



OPEN Weighted average algorithm adjusted a novel (1 + FOPI)-FOPI-TID controller structure for AGC with integration of non-linearities and cyber-attack

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The integration of diverse energy sources and the advent of smart grids have intensified the challenges in load frequency management (LFM). Modern power systems are increasingly vulnerable to inherent nonlinearities, such as generation rate constraints, governor dead bands, boiler dynamics, and communication delays, as well as sophisticated cyber-attacks, which collectively threaten frequency stability and tie-line power balance. To address these challenges, this study proposes a novel cascade controller, designated as (1 + FOPI)-FOPI-TID, for robust automatic generation control in hybrid two-area power systems. The controller uniquely combines fractional-order (FO) dynamics with a tilt-integral-derivative stage and is optimized using a green metaheuristic, the weighted average algorithm (WAA). The WAA effectively balances exploration and exploitation to achieve superior parameter tuning. The proposed control architecture processes both area control error (ACE) and frequency deviation (Δf) signals through dedicated stages, enabling enhanced disturbance rejection and transient response. The system model incorporates a comprehensive set of nonlinearities and evaluates resilience against resonance-based cyber-attacks. Comprehensive simulation studies under both AC and HVDC tie-line configurations demonstrate that the WAA-optimized (1 + FOPI)-FOPI-TID controller significantly outperforms existing schemes, including PD-PI, PIFOD-(1 + PI), and PIDF(1 + FOD). Key performance metrics show a 45.3% reduction in the integral of time-weighted absolute error (ITAE) and improvements in settling times of 47.7% for Δf_1 and 32.8% for Δf_2 . Sensitivity analysis confirms robustness under $\pm 25\%$ parameter variations and random load perturbations. During cyber-attacks, the controller maintains the lowest Rate of Change of Frequency (RoCoF), underscoring its dual capability in stabilizing grid dynamics and mitigating cyber-physical threats. These results validate the controller's potential to enhance operational resilience and reliability in future smart grids.

Keywords Automatic generation control, (1 + FOPI)-FOPI-TID controller, Weighted average algorithm, Cyber-attack, Power systems nonlinearities, Random step load

Abbreviations

LFC	Load frequency control
AGC	Automatic generation control
FO	Fractional order
RLP	Random step load
ITAE	Integral time multiplied absolute error
NRT	Non-reheat thermal
MSTA	Multi-source two-area

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HVDC	High voltage direct current
GDB	Governor dead band
GRC	Generation rate constraints
CTD	Communication time delay
SLP	Sudden load perturbation
PID	Proportional-Integral-Derivative
TID	Tilt integral derivative
BD	Boiler dynamic
CC	Cascade controller
PSI	Power system interconnection
WWA	Weighted average algorithm
i	Related to number 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.)
T_S	Settling time (s)
f	Operating frequency (Hz)
P_R	Rated Power for each area (MW)
B_i	Bias frequency (p.u.MW/Hz)
K_H	Contributing factors for hydro unit
K_G	Contributing factors for gas unit
K_{DC}	HVDC gain (Hz/p.u.)
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}	Time constant of steam turbine (s)
T_{gi}	Time constant of speed governor (s)
T_{12}	Synchronizing coefficient (p.u.)
T_{RSi}	Reset time of hydro turbine (s)
T_{GHi}	Time constant of hydro turbine (s)
T_{Wi}	Nominal initial time of water in penstock (s)
T_{RHi}	Hydro turbine speed governor droop time constant (s)
T_{PSi}	Time constant of power system (s)
K_T	Contributing factors for thermal unit
T_{DC}	HVDC time constant (s)
b_g	Gas turbine constant of positioner (s)
c_g	Gas turbine valve positioner(s)
$\bar{Y}_C$	Lag time of gas turbine (s)
X_C	Lead time of gas turbine (s)
T_{CRi}	Time delay of Gas turbine combustion (s)
T_{CDi}	Gas turbine compressor discharge volume (s)
T_{fi}	Gas turbine fuel time constant (s)

The stability and efficiency of modern electrical power systems are fundamentally governed by the precise balance between generation and demand, a critical task managed by load frequency control (LFC) or automatic generation control (AGC). As global energy consumption rises and power grids evolve into increasingly interconnected networks, incorporating a diverse mix of conventional thermal plants, hydroelectric facilities, gas turbines, and renewable sources, the challenge of maintaining system frequency within narrow operational limits has become markedly more complex^{1,2}. These interconnected systems, while enhancing reliability and enabling economic power exchange, exhibit heightened dynamic sensitivity. Even minor load perturbations can trigger frequency deviations and unscheduled tie-line power flows, potentially leading to instability, equipment stress, and, in extreme cases, cascading failures³. Consequently, the development of advanced, robust control strategies for AGC is paramount for ensuring the security and reliability of future power networks.

This imperative is further intensified by two distinct yet converging sets of challenges: inherent physical nonlinearities and emerging cyber-physical vulnerabilities. Traditional linear models often fail to capture the true dynamic behavior of practical systems. Critical physical constraints, including generation rate constraints (GRC) that limit how fast a plant can ramp output, the nonlinear governor dead band (GDB) that causes insensitivity to small speed changes, slow-acting boiler dynamics (BD) in thermal units, and inevitable communication time delays (CTD) in signal transmission, collectively degrade control performance^{4–6}. These nonlinearities manifest as increased overshoot, prolonged settling times, and persistent oscillations following disturbances. Simultaneously, the digital transformation of the grid through smart technologies introduces a new frontier of risk. The very communication channels and digital controllers that enable advanced AGC also expose the system to sophisticated cyber-attacks. Threats such as stealthy resonance-based attacks (ResA), which subtly manipulate load signals to drive the system into instability at its natural oscillatory modes, pose a serious and plausible danger^{7–9}. This dual challenge, managing complex physical dynamics while fortifying the system against intelligent cyber threats, defines a critical research gap in contemporary AGC design.

