD-TI CC [27]												
TD	-5.000	—	-4.776	—	-5.000	—	4.6499	—	-4.983	—	-4.704	2.000
TI	-4.700	-4.994	—	—	-5.000	4.9982	—	—	-5.000	-4.960	—	2.000
HHO: PD-PI CC [17]												
PD	5.0000	—	5.0000	—	5.0000	—	0.4447	—	5.0000	—	-5.000	—
PI	5.0000	5.0000	—	—	5.0000	-2.626	—	—	5.0000	5.0000	—	—
FHO: (1+PI)-PI-TID CC (Proposed)												
1+PI	4.9160	5.000	—	—	-5.000	-4.9976	—	—	5.000	5.000	—	—
PI	-4.538	-5.000	—	—	-1.9503	4.8864	—	—	-4.9977	5.000	—	—
TID	-1.999	-0.7138	-1.9466	87.7242	-2.000	0.9882	1.8814	2.3894	-2.000	-2.000	2.000	1.8512
FHO: (1+PI)-PI-PID CC (Proposed)												
1+PI	5.000	1.6813	—	—	5.000	-5.000	—	—	-4.9995	4.9945	—	—
PI	-5.000	-4.6710	—	—	-2.9744	-2.6832	—	—	-4.2672	-5.000	—	—
PID	-2.000	-2.000	-0.4823	—	-0.9346	-2.000	0.4787	—	-1.1239	1.9834	-2.000	—

TABLE 9. Comparative performance of FHO: (1+PI)-PI-TID CC test model 3 under 1% SLP (scenario 1).

Algorithm	$\mathcal{L}$	ST (0.0002 band) T_s (s)			Undershoot(-ve)		
		ΔF_1	ΔF_2	ΔP	$\Delta F_1 \times 10^{-3}$	$\Delta F_2 \times 10^{-3}$	$\Delta P \times 10^{-4}$
FHO: (1+PI)-PI-TID	0.0009715	0.399	0.000	0.000	2.025	0.1401	0.700
FHO: (1+PI)-PI-PID	0.001678	1.420	0.697	0.000	3.198	0.2035	1.431
HHO: PD-PI [17]	0.007636	0.599	1.982	0.930	3.640	0.6063	2.884
TD-TI [27],	0.005725	2.578	1.021	0.331	5.085	0.9775	2.701
FHO: TID	0.02653	1.606	5.379	3.621	10.00	2.0770	14.07
FHO: PID	0.03538	2.766	6.209	4.255	9.253	2.0130	13.72
IPA: TID [64]	0.05780	5.178	4.630	3.520	5.171	1.478	8.512
TLBO: PID [2]	0.06800	5.850	10.013	3.857	8.357	1.638	9.434
% Improvement by (1+PI)-PI-TID	42.1%	33.4%	100%	100%	36.7%	31.2%	51.1%

is used to determine these initial places.

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} x_1^1 & x_1^2 & \cdots & x_1^j & \cdots & x_1^d \\ x_2^1 & x_2^2 & \cdots & x_2^j & \cdots & x_2^d \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_i^1 & x_i^2 & \cdots & x_i^j & \cdots & x_i^d \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_n^1 & x_n^2 & \cdots & x_n^j & \cdots & x_n^d \end{bmatrix},$$

where $\begin{cases} i = 1, 2, \dots, n. \\ j = 1, 2, \dots, d. \end{cases}$

$$x_i^j = x_{i,min}^j + r \cdot (x_{i,max}^j - x_{i,min}^j) \quad (17)$$

While the rest of the SCs are prey, the fittest ones are referred to be FHs. As presented in [57] and [58], the aspect is represented as:

$$FH = \begin{bmatrix} FH_1 \\ FH_2 \\ \vdots \\ FH_h \\ \vdots \\ FH_n \end{bmatrix}, h = 1, 2, \dots, n. \quad (18)$$

$$PR = \begin{bmatrix} PR_1 \\ PR_2 \\ \vdots \\ PR_k \\ \vdots \\ PR_m \end{bmatrix}, k = 1, 2, \dots, m. \quad (19)$$

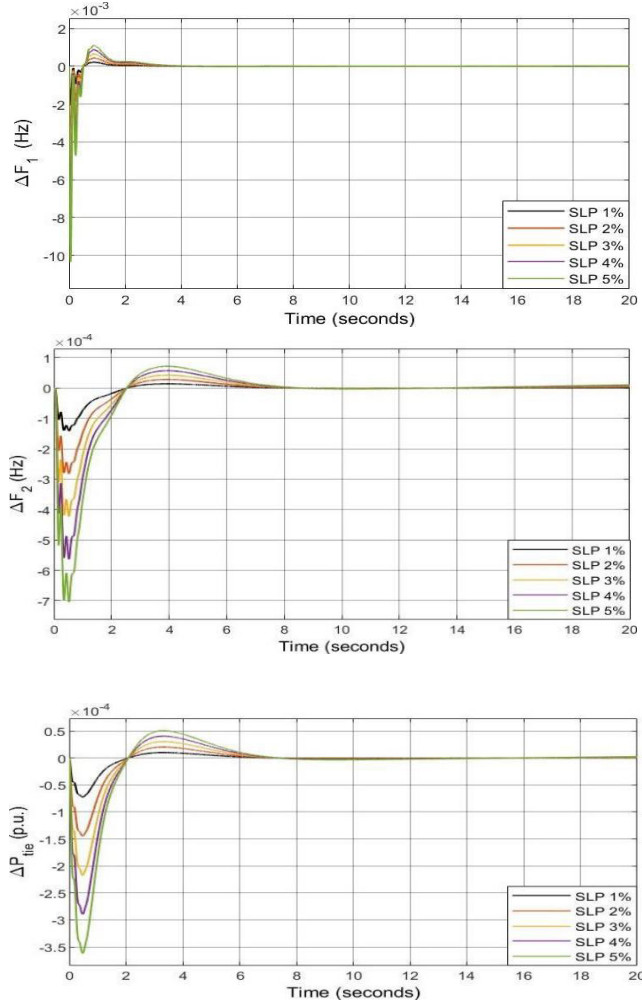


FIGURE 17. Transient responses of scenario 3 for 1–5% SLP in area-1 with HVDC.

The entire separation between the prey and the FH is expressed as in [58]:

$$D_k^h = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2},$$

$$\text{where } \begin{cases} h = 1, 2, \dots, n. \\ k = 1, 2, \dots, d. \end{cases} \quad (20)$$

(x_1, y_1) and (x_2, y_2) represent the coordinates of the FHs and prey.

To make the prey flee for its life, each bird grabs a burning stick and deposits it in an appropriate spot. As with some birds' eagerness to use flaming sticks from outside FH territory, these two behaviors can be used as position-updating activities in FHO's primary search loop, such as

$$FH_h^{new} = FH_h + (r_1 \times GB - r_2 \times FH_{near}) \quad (21)$$

where GB is the global best solution in the X that is thought to be the main fire; FH_{near} is one of the other FHs in the X ; and FH_h^{new} is the new position vector of the h^{th} FH (FH_h).

The prey that hides, runs away, or inadvertently enters FH area can be expressed as follows in the following step of the algorithm:

$$PR_q^{new} = PR_q + (r_3 \times FH_h - r_4 \times SP_h), \quad (22)$$

The following is the formulation for prey that wanders into FH's areas and tries to avoid capture by hiding in a more secure area:

$$PR_q^{new} = PR_q + (r_5 \times FH_{Alter} - r_6 \times SP),$$

$$\text{where } \begin{cases} h = 1, 2, \dots, n. \\ q = 1, 2, \dots, r. \end{cases} \quad (23)$$

r_5 and r_6 control the movements of prey in the direction of the FHs and the safe areas outside the domain. Equations (25) and (26) provide the formula for SP_h and SP . The FHO flowchart is displayed in Fig. 8.

$$SP_h = \frac{\sum_{q=1}^r PR_q}{r}, \begin{cases} h = 1, 2, \dots, n. \\ q = 1, 2, \dots, r. \end{cases} \quad (24)$$

$$SP = \frac{\sum_{k=1}^m PR_k}{m}, k = 1, 2, \dots, m. \quad (25)$$

where PR_q is the q^{th} prey encircled by the h^{th} FH (FH_h), and PR_k is the k^{th} prey in the X .

A. THE PROPOSED FHO BASED (1+PI)-PI-TID CC

The FHO system refines gains in (1+PI)-PI-TID controllers using the ITAE criteria. In Fig. 9, the ITAE-based controller combines tie-line power error and frequency deviation for system output evaluation. The FHO generates new gains by minimizing ITAE values iteratively. The controller gains K_{p1} and K_{i1} for (1+PI) controller, K_{p2} and K_{i2} for the PI controller and T_i , n , K_{i3} , and K_d for the TID controller, which serve as input variables for the FHO. Optimal gains are derived from the lowest ITAE value, reducing system deviations.

A crucial factor in metaheuristic algorithms for FHO-based (1+PI)-PI-TID real-time implementation is population size [1]. As noted by [59], "high beginning population numbers do not perform better than tiny populations when it comes to finding the best solution," which satisfies the output results and is suitable for LFC situations that occur in real-time.

IV. RESULTS AND DISCUSSION

As previously mentioned, four test models of controlled experiments are detailed: the NRTPSI with and without GDB and the MUMA with and without nonlinearities of GRC, GDB, BD, and CTD under two proposed CC structures, (1+PI)-PI-PID and (1+PI)-PI-TID. These models are implemented in the MATLAB/SIMULINK environment on an Intel Core i-5 processor. In the FHO methodology, 25 initial candidates form the population, with a maximum of 30 iterations and 750 function evaluations (MaxFes) selected. The comprehensive examination of the stability of the proposed (1+PI)-PI-TID CC involves two tests covering various scenarios. Each experiment is meticulously analyzed individually, as outlined in Table 1.

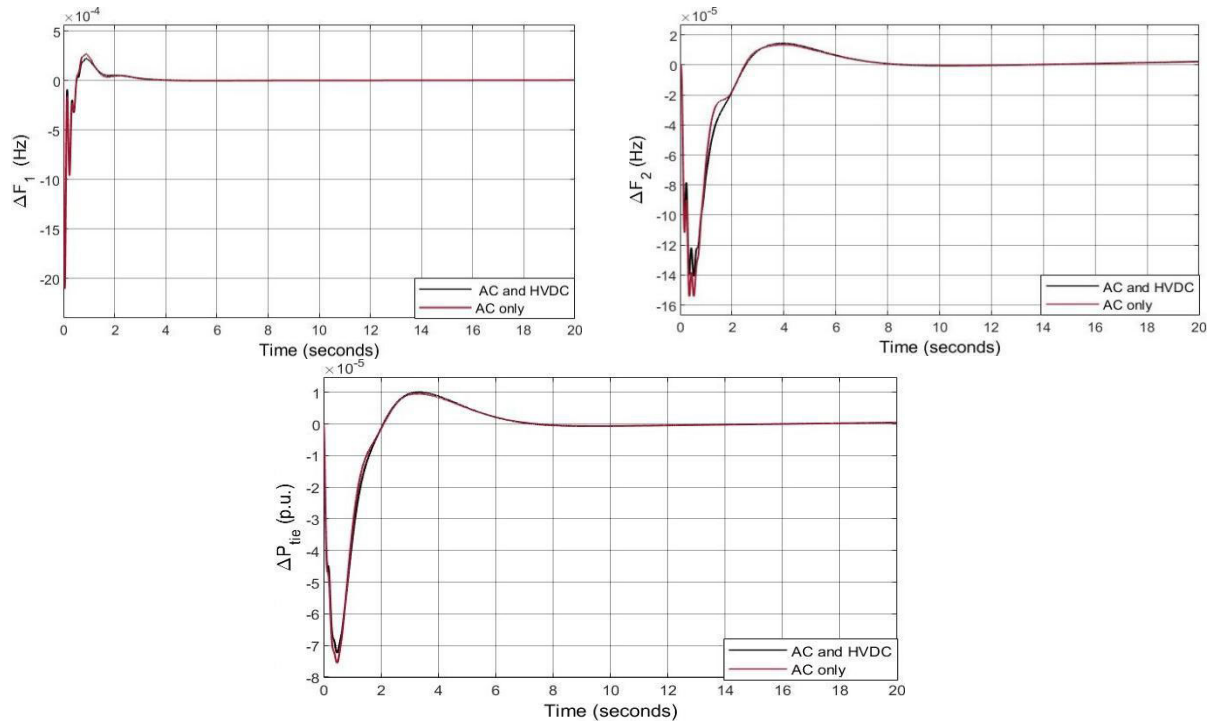


FIGURE 18. Transient responses comparison at 1% SLP in area-1 between AC-DC parallel link and AC tie-line only at the same FHO: (1+PI)-PI-TID CC gains.