In response to the need for improved regulation, control strategies have progressed significantly beyond the ubiquitous Proportional-Integral-Derivative (PID) controller. While PID variants, often tuned via classical or heuristic methods, remain widely used for their simplicity¹⁰, their performance is frequently inadequate in handling the multifaceted nonlinearities and high variability of modern, multi-source grids^{11,12}. This has spurred interest in cascade control (CC) architectures, where two or more controllers are arranged in series, offering superior disturbance rejection and set-point tracking by correcting errors at multiple stages¹³. This evolution highlights the need for more structured and multi-stage control architectures in modern LFM design. The search for optimal parameters for these advanced structures has naturally aligned with the rise of metaheuristic optimization. Algorithms such as TLBO², PSO¹⁴, Whale optimization algorithm¹⁵, Jaya optimization¹⁶, differential evolution¹⁷, hybrid PSO-BFOA algorithm^{18,19}, grey wolf optimization²⁰, and others, have been extensively applied to tune AGC controllers, demonstrating the ability to find high-performance solutions in complex, non-convex search spaces.

A parallel and transformative advancement has been the incorporation of Fractional-Order (FO) calculus into control theory. Unlike integer-order controllers, FO controllers possess non-integer differentiation and integration orders, providing additional tuning parameters that grant greater flexibility to shape the dynamic response. This has led to the development of effective strategies like the FOPID controller^{21,22}, and more sophisticated cascade designs such as the PIFOD-(1 + PI) and FOPD-FOPID^{23,24} for multi-area systems. The quest for further performance gains continues to yield novel hybrid structures, including tri-stage controllers like (1 + PI)-PI-PID²⁵ optimized via enhanced artificial bee colony-particle swarm optimization (IABC-PSO)²⁵, hybrid 2DOF-PID-TD controllers²⁶, fuzzy-FOPID + PIDN schemes for deregulated two-area systems²⁷, and fuzzy-PIDF-(1 + PI) controllers²⁸. These developments collectively illustrate the growing shift toward multi-stage and FO-based control architectures for advanced AGC applications.

Despite these considerable advances, a synthesis of the literature reveals several persistent limitations that this work seeks to address. First, many studies validate controller performance under a simplified set of assumptions, often incorporating only one or two nonlinearities. There is a lack of comprehensive evaluation under the simultaneous action of GRC, GDB, BD, and CTD within a hybrid (thermal-hydro-gas-nuclear) generation environment. Second, while cybersecurity is recognized as a paramount concern, very few AGC studies integrate realistic, dynamic cyber-attack models into their simulation-based validation, leaving a gap in understanding controller resilience. Third, the proliferation of complex cascade controller structures is sometimes driven primarily by numerical optimization outcomes, with insufficient explanation of the control-theoretic rationale behind the specific signal flow and component selection. Finally, the claimed superiority of newer metaheuristic optimizers often lacks rigorous benchmarking against established algorithms in the specific context of the AGC tuning problem.

To bridge these identified gaps, this paper proposes a novel, carefully justified fractional-order cascade controller, designated as the (1 + FOPI)-FOPI-TID, specifically tailored for automatic generation control of two-area power systems. The proposed controller simultaneously utilizes the area control error (ACE) and frequency deviation (ΔF) signals, incorporating fractional-order dynamics and a tilting integral block $s^{-1/n}$ to enhance transient response, disturbance rejection, and robustness²⁹. Optimal parameter tuning is achieved using the weighted average algorithm (WAA)³⁰. The straightforward yet efficient search process of the Weighted Average Algorithm (WAA), which is based on deterministic weighted average of potential solutions based on their fitness scores, sets it apart from other metaheuristic techniques. WAA avoids complicated population dynamics and requires fewer control parameters than evolutionary and swarm-based algorithms, which rely on several stochastic operators and algorithm-specific parameters. WAA is ideally suited for controller tuning in large-scale interconnected power systems because the adaptive weighting technique allows for a natural balance between exploration and exploitation, leading to quick convergence, numerical robustness, and less computational effort.

In accordance with the “no-free-lunch” principle³¹, the dual exploration-exploitation capability of WAA ensures robust regulation in the presence of GRC, GDB, BD, CTD, and stealthy cyber threats. Its novelty lies in the dynamic adjustment of search space via weighted population positions, which enhances convergence stability.

The Contributions of this study are summarized as follows:

- i. A novel tri-stage FO CC, designed as (1 + FOPI)-FOPI-TID, is proposed for AGC of PSI to enhance frequency regulation and tie-line power stability.
- ii. The proposed controller employs dual input signals, ACE and ΔF , enabling faster disturbance rejection and improved transient performance compared to conventional single-input CC structures.
- iii. The WAA, a recent metaheuristic algorithm, is utilized for the optimal tuning of the proposed controller parameters, providing an effective balance between exploration and exploitation and ensuring robust convergence characteristics.
- iv. A realistic multi-source two-area power system model is developed by incorporating GRC, GDB, BD, and CTD nonlinearities.
- v. The cyber-resilience of the proposed LFC scheme is explicitly investigated by subjecting the system to resonance-based cyber-attack scenarios, assessing frequency deviation and rate-of-change-of-frequency (Ro-CoF) performance.

Materials and methods

Modelling of hybrid power system

The investigated system in Fig. 1 is a two-area interconnected power system with multi-source generation in each control area. Area-1 consists of thermal reheat, hydro, gas, and nuclear power generation units, while Area-2 comprises an identical combination of generation sources.

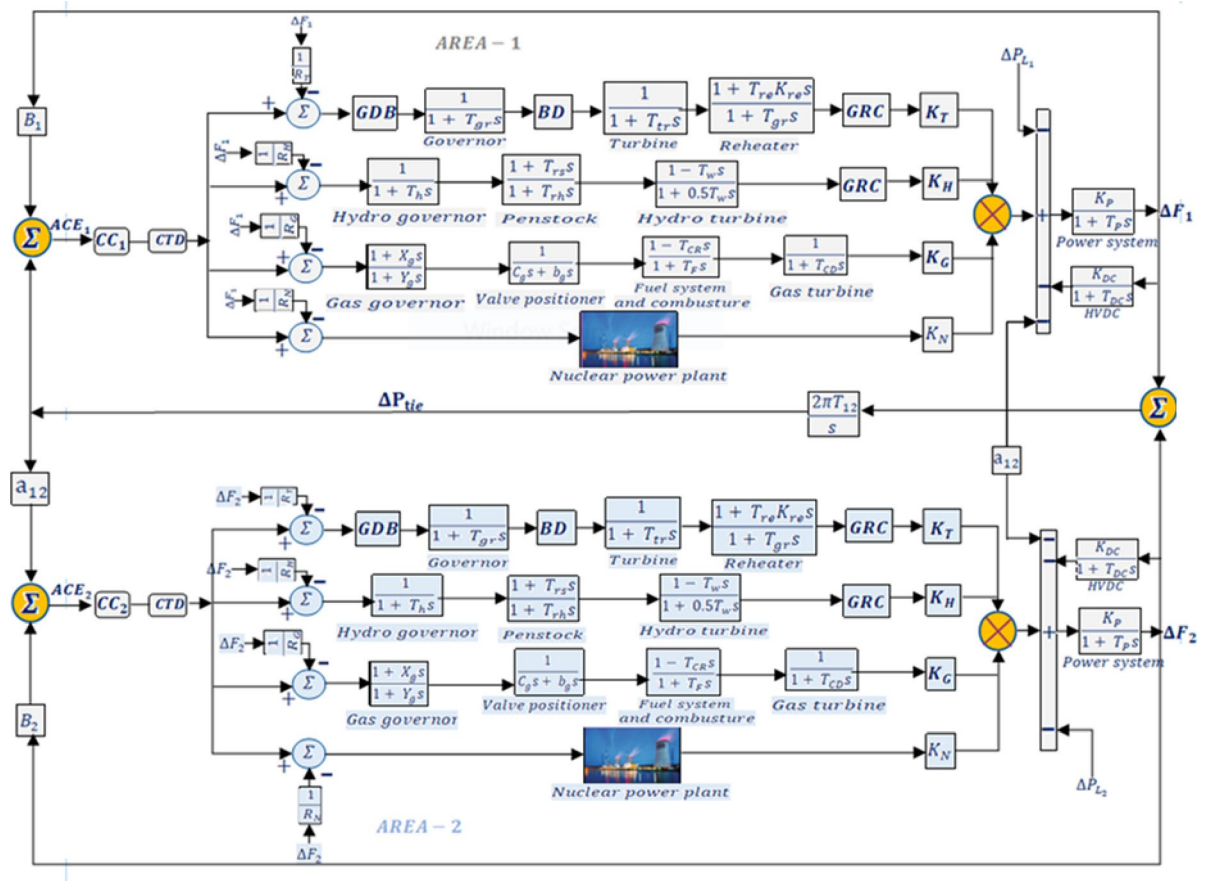


Fig. 1. Transfer function model of the tested PSI.

The power demand is represented in a step load form, with an increment of ΔP_{11} for area1 and ΔP_{12} for area-2. 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} . Frequency regulation is achieved through feedback mechanisms utilizing the speed regulation (R) and frequency bias factors (B), which stabilize system dynamics by adjusting tie-line power and frequency deviations³².

The effect of combining tie-line power error and frequency fluctuation is attributed to the ACE^{17,33}. The area-specific ACEs are:

$$\begin{aligned} ACE_1 &= \Delta P_{tie} + B_1 \Delta F_1 \\ ACE_2 &= \Delta P_{tie} + B_2 \Delta F_2 \end{aligned} \quad (1)$$

In the event of a load disturbance on the PS, ACEs are employed as a regulating signal to reduce ΔP_{tie} and ΔF_i to zero at the steady state.

The integration of the HVDC link in the PSI allows for additional investigation. The generation rates from thermal, hydro, gas, and nuclear units are managed by independent secondary controllers in each sector, with AC-DC parallel lines connecting these units, as illustrated in Fig. 1. The DC link is modeled using a first-order transfer function, characterized by a gain of K_{DC} and a time constant of T_{DC} . This first-order transfer function effectively describes the behavior of the DC link.

$$\Delta P_{tie,DC} = \frac{K_{DC}}{1 + T_{DC}s} \quad (2)$$

The HVDC links are increasingly being utilized for power exchange across control areas alongside existing high-voltage AC links. Research indicates that HVDC links, when operating in tandem with conventional AC systems, provide cost-effective and environmentally friendly benefits while also ensuring higher-quality electric power delivery³⁴. Moreover, it reinforces the system's resistance to minor disruptions³⁵.

Nonlinear test models

Several physical nonlinearities are incorporated into the test model of the PSI to enhance realism. As shown in Figs. 1 and 2, the test model includes nonlinearities such as GDB, GRC, BD, and CTD. To limit the rate of generation change, a significant nonlinear component known as GRC is added. The typical benchmark for

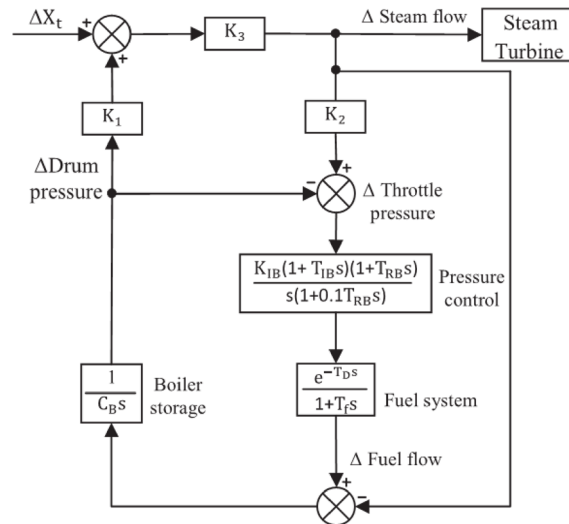


Fig. 2. Boiler dynamic nonlinearity.

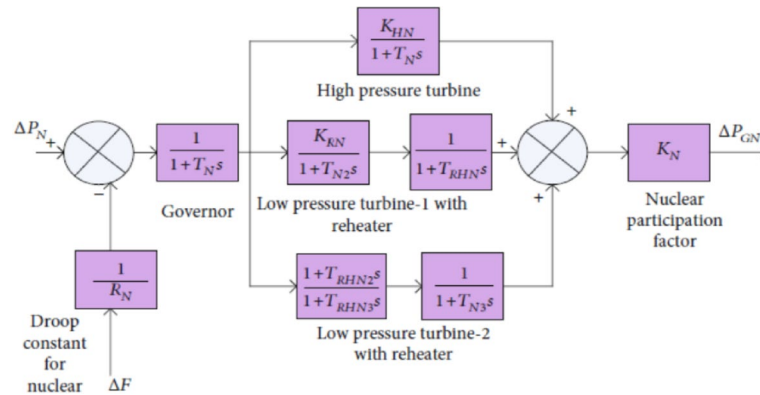


Fig. 3. Nuclear power plant transfer function model.