TABLE 10. FHO optimized controller gains for Test model 4 at scenario 1 (1% SLP in area 1).

Algorithm	Area_1				Area_2			
	K_P	K_I	K_D	n	K_P	K_I	K_D	n
FHO: TID	5.000	4.9976	6.36e-4	2.000	1.6614	0.0426	0.7290	3.5543
FHO: PID	5.0000	5.0000	0.0000	—	2.9861	0.5464	0.0000	—
FHO: PD-PI CC								
PD Controller	4.4723	—	1.3827	—	4.9889	—	1.1497	—
PI Controller	0.7802	3.5628	—	—	0.1132	0.0491	—	—
FHO: (1+PI)-PI-TID CC								
(1+PI) Controller	3.5638	0.000	—	—	1.9360	0.5170	—	—
PI Controller	2.1497	0.000	—	—	0.1276	0.0000	—	—
TID Controller	1.0007	1.6915	0.1764	6.8303	1.3478	0.0000	2.3891	92.7872
FHO: (1+PI)-PI-PID CC								
1+PI Controller	4.4153	1.0258	—	—	0.4977	0.0078	—	—
PI Controller	0.3976	1.4496	—	—	0.6061	1.9914	—	—
PID Controller	2.0000	1e-7	0.3509	—	1.5098	0.2794	0.0124	—

A. TEST MODEL 1 (NRTPSI WITHOUT GDB)

In scenario 1, the FHO: (1+PI)-PI-TID scheme is initially applied to PSI in a linear phase, addressing AGC issues under a 10% SLP in area 1 of NRTPSI. Initially, the tuned parameters of FHO are demonstrated in Table 2 [57]. The proposed controller's gains are listed with competitors in Table 3. The contrasting with schemes like HHO: PD-PI CC [17], ISFS: PID [36], DSA: (1+PD)-PID [6], FHO: (1+PI)-PI-PID CC [30], and IGWO: PID [60] is shown in Table 4. Notably, the FHO: (1+PI)-PI-TID CC exhibits superior performance,

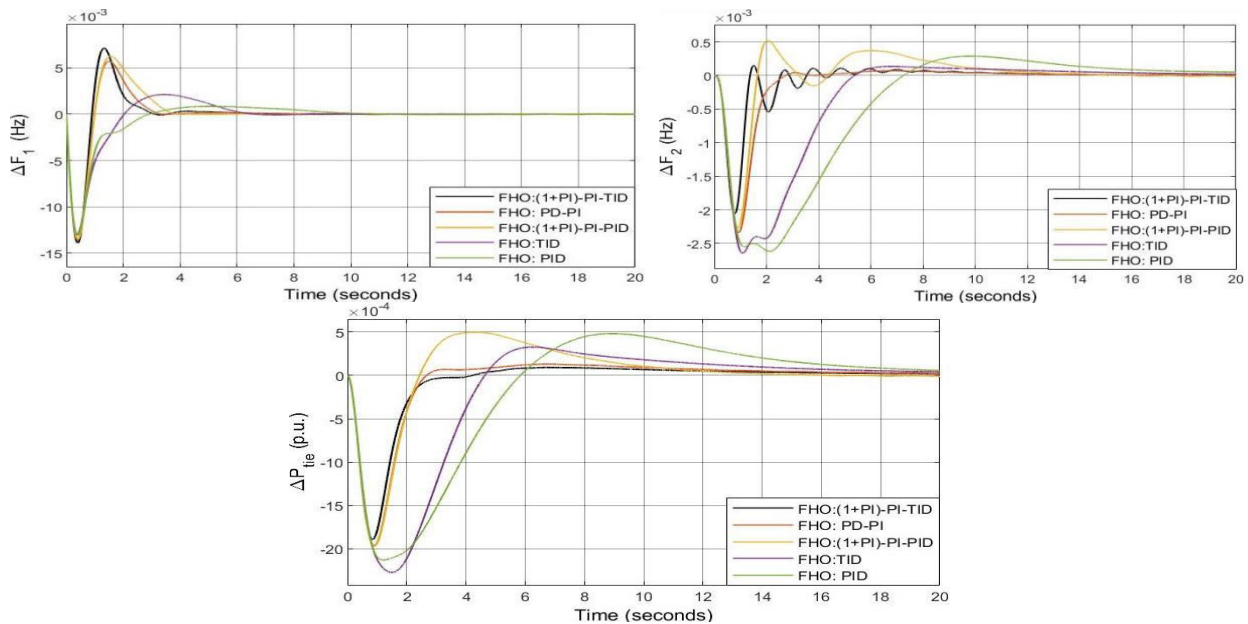
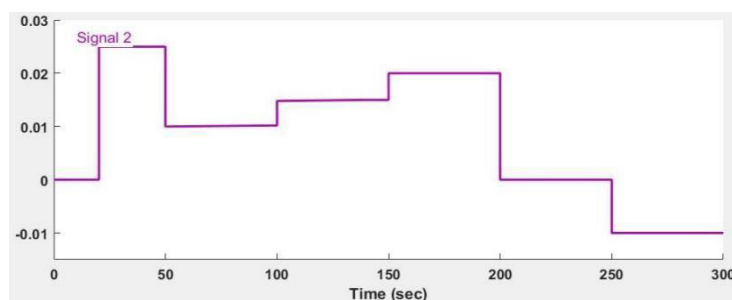
with significantly lower values for ITAE and ITSE metrics, showcasing improvements of 84.3% and 90.8%, respectively.

Enhanced stability is evidenced by reduced settling times for frequency and tie-line power deviations, peak undershoots, and dynamic response depicted in Fig. 10.

In scenario 2, the FHO: (1+PI)-PI-TID CC and other controllers are further evaluated at 20% SLC in area 1, confirming the FHO's superiority over competitors, as illustrated in Fig. 11. Scenario 3 involves a robust investigation with a 10% step load increase in area 1 and a 20% step load increase

TABLE 11. Comparison performance of several controllers for scenario 1.

Algorithm	$\mathcal{L}$		ST (0.002 band) (s)			Undershoot(-ve)		
	ITAE	ITSE $\times 10^{-5}$	ΔF_1	ΔF_2	ΔP	ΔF_1 $\times 10^{-3}$	ΔF_2 $\times 10^{-3}$	ΔP $\times 10^{-4}$
FHO: (1+PI)-PI-TID	0.03502	8.398	1.974	0.804	0.000	0.014	2.053	18.89
FHO: PD-PI	0.04086	8.778	2.378	1.145	0.000	0.014	2.338	19.70
FHO: (1+PI)-PI-PID	0.05979	12.07	2.830	1.074	0.000	0.013	2.272	19.73
FHO: TID	0.08965	13.53	3.963	2.525	2.176	0.013	2.647	22.74
FHO: PID	0.14070	15.23	2.110	3.343	2.057	0.013	2.619	21.32
% Reduction	16.7%	4.5%	20%	42.4%	—	—	13.8%	4.4%

**FIGURE 19.** Transient response with various controllers but same optimizer at scenario 1.**FIGURE 20.** Random step loads ΔP_{D1} in area 1.

in area 2, concluding the experiment's evaluation, as shown in Figure 12. The performance of the proposed FHO: (1+PI)-PI-TID CC surpasses that of competitors, as demonstrated in Table 4 and Figures 10, 11, and 12.

B. TEST MODEL 2 (NRTPSI WITH GDB)

In scenario 1: To demonstrate the adaptability of the FHO, the convergence characteristics of FHO, particle swarm

optimization (PSO) [3], [42], and the sine cosine algorithm (SCA) [65] are analyzed in the context of the (1+PI)-PI-TID CC using test model 2. Each optimizer is configured with a population size of 30 search agents, 100 iterations, and 30 runs. The convergence graph of FHO, extracted from an NRTIPS with GDB, is depicted in Fig. 13. Furthermore, a comparison of the minimum, maximum, average, and standard deviation of the ITAE values J_{ITAE} in Table 5 illustrates

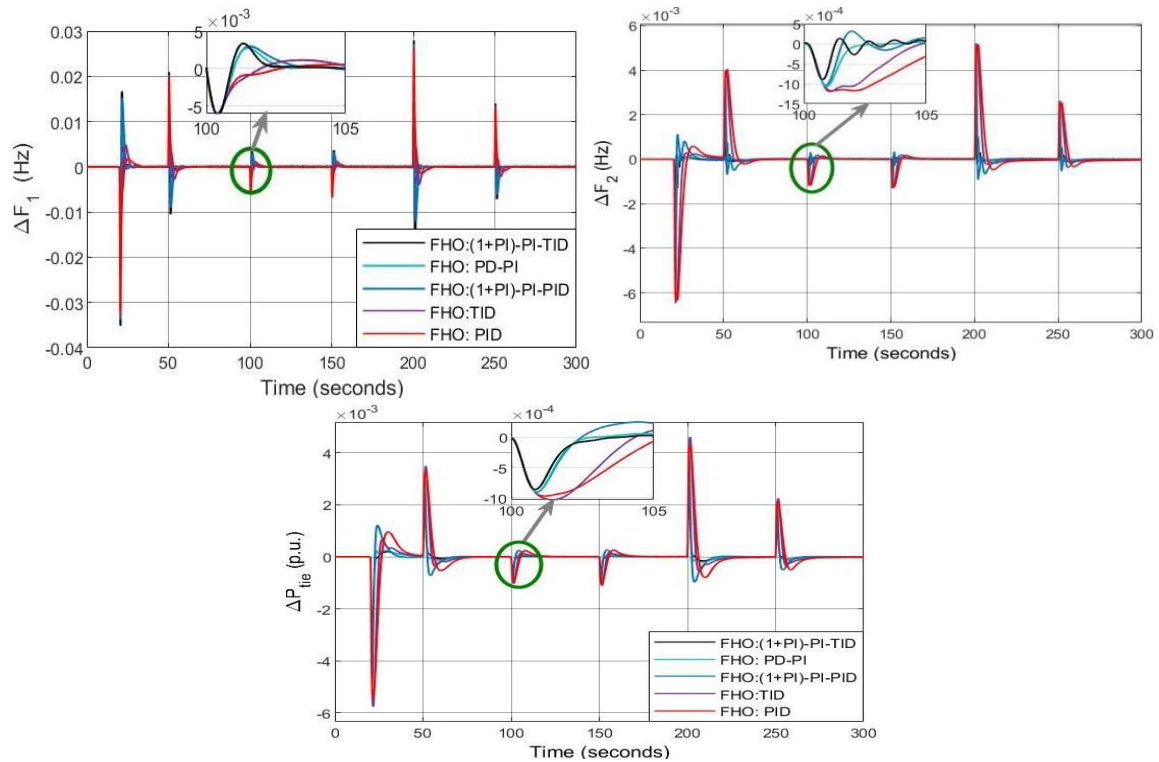


FIGURE 21. Transient response with various algorithm techniques.

TABLE 12. Percentage variations in hybrid power system parameters.