thermal plants is a GRC value of 3% per minute. To prevent excessive generation, the GRC for the thermal system is specified as $|\Delta P_g| \leq 0.0005 \text{ p.u. MW/s}$. To efficiently control generation levels, the saturation block of the thermal unit is restricted to ± 0.0005 . A GRC of 360% per minute for decreasing generation and 270% per minute for increasing generation was taken into consideration for hydropower plants. This means that for decreasing generation, $|\Delta P_g(s)| \leq 0.06 \text{ p.u. MW/s}$, and for increasing generation, $|\Delta P_g(s)| \leq 0.045 \text{ p.u. MW/s}$. According to³⁶ and³⁷, the system model includes a saturation block in the hydro turbine that is limited between -0.06 and 0.045. According to Gheisarnejad M.^{38,39}, the GDB nonlinearity is spelled out as:

$$G_d(s) = \frac{0.8 - \frac{0.2}{\pi}s}{1 + T_g s} \quad (3)$$

Figure 3. presents a simplified dynamic model of a nuclear power plant for load frequency control analysis. It includes the governor, high- and low-pressure turbine stages with reheater dynamics, and a nuclear participation factor. Frequency deviation is processed through droop and governor dynamics, while turbine-reheater blocks capture the slow response of nuclear units. The aggregated turbine output determines the incremental nuclear power contribution, enabling assessment of nuclear participation in frequency regulation under load disturbances.

Similarly, a boiler dynamic nonlinearity is added to the thermal reheat system, as illustrated in Fig. 2.^{11,40} The figure presents a dynamic boiler-steam turbine model used in load frequency control studies of thermal power plants, capturing the interactions among the boiler, fuel system, pressure control loop, and steam turbine. The control input signal regulates steam flow to the turbine through appropriate gain factors, while feedback from drum and throttle pressure deviations ensures stable operation. Boiler dynamics are represented using a storage model, and the pressure control loop incorporates proportional-integral with lead-lag characteristics. The fuel system is modeled as a first-order process with time delay to account for fuel transport and combustion

effects. Overall, the model effectively represents the dominant delayed and nonlinear dynamics of thermal units for frequency regulation analysis under load disturbances.

Additionally, a CTD is incorporated after the controller design to enhance the realism of the system. According to⁴¹ and ⁴², this study used a time delay parameter (τ_d) value of 0.25 s, which is normally in the [0:1] range:

$$e^{-s\tau_d} = \frac{1 - \frac{\tau_d}{2}s}{1 + \frac{\tau_d}{2}s} \quad (4)$$

Cyber attack

Cyber-attacks in LFM are increasingly important to consider in order to ensure the reliable and secure operation of modern PSs, as such attacks may disrupt control actions and lead to severe operational consequences. In this work, a resonance-based cyber-attack (ResA) is adopted as a physics-informed and literature-supported representation of stealthy load manipulation scenarios reported in recent studies on cyber-physical power systems. In a ResA, an attacker introduces load variations that follow a resonance source while remaining within permissible operating limits, thereby avoiding immediate detection by conventional protection mechanisms^{9,43}. Although these variations are small in magnitude, their persistent nature can induce pronounced frequency deviations and elevated RoCoF, which may threaten system stability.

The attack parameters, including amplitude and frequency, are selected based on established literature to reflect realistic adversarial behavior rather than idealized worst-case conditions. This choice ensures that the injected disturbances remain credible and allows a fair comparative assessment, as all controllers are evaluated under identical attack conditions. In practical power systems, RoCoF-based protection relays are widely deployed to mitigate such disturbances. Typical RoCoF relay thresholds lie within the range of 0.1–1.0 Hz/s, depending on system inertia characteristics⁹, and exceeding these limits may trigger protective actions that result in major system disruptions. Under the considered ResA, the manipulated load signal is verified for plausibility by the power generation system; once accepted, the attacker can influence system dynamics in a sustained manner^{9,43}.

In this study, RoCoF is employed as the primary cyber-resilience indicator due to its direct relevance to frequency protection schemes and operational security in interconnected power systems. While additional cyber-resilience metrics, such as observability degradation and control signal distortion, are recognized as important complementary indicators, their detailed investigation is beyond the scope of the present work and is identified as a direction for future research. The mathematical representation of the resonance-based cyber-attack is given by:

$$\Delta P_{L2} = -0.1 \cdot \text{sign}[\Delta f_2] \quad (5)$$

which relates the injected load disturbance to the frequency variation in the second control area, consistent with previously reported models⁴³.

Design of proposed (1 + FOPI)-FOPI-TID controller structure

As shown in Table 1, the literature controller structures include two-stage configurations such as PIDF-(1 + FOD), PIFOD-(1 + PI), and PDF-(1 + PI), where the *ACE* is the sole input. In contrast, the PD-PI controller utilizes both *ACE* and ΔF as inputs; however, ΔF is directly fed into the secondary PI controller, which limits disturbance rejection. Additionally, the tri-stage (1 + PI)-PI-PID controller incorporates *ACE*, ΔF , and ΔP_{tie} , but retains a conventional PID structure, with ΔP_{tie} passing through only one controller, the PID. These controller structures are shown in Fig. 4. A comparative analysis of controller attributes provided in terms of controller structure, number of stages, scale of PSI, and limitations and advantages are summarized in Table 1.

This paper introduces a novel controller structure of (1 + FOPI)-FOPI-TID, as illustrated in Fig. 5. This configuration allows for the swift rejection of disturbance sources before they can propagate through the system. The unique controller incorporates two input signals: the main *ACE* and ΔF . This feature distinguishes it from other CC configurations in the field, as the *ACE* serves as the primary input to the (1 + FOPI) controller,

Ref	Scale	CC structure	Input Signals	Limitations	Advantages
44	Maritime microgrid	PI-(1 + PD)	ΔF	- PID controller and conventional structure - It depends on <i>ACE</i> or ΔF only	- Reduces high-frequency noise better than single PID - Better stability and faster disturbance rejection
45	Two-area hydrothermal IPS in deregulated environment	PIDF-(1 + FOD)	<i>ACE</i>		
46	Three-area system with GRC & FACTS	PDF + (1 + PI)	<i>ACE</i>		
47	Two-area of different test models	PD-PI	<i>ACE</i> , and ΔF	- ΔF only passes to PI controller, losing disturbance rejection since it does not pass through two controllers - Using PID controller	- Fast stabilization with minimal peaks - Enhances robustness and flexibility in high-variability conditions
25	Two area: reheat, thermal, and hydropower PSI	(1 + PI)-PI-PID	<i>ACE</i> , ΔF and ΔP_{tie}	- Using PID controller - ΔP_{tie} only passes to PID controller, losing disturbance rejection as it does not pass through two controllers	
23	Two-area microgrid with tidal PS	PIFOD-(1 + PI)	<i>ACE</i>	- Tested on small PSs and one input <i>ACE</i>	- Cascade controller attain good transient response

Table 1. Controller structure, scale, input, limitations, and advantages.