Parameters	% of Change	ITAE	Settling time (0.0002 band) T_s (s)			Undershoot(-ve)		
			ΔF_1	ΔF_2	ΔP	$\Delta F_1 \times 10^{-3}$	$\Delta F_2 \times 10^{-3}$	$\Delta P \times 10^{-4}$
T_t	+40	0.03658	4.730	2.397	2.206	14.0	2.048	18.94
	Nominal	0.03502	4.702	2.376	2.184	14.0	2.053	18.94
	-40%	0.04636	4.638	2.383	2.227	14.0	2.058	18.94
T_r	+40	0.05630	4.809	2.376	2.227	14.0	2.059	18.95
	Nominal	0.03502	4.787	2.369	2.206	14.0	2.059	18.95
	-40%	0.04883	3.142	2.383	2.184	14.0	2.059	18.95
T_w	+40	0.05270	5.973	2.362	2.170	14.0	2.118	19.40
	Nominal	0.03502	4.705	2.383	2.206	14.0	2.056	18.93
	-40%	0.05817	4.762	2.397	2.617	14.0	1.942	18.09
T_{12}	+40	0.05281	3.746	2.824	1.899	14.0	2.742	24.45
	Nominal	0.03502	4.589	2.376	2.198	14.0	2.057	18.92
	-40%	0.04478	5.973	3.394	3.394	14.0	1.275	12.43

that FHO outperforms SCA and PSO in addressing AGC challenges.

Table 6 displays the optimized controller gains of the proposed CCs in comparison with competitors. In scenario 2, the system's ST, undershoots, and the cost function ITAE are also evaluated against documented techniques like ISFS: PID [53], HBFO-PSO: PI [3], and CPSO: PI [63]. Table 7 illustrates these assessments conducted under a 1% SLP at area 1, highlighting the performance of the proposed approach in the presence of GDB. Notable enhancements

of 10.7% in ITAE and 6.4%, 100%, and 100% in settling time for ΔF_1 and ΔF_2 , as well as ΔP_{tie} , respectively, are shown in Fig. 14. Table 7 and Fig. 14 demonstrate how the FHO: (1+PI)-PI-TID CC technique significantly enhances dynamic response characteristics. When compared to competitors' strategies, the proposed approach enhances the undershoot by 6.7%, 53.6%, and 18.8%. Through detailed data analysis, it is evident that the proposed controller outperforms other methods in the literature, especially when facing nonlinear operational challenges.

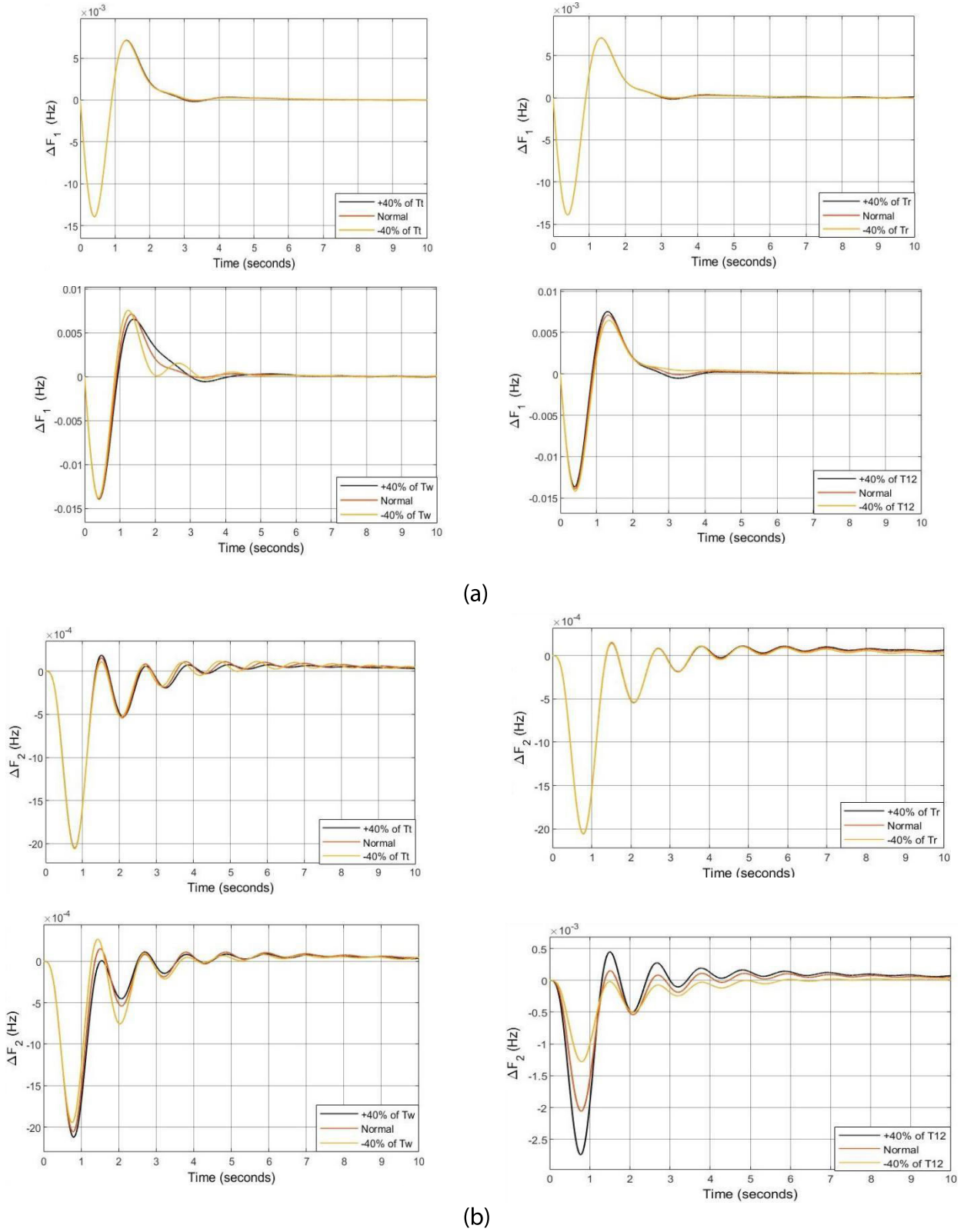


FIGURE 22. (a): Variation of T_t , T_r , T_w , and T_{12} power system parameters for ΔF_1 . (b): Variation of T_t , T_r , T_w , and T_{12} power system parameters for ΔF_2 .

In scenario 3, Figure 15 illustrates the differences in transient responses between the FHO: (1+PI)-PI-TID CC and

alternative controllers, which were tested under a 3% SLC in area 1. The analysis reveals that when confronted with GDB

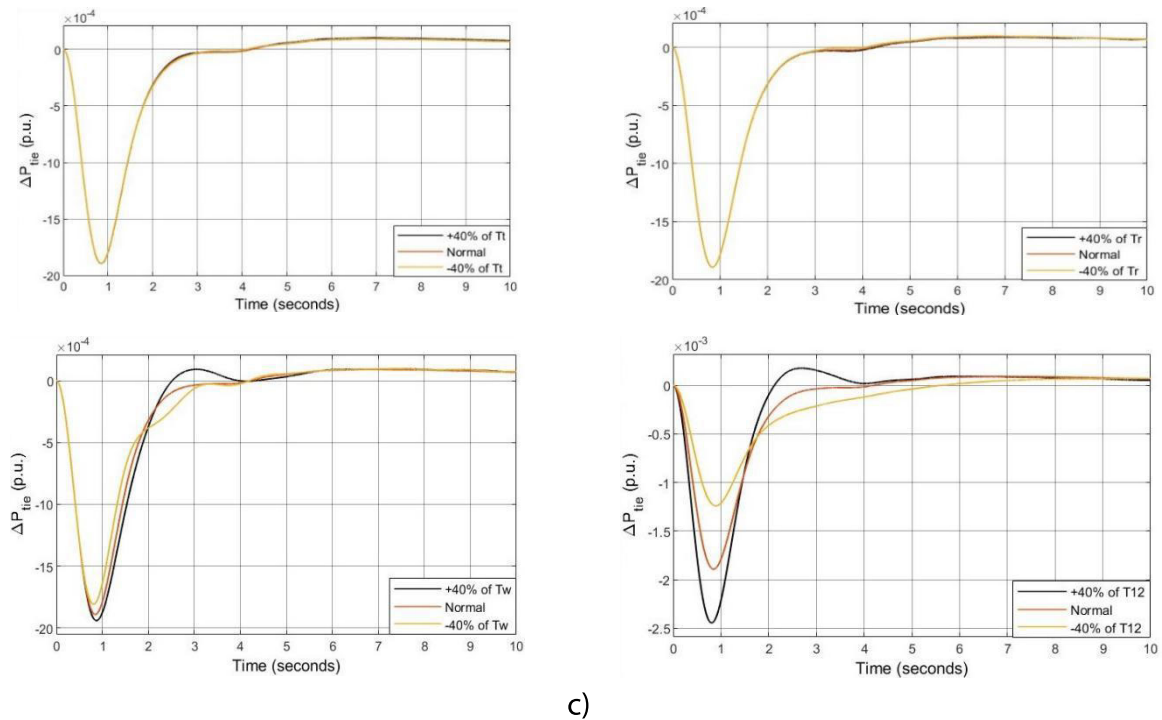


FIGURE 22. (Continued.) (c): Variation of T_t , T_r , T_w , and T_{12} power system parameters for ΔP .

non-linearity, the FHO-driven (1+PI)-PI-TID CC surpasses all competitors. These results unequivocally demonstrate the robustness and effectiveness of the FHO: (1+PI)-PI-TID CC across various SLP levels.

C. TEST MODEL 3 MUMA POWER SYSTEM WITH HVDC INTEGRATION

An additional investigation was conducted by integrating the HVDC link into the MUMA PSI across three distinct scenarios.

In scenario 1, the effectiveness of the FHO: (1+PI)-PI-TID CC was examined and compared with other soft computing-based controllers under a 1% SLP in area 1. Table 8 showcases the controller gains for gas, hydro, and reheat thermal units determined by the FHO-based ITAE criterion. Additionally, Table 9 presents comparative performance in terms of ITAE value, settling time and undershoot. In contrast to the proposed FHO: (1+PI)-PI-TID CC (ITAE = 0.0009715), demonstrating a 42.1% improvement, alternative methods in the literature such as HHO: PD-PI CC [17] (ITAE = 0.007636), TD-TI CC [27], (ITAE = 0.005725), TLBO: PID [2] (ITAE = 0.0680), and IPA: TID [64] (ITAE = 0.0578 exhibit higher ITAE values. Moreover, there is a notable decrease in settling times for frequency and tie-line power deviations (33.4% improvement for ΔF_1 and 100% for ΔF_2) and peak undershoots (36.7% improvement for ΔF_1 , 31.2% for ΔF_2 , and 51.1% for ΔP), thereby enhancing system stability. The transient responses are illustrated in Fig. 16. These findings affirm that at a

1% SLP, the FHO: (1+PI)-PI-TID CC technique is better suited for hybrid power systems due to its improved dynamic responsiveness.

In scenario 2, the SLP is incrementally raised from 1% to 5% in steps of 1% to further emphasize the robustness of the proposed controller. Figure 17 depicts the dynamic responses of the system with HVDC. It is clear from the results that the recommended FHO: (1+PI)-PI-TID CC is dependable and exhibits excellent performance across a range of SLP values.

Moving on to scenario 3, an in-depth examination of the MUMA power system focuses specifically on comparing the AC tie-line and the AC-DC parallel link. A direct comparison between the AC links and the AC-DC parallel tie-lines is presented in Fig. 18, demonstrating the improved system operation when the AC-DC connection is integrated into the transmission line. Despite utilizing the same FHO: PD-PI CC gains, they display notable distinctions at lower levels, highlighting the FHO: PD-PI CC as a versatile and superior controller.