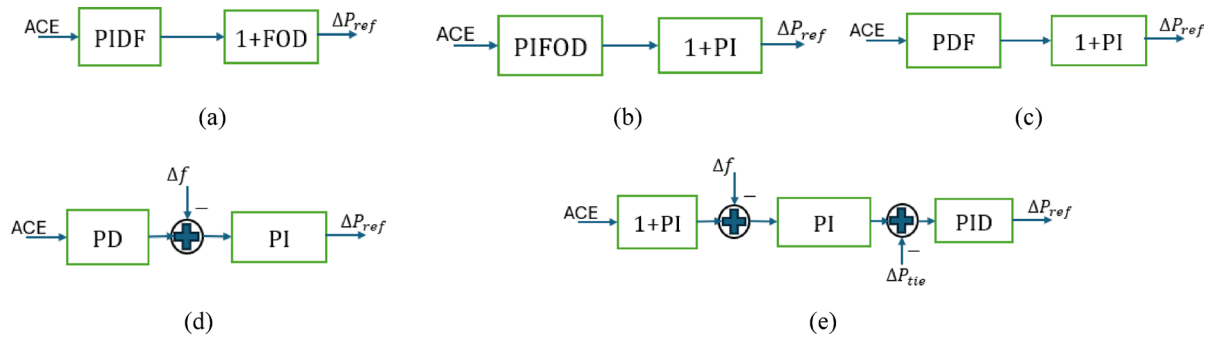


Fig. 4. The literature controller structure: (a) PIDF-(1 + FOD), (b) PIFOD-(1 + PI), (c) PDF-(1 + PI), (d) PD-PI, and (e) (1 + PI)-PI-PID.

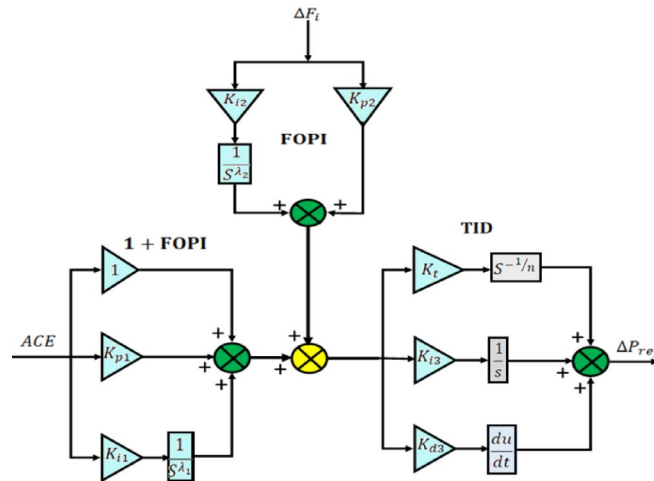


Fig. 5. Proposed structure of (1 + FOPI)-FOPI-TID CC.

in parallel, the ΔF is the input to the FOPI controller, and the combined output of both feeds into the TID controller.

Although the ACE already contains frequency deviation information ($ACE = \Delta P_{tie} + \Delta F_i$), using both ΔF_i and ACE as inputs in the proposed controller is intentional and meaningful. The two signals represent different aspects of system behavior. The frequency deviation ΔF_i reflects fast local changes caused by sudden load disturbances and is useful for taking quick corrective action. On the other hand, the ACE signal represents the overall control objective, as it includes both frequency deviation and tie-line power deviation, and is responsible for coordinating power exchange between areas and restoring steady-state operation. By assigning ΔF_i and ACE two different stages of the CC, the proposed structure separates fast local response from slower inter-area regulation. Even though these signals are mathematically related, they act on different time scales, and their combined use does not lead to conflicting control actions. Instead, this structured design improves disturbance rejection, damping, and robustness, especially in the presence of nonlinearities and uncertainties.

Therefore, the proposed controller is not unnecessarily complex but rather designed to handle the practical dynamic characteristics of interconnected power systems more effectively. The S-domain representations of the (1 + FOPI), FOPI, and TID controllers are as follows:

$$G_{1+FOPI}(s) = 1 + K_{p1} + K_{i1}s^{-\lambda_1} \quad (6)$$

$$G_{FOPI}(s) = K_{p2} + K_{i2}s^{-\lambda_2} \quad (7)$$

$$G_{TID}(s) = K_t s^{-1/n} + \frac{K_{i3}}{s} + K_d s \quad (8)$$

where K_{pi} , K_i , K_t , K_d are proportional, integral, tilt, derivative, while λ , and n are the fractional parameters of integral and tilt factors. Achieving optimal performance for this controller requires the simultaneous optimization of these ten parameters. To fulfill this objective and attain fair comparison, a WAA is selected for this study to tune the proposed and the literature controller structures.

In this study, The FO operators were realized using the Oustaloup recursive approximation method, which provides accurate finite-dimensional representations of fractional differ-integrators over the selected frequency band [0.01–100] rad/s. This choice ensures numerical stability and efficient implementation in MATLAB/Simulink. The controller parameters are optimized offline, and the resulting implementation requires only low-order filters and simple algebraic operations, making the proposed control scheme computationally efficient and suitable for real-time deployment in large-scale interconnected power systems, even in the presence of communication delays.

The proposed (1 + FOPI)–FOPI–TID CC architecture is motivated by the physical structure and different response time requirements of automatic generation control rather than mathematical complexity alone. Each stage is assigned a distinct control role: the (1 + FOPI) loop, driven by the area control error, ensures accurate steady-state regulation and coordinated inter-area power exchange, with fractional-order integration enhancing robustness to uncertainties and low-frequency oscillations. The FOPI loop directly processes local frequency deviation, enabling rapid disturbance rejection and improved damping under sudden load changes and nonlinear operating conditions. The final TID stage functions as a dynamic compensator, where the tilt component provides wide-band damping, the integral term removes residual steady-state offsets, and the derivative term improves transient shaping without excessive noise amplification. This cascade configuration deliberately separates fast local frequency control from slower inter-area regulation, reducing control interaction and avoiding aggressive gain tuning required in simpler single- or dual-loop fractional controllers. As a result, the proposed structure closely reflects the physical control objectives of interconnected power systems, thereby enhancing robustness, interpretability, and practical applicability beyond purely performance-based validation.

Performance index of LFM

Customer demand changes affect the PS's frequency, which causes ΔF_i and ΔP_{tie} to deviate from their nominal values. With an appropriate Performance function, it is advised to first successfully use contemporary heuristic optimization-based controller techniques in order to improve LFM performance^{39,48,49}. The ISE, ITAE, IAE, and ITSE are some of the common performance functions that have been literature to address AGC issues and restore nominal performance^{43,50}.

The ITAE criterion was chosen as the primary objective because of its proven effectiveness in minimizing sustained deviations and improving damping in AGC studies, thereby ensuring faster convergence and reduced steady-state error⁵¹. ITAE provides a balanced trade-off between transient suppression and long-term stability, which aligns with the focus of this work. The application of the ITAE criterion will be essential in this investigation in order to modify the (1 + FOPI)–FOPI–TID CC's scaling parameters. This objective is represented by the symbol ξ as follows:

$$\xi = \text{ITAE} = \int_0^{t_{\text{sim}}} t \cdot [\Delta F_1 + \Delta F_2 + \Delta P_{tie}] dt \quad (9)$$

In order to find out optimistic controller gains on a large scale, the gains range are chosen in the range [0, 2] as in^{24,36} for non-linear MST model. The n and λ in the range [2, 3]^{52,53} and [0, 2]¹¹ respectively. In conclusion, by exploiting the WAA metaheuristic algorithm, optimal or near optimal set of (1 + FOPI)–FOPI–TID CC parameters is derived within the recommended edges for the smallest value of ξ .

Weighted average algorithm (WAA)

The two main steps of population-based meta-heuristic algorithms are exploitation and exploration. Exploration is concerned with avoiding local optima in the search space (SS), whereas exploitation is concerned with bettering solutions found during exploration. This approach is best shown by the WAA, which strikes a balance between exploration and exploitation. To keep this equilibrium, it uses movement strategies based on random constants and iteration numbers and calculates the population's weighted average position (WAP) at each iteration.

The weighted average position's inspiration

Each element is given a certain weight in order to calculate the WAP; the final average is more affected by the higher weights. The SS directs the updating of each person's location for the subsequent iteration during each iteration. Individual positions, their personal best position (PBP), and the global best position (GBP) form the basis of the new SS. The global position is the best fitness value for the entire population, whereas a person's PBP is the maximum fitness value attained during its movement history. Together with the PBP and GBP, the WAP is used to update future positions and represents the current population distribution.

Algorithm and mathematical model

Matrix S , which represents a collection of potential solutions, is used to randomly begin the optimization process:

$$S = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_i \\ \vdots \\ S_n \end{bmatrix} = \begin{bmatrix} s_1^1 & s_1^2 & \cdots & s_1^j & \cdots & s_1^d \\ s_2^1 & s_2^2 & \cdots & s_2^j & \cdots & s_2^d \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ s_i^1 & s_i^2 & \cdots & s_i^j & \cdots & s_i^d \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ s_n^1 & s_n^2 & \cdots & s_n^j & \cdots & s_n^d \end{bmatrix}, \text{ where } \begin{cases} i = 1, 2, \dots, n. \\ j = 1, 2, \dots, d. \end{cases}$$

where d is the dimension of the deemed problem, n is the number of solutions candidate along the SS, and S_i is the i^{th} candidate solution, ³⁰. The starting positions s_i^j are disclosed randomly as:

$$s_i^j = LB_j + rand. (UB_j - LB_j)$$

where LB_j refer to the j^{th} lower bound value, $rand$ is a random number within $[0:1]$ range, and UB_j expresses the j^{th} upper bound value.

Weighted average position (WAP)

First, each participant's fitness is determined, then the population is rearranged according to the cost function to determine the WAP. The first N candidates in the population are then chosen in order to compute the WAP in the manner described below:

$$N_{candidate} = (nP - 4) \frac{it - 1}{1 - Max_{It}} + nP$$

$$SUM_{Fitness} = \sum_{i=1}^{N_{candidate}} Fitness(S_i)$$

$$X_{miu} = \frac{\sum_{i=1}^{N_{candidate}} S_i (SUM_{Fitness} - Fitness(S_i))}{SUM_{Fitness} (N_{candidate} - 1)}$$

where S_i is the i^{th} candidate solution, $SUM_{Fitness}$ is the total fitness values of the chosen candidates, nP is the populations number, $Fitness$ is the function used to calculate the fitness value, $N_{candidate}$ is the number of chosen candidate solutions, $N_{candidate}$ is the applicant solutions number, X_{miu} is WAP. Besides, it is the current iteration number, and Max_{It} is the limit number of iterations.

(a) Exploitation or exploration process

The search phase for the potential solution, i.e., exploration or exploitation, should be identified during the iteration process:

$$f(it) = (\alpha \cdot rand - 1) \sin \left(\pi \frac{it}{Max_{It}} \right)$$

The balance between exploration and exploitation phases is controlled by the constant α . An equilibrium is reached if $f(it) = 0.5$. Candidate solutions with $f(it) \geq 0.5$ move in accordance to their exploitation capabilities, whereas those with $f(it) < 0.5$ move in accordance to their exploration abilities³⁰

(b) Exploitation phase

The exploitation strategy in the WAA directs search agents towards areas likely to yield new global best values. To efficiently exploit the SS, the WAA employs three movement strategies that incrementally move search agents closer to the optimal solution as shown in Fig. 6.

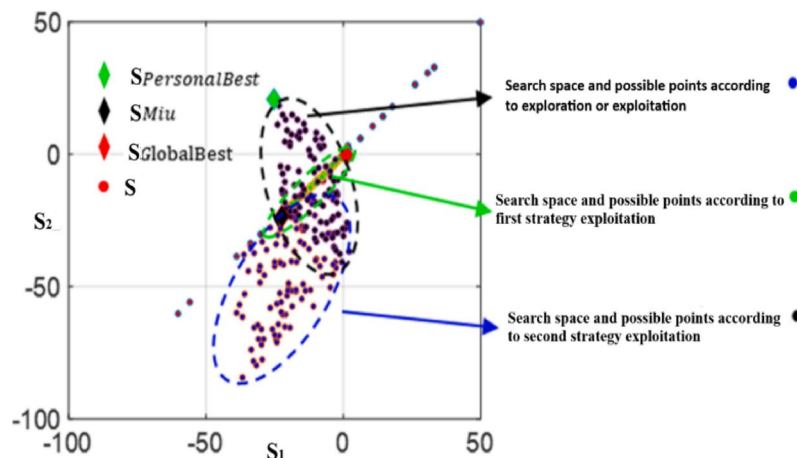


Fig. 6. Diagram of search agent position updating based on exploitation strategies.