D. TEST MODEL 4 MUMA POWER SYSTEM CONSIDERING NONLINEARITIES

1) SCENARIO-1 (ANALYZES CONTROLLER PERFORMANCE)

In the assessment, the FHO calibrated all controllers to ensure a fair comparison. The effectiveness of the proposed (1+PI)-PI-TID and (1+PI)-PI-PID controllers was validated by comparing them against a variety of alternative controllers, including single PID and TID controllers, as well as cascaded configurations like PD-PI, all under identical conditions. The

gain values for all controllers are detailed in Table 10. A comprehensive performance analysis of the various controllers is presented in Table 11, focusing on transient metrics such as ITAE, undershoot, and settling time for ΔF_1 , ΔF_2 , and ΔP_{tie} . In both areas 1 and 2, the FHO: (1+PI)-PI-TID controller technique outperformed the PID, TID, PD-PI controllers, and the (1+PI)-PI-PID controller, as illustrated in Figure 19.

When compared to the top-performing PD-PI controller from existing literature, the (1+PI)-PI-TID controller demonstrated significant improvements across various metrics. Specifically, the (1+PI)-PI-TID controller achieved a 16.7% enhancement in ITAE value and a 20% reduction in settling time for ΔF_1 compared to the PD-PI controller. However, it is notable that no improvements were observed for ΔP_{tie} . Additionally, the undershoot was markedly reduced by 13.8% for ΔF_2 and 4.4% for ΔP_{tie} when contrasting the (1+PI)-PI-TID controller with the PD-PI controller. These reductions in undershoot indicate a more stable response under dynamic conditions.

Overall, the comprehensive analysis and comparisons conducted clearly demonstrate that the proposed (1+PI)-PI-TID controller excels across multiple performance aspects. Its ability to achieve superior results in terms of ITAE, settling time, and undershoot highlights its effectiveness and superiority over existing controllers. This positions the (1+PI)-PI-TID controller as a robust solution for managing dynamic variations in control systems, making it a valuable option for practical applications in various engineering fields. The results suggest a strong potential for integration into systems requiring reliable and efficient control strategies.

2) SCENARIO-2 (PERFORMANCE ANALYSES UNDER RANDOM LOAD PERTURBATION)

To check the robustness of the proposed scheme, the dynamic analysis of the FHO: (1+PI)-PI-TID CC was conducted under a random step load (RSL) pattern in area 1. The RSL perturbation involves a sequence of sudden generating unit outages or abrupt load switches, representing a mix of random load variations. This scenario is depicted in Fig. 20. The transient response to this scenario is illustrated in Figure 21, where Figures 21a and 21b display the frequency changes in areas 1 and 2, respectively, while Figure 21c shows the power fluctuations in the tie-line power. The SLP time at 100 seconds is zoomed in for clarity in these figures. From the results presented in Figure 21, it is evident that the FHO: (1+PI)-PI-TID controller exhibits consistent dynamic performance when compared to other controllers reported in the literature. The controller demonstrates reduced undershoot and overshoot, as well as faster convergence, underscoring its robustness and effectiveness in managing dynamic variations under randomized loading conditions in area 1. This analysis highlights the controller's capability to maintain stability and performance in the face of unpredictable load changes, making it a strong candidate for practical applications.

3) SCENARIO-3 (SENSITIVITY ANALYSIS/ROBUSTNESS)

A sensitivity analysis was conducted to evaluate the robustness of the FHO-optimized (1+PI)-PI-TID CC. The stability of the proposed controller was assessed by comparing the responses of the original parameters to various metrics when parameters such as T_t , T_r , T_w , and T_{12} are varied by approximately $\pm 40\%$ under $\Delta P_{L1} = 1\%$ SLP at area 1, as outlined in [9]. Table 12 and Figs. 22a, 22b, and 22c demonstrate the suggested controller's reliability under altered system settings. The impact of parameter fluctuations on the ITAE criterion, settling time, and undershoot achieved by the proposed FHO: (1+PI)-PI-TID CC under modifications of system parameters was found to be negligible. For instance, for T_t , the nominal ITAE is 0.03502; when the change is made $\pm 40\%$, the ITAE value is changed to 0.03658 for up change and 0.04634 for down change. The analysis reveals that even with significant variations of up to 40% in parameters, the proposed FHO: (1+PI)-PI-TID CC exhibits robustness and maintains excellent performance, with minimal effects on the key evaluation metrics. This underscores the robust nature of the controller and its ability to perform effectively under varying system conditions.

This robustness is especially useful in real-world situations where climatic changes, load variances, and component aging can cause system characteristics to vary. Under these conditions, the controller performs well, proving its practicality and durability. In conclusion, the sensitivity analysis shows that the FHO: (1+PI)-PI-TID controller is resilient and may be used in dynamic contexts. The results show that the controller can handle large parameter fluctuations while meeting performance metrics, making it a good candidate for complex control applications.

V. CONCLUSION

In this scientific paper, a detailed investigation was conducted on a four-test model of interconnected power systems, considering various nonlinearities and utilizing the innovative fire hawk optimization (FHO) technique. Two cascade controllers, namely (1+PI)-PI-TID and (1+PI)-PI-PID, were implemented and thoroughly evaluated. The research encompassed the analysis of system responses under random step load conditions and other dynamic scenarios. Comparisons with existing strategies revealed a substantial percentage improvement in the dynamic responsiveness and robustness of the proposed (1+PI)-PI-TID controller. Additionally, the study explored the impact of nonlinearity on power system operations, examining factors such as GDB, BD, CTD, and GRC. A sensitivity analysis demonstrated that the proposed controllers exhibit remarkable stability and performance, showcasing a significant percentage improvement even when system parameters are varied by a substantial margin. This is backed up by the percentage improvement in ITAE of 84.3%, 10.7%, 42.1%, and 16.7%, and in settling time of change in frequency of 7.7%, 6.4%, 33.4%, and 20% (ΔF_1) and 100%, 100%, 100%, and 42.4% (ΔF_2) in

areas 1 and 2 of scenario 1 of the four test models under study, respectively, in lieu of HHO: PD-PI and (1+PI)-PI-PID schemes.

In conclusion, this research significantly advances load frequency control systems by introducing the FHO technique and designing novel cascade controllers. The findings underscore the effectiveness and reliability of the (1+PI)-PI-TID controller, showcasing a notable percentage improvement in enhancing system stability and performance across various operating conditions. These advancements pave the way for more sustainable and resilient power systems in the future.

APPENDIX A

TWO-AREA NON REHEAT THERMAL POWER SYSTEM PARAMETERS [1], [66]

$$\begin{aligned} P_R &= 2000\text{MW}; f = 60\text{ Hz}; B_1 = B_2 = 0.425\text{ p.u.} \frac{\text{MW}}{\text{Hz}}; \\ P_L &= 1000\text{MW}; R_1 = R_2 = 2.4 \frac{\text{Hz}}{\text{p.u.}}; T_{g1} = T_{g2} = 0.08\text{ s}; \\ T_{t1} &= T_{t2} = 0.3\text{ s}; K_{PS1} = K_{PS2} = 120 \frac{\text{Hz}}{\text{pu}}; \\ T_{PS1} &= T_{PS2} = 20\text{ s}; 2 * \pi * T_{12} = 0.545\text{p.u.}; a_{12} = -1. \end{aligned}$$

APPENDIX B

TWO-AREA NON REHEAT THERMAL POWER SYSTEM PARAMETERS WITH GDB [1], [66]

$$\begin{aligned} B_1 &= B_2 = 0.425\text{p.u.} \frac{\text{MW}}{\text{Hz}}; R_1 = R_2 = 2.4 \frac{\text{Hz}}{\text{pu}}; \\ T_{g1} &= T_{g2} = 0.2\text{ s}; T_{t1} = T_{t2} = 0.3\text{ s}; K_{PS1} = K_{PS2} = 120 \frac{\text{Hz}}{\text{pu}}; \\ T_{PS1} &= T_{PS2} = 20\text{ s}; 2 * \pi * T_{12} = 0.0707\text{p.u.}; a_{12} = -1. \end{aligned}$$

APPENDIX C

MULTI-UNIT MULTI AREA POWER SYSTEM PARAMETERS [1], [66], [67]

$$\begin{aligned} B_1 &= B_2 = 0.4312\text{p.u.} \frac{\text{MW}}{\text{Hz}}; R_1 = R_2 = R_3 = 2.4\text{ p.u.} \frac{\text{MW}}{\text{Hz}}; \\ T_{sg1} &= T_{sg2} = 0.08\text{s}; T_{t1} = T_{t2} = 0.3\text{ s}; K_{r1} = K_{r2} = 0.3; \\ T_{r1} &= T_{r2} = 10\text{ s}; K_{PS1} = K_{PS2} = 68.9566\text{ Hz/p.u.}; \\ T_{12} &= 0.0433\text{p.u.}; a_{12} = -1; T_{w1} = T_{w2} = 1\text{ s}; \\ T_{RS1} &= T_{RS2} = 5\text{ s}; T_{RH1} = T_{RH2} = 78.75\text{ s}; \\ T_{GH1} &= T_{GH2} = 0.2\text{ s}; X_C = 0.6\text{ s}; Y_C = 1\text{s}; c_g = 1\text{ s}; \\ b_g &= 0.05\text{ s}; T_{F1} = T_{F2} = 0.23\text{ s}; K_T = 0.543478; \\ K_H &= 0.326084; K_G = 0.130438; K_{DC} = 1; T_{DC} = 0.2\text{s}; \\ T_{CR1} &= T_{CR2} = 0.01\text{ s}; T_{CD1} = T_{CD2} = 0.2\text{ s}; \\ T_{PS1} &= T_{PS2} = 11.49\text{ s}. \end{aligned}$$

APPENDIX D

MUMA GAIN [1]

$$K_T = 0.543478, K_H = 0.326084, \text{ and } K_G = 0.130438$$

DECLARATIONS

CONFLICT OF INTEREST

There is no conflict of interest.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors.

INFORMED CONSENT

There was no need of informed consent.

DATA AVAILABILITY

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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MOSES AWAL was born in Uganda. He received the B.Sc. degree in physics and mathematics and the M.Sc. degree in physics with electronics from Mbarara University of Science and Technology (MUST). His research interests include electronics, electrical, and power engineering (EEPE).



MICHAEL ROBSON ATIM was born in Uganda. He received the master's degree in physics/electronics and the Ph.D. degree in physics from the Faculty of Science, Mbarara University of Science and Technology (MUST). He is currently a Senior Lecturer with the Faculty of Science and Education, Physics Department, Busitema University. His major research interests include applied electronics, fuzzy logic, radiology, power distribution, and automated systems.



JIMMY NABENDE WANZALA was born in Uganda. He received the master's and Ph.D. degrees in physics/electronics from the Faculty of Science, Mbarara University of Science and Technology (MUST). He is currently a Lecturer with MUST. His research interests include applied electronics, medical physics, biophysics, convolutional neural networks, machine learning, radiology, fuzzy systems, and automated systems.



ical technologies, especially for low and middle-income countries.

JOHNES OBUNGOLOCH was born in Uganda. He is currently a Senior Lecturer with the Department of Biomedical Engineering and Dean of Faculty of Applied Science and Technology, Mbarara University of Science and Technology (MUST). He has broad experience working with medical technologies. He has expertise in the installation, maintenance, and repair of medical equipment. He has a background in biomedical engineering (Ph.D.) with specific interests in appropriate medical technologies, especially for low and middle-income countries.



Department, Faculty of Engineering, Almaaqaal University, Basrah, Iraq. He is an accomplished academic with a strong background in electronic and communication engineering. His research interests include digital design, optimization algorithms, automatic generation control, and interconnected power systems.

MOHAMED BARAKAT received the B.Sc. and M.Sc. degrees from the Electronic Engineering Department, Menoufia University, Egypt, in 2011 and 2019, respectively, and the Ph.D. degree from the Faculty of Engineering, Minia University, Minya, Egypt, in 2022. He is currently an Assistant Professor with the Communication and Computer Department, Faculty of Engineering, Canadian International College, Giza, Egypt. He is also an Assistant Professor with the Control and Computer

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