- (i) The first strategy exploits the SS using the WAP of the entire population, PBP, and GBPs.

$$S_i(it+1) = r_{11} \cdot (S_{miu}(it) - S_{Global_{best}}(it)) + r_{12} \cdot (S_{miu}(it) - S_{Personal_{best}}(it)) + r_{13} \cdot S_{miu}(it)$$

where r_{ij} are random values within [0–1], to modify the expansion of the search space around the personal best $S_{Personal_{best}}$ and GBP $S_{Global_{best}}$ to express the PBP and GBP in the iteration numbers (it).

- (ii) The second technique ignores the GBP and concentrates on the region between the PBP and the population's WAP in order to narrow the SS. This method, in contrast to the first technique, prioritizes a narrower area for exploitation. Using the following, the new SS is produced³⁴:

$$S_i(it+1) = r_{21} \cdot (S_{miu}(it) - S_{Personal_{best}}(it)) + r_{22} \cdot S_{Personal_{best}}(it)$$

This approach shows a greater bias towards improving accuracy and convergence rate by guiding movement from the agent's PBP towards the population's WAP.

- (iii) The third trick deals with the SS between the GBP and the population's WAP. Each candidate's position update is determined for this purpose using the formula below:

$$S_i(it+1) = r_{31} \cdot (S_{miu}(it) - S_{Global_{best}}(it)) + r_{32} \cdot S_{Global_{best}}(it)$$

This approach has a narrow SS that concentrates on the area between the GBP and the WAP. Both the accuracy and the pace of convergence are improved by this focused movement³⁴.

- (c) Exploration phase

The exploration of the solution space utilizes two strategies: the Levy Flight method and dynamic movement distances. The Levy flight method focuses on the GBP, creating a broad search area around the WAP. This involves short movements for local optimization and longer movements to explore distant regions. Candidates dynamically move in various directions from the GBP, enhancing exploration and balancing the exploitation of current solutions. The Levy flight model follows a Levy distribution, characterized by mostly small strides with occasional larger ones, reflecting natural patterns observed in birds and insects, expressed as³⁰:

$$X = \frac{U}{|V|^{1/\beta}}, U = normal(0, \sigma_u^2) \& V = normal(0, \sigma_v^2)$$

where X is the step length of the Levy flight influenced by the parameter β , and Γ stands for the Gamma distribution function. Besides, V and U satisfy normal distributions with standard deviations equal to σ_v and σ_u respectively, and zero mean values. The first exploration technique, which is based on a controlled adjustment of step length X , is as follows:

$$S_{i,j}(it+1) = S_{Global_{best}}(it) + X$$

where $S_{i,j}(it+1)$ denotes the j^{th} position of the i^{th} solution at the next iteration. In certain instances, the algorithm's global optimum might be located close to the GBP yet too far from the ideal GBP value. When using the first method in such circumstances, the WAA runs the danger of convergent to a local optimum. The second movement method is used to modify the SS in order to reduce this danger³⁴:

$$S_i(it+1) = LB_{min} + rand.(UB_{min} - LB_{min})$$

where the lower and upper boundaries' minimum values are denoted by LB_{min} and UB_{min} , respectively. By using this tactic, the search agents can shift to different locations within the SS in an effort to locate possibly superior areas.

The WAA system optimizes gains in (1 + FOPI)-FOPI-TID controllers using the ITAE criteria. It iteratively generates new gains by minimizing ITAE values, aiming for the lowest ITAE to reduce system deviations. Research indicates that larger initial populations do not necessarily outperform smaller ones in finding optimal solutions, making the approach suitable for real-time LFM scenarios⁵⁴. The operational framework of the proposed WAA is depicted in the flowchart presented in Fig. 7, which outlines the sequential logic and decision-making steps involved in the algorithm.

Results and discussion

This study investigates the effectiveness of a novel (1 + FOPI)-FOPI-TID controller using a combination of hybrid power sources and non-linearities, GRC, GDB, BD, and CTD, alongside cyber-attacks. To achieve the LFM

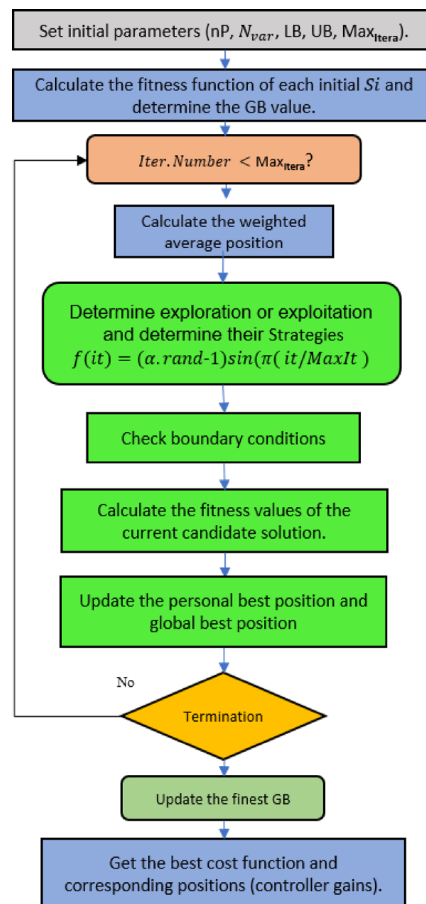


Fig. 7. WAA flowchart.

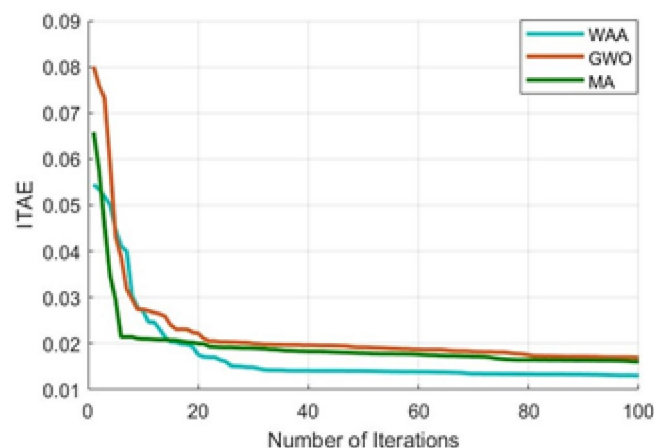


Fig. 8. The convergence characteristic curves of PSO, GWO, and the proposed FHO.

goal, the controller coefficients are optimized with the WAA optimizer in MATLAB, integrated with Simulink on an Intel Core i-5 processor. The WAA-based controller settings for the cases study after 100 iterations of optimization are conducted. The robustness of the proposed controller is compared to other regulators, including PIDF(1 + FOD), PIFOD-(1 + PI), (1 + PI)-PI-PID CC, PDF-(1 + PI), and PD-PI CCs, all under fixed load changes of 1% SLP. Results from the analyzed multiarea PSI are thoroughly examined in subsequent case studies.

Case 1: Effectiveness of the WAA algorithm

To demonstrate the adaptability of the WAA, the convergence characteristics of WAA, mayfly algorithm (MA)⁴³, and grey wolf optimization (GWO)⁵⁵ are analyzed in the context of the (1 + FOPI)-FOPI-TID CC using

Algorithm	Minimum	Maximum	Average	St. deviation
WAA	0.013810	0.015443	0.014287	0.00085502
MA	0.016109	0.022811	0.018863	0.00336873
GWO	0.016967	0.023063	0.022399	0.00334436

Table 2. ITAE values for WAA, MA, and GWO at case1.

WAA based CC structure	Area 1							Area 2						
	K_P/K_t	K_I	K_D	μ	λ	n	N	K_P/K_t	K_I	K_D	μ	λ	n	N
<i>PIDF (1 + FOD)</i>														
PIDF	0.6333	2.0000	1.3e-4	–	–	–	–	1.5019	0.1495	2.0000	–	–	–	–
(1 + FOD)	–	–	–	0.2611	–	–	23.53	–	–	–	1.0e-6	–	–	0.0126
<i>WAA: PIFOD-(1 + PI)</i>														
PIFOD	0.6583	2.0000	7.02e-05	0.9757	–	–	–	2.0000	0.2769	0.3816	0.3802	–	–	–
(1 + PI)	2.0000	1.129e-7	–	–	–	–	–	0.0527	0.00373	–	–	–	–	–
<i>PD-PI CC</i>														
PD	2.0000	–	0.4935	–	–	–	–	2.0000	–	2.0000	–	–	–	–
PI	0.2709	1.9308	–	–	–	–	–	0.0569	0.0873	–	–	–	–	–
<i>(1 + FOPI)-FOPI-TID CC</i>														
(1 + FOPI)	1.2777	2.0000	–	–	1e-5	–	–	2.0000	0.0786	–	–	1.9977	–	–
FOPI	0.6731	0.0769	–	–	0.9628	–	–	1.0e-4	0.0031	–	–	0.4319	–	–
TID	1.9995	1.6399	0.2435	–	–	2.5071	–	1.0e-6	0.0000	0.0000	–	–	2.999	–
<i>(1 + PI)-PI-PID CC</i>														
1 + PI	1.6919	1.8777	–	–	–	–	–	1.6752	1.2e-05	–	–	–	–	–
PI	0.3219	1.9545	–	–	–	–	–	0.3582	1.3421	–	–	–	–	–
PID	0.8823	0.0000	0.1154	–	–	–	–	1.2419	1.0861	0.1967	–	–	–	–
<i>PDF-(1 + PI)</i>														
PDF	2.0000	–	0.2135	–	–	–	0.2135	0.0311	–	0.5343	–	–	–	100
(1 + PI)	0.0000	2.0000	–	–	–	–	–	0.0000	2.0000	–	–	–	–	–

Table 3. WAA optimized controller gains under 1% SLP in area 1.

WAA based:	ξ	ST (0.0002 band) (s)			Undershoot(-ve)		
	ITAE	ΔF_1	ΔF_2	ΔP	$\frac{\Delta F_1}{\times 10^{-3}}$	$\frac{\Delta F_2}{\times 10^{-3}}$	$\frac{\Delta P}{\times 10^{-4}}$
(1 + FOPI)-FOPI-TID	0.01381	1.707	1.735	1.355	13.0	1.621	14.15
PIFOD-(1 + PI)	0.02526	3.264	3.393	1.723	13.0	2.316	16.22
PD-PI	0.02644	3.494	2.582	2.617	13.0	1.871	15.62
PIDF(1 + FOD)	0.03170	4.460	3.890	2.865	13.0	2.416	16.33
(1 + PI)-PI-PID	0.03390	4.157	4.915	4.177	13.0	1.675	15.34
PDF-(1 + PI)	0.03493	4.661	2.610	2.858	13.0	2.388	16.17
% Reduction	45.3%	47.7%	32.8%	21.4%	—	3.2%	7.8%

Table 4. Comparison performance of several controllers for case 2. Significant values are in [bold].

a test model as in Fig. 1. Each optimizer is configured with 100 iterations. The convergence graph of WAA, extracted from MSTa with GDB, GRC, BD, and CTD nonlinearities is depicted in Fig. 8, showcasing WAA's swift convergence and effectiveness in enhancing AGC control strategies to optimize system performance. Furthermore, a comparison of the minimum, maximum, average, and standard deviation of the ITAE values, ξ_{ITAE} , in Table 2 illustrates that WAA outperforms MA and GWO in addressing AGC challenges.

Case 2: Analyses of controller's performance

This study conducted a comprehensive performance comparison between the proposed (1 + FOPI)-FOPI-TID controller and various two-stage and three-stage control approaches, including PIDF(1 + FOD), PIFOD-(1 + PI), (1 + PI)-PI-PID CC, PDF-(1 + PI), and PD-PI CC under WAA scheme. The gains of these controllers are listed in Table 3. The evaluation metrics focused on the ITAE value, minimum undershoot (Ush), and settling time (T_s), considering changes in ΔF_1 , ΔP_{tie} , and ΔF_2 . Overall, Table 4 compares the performance of each optimization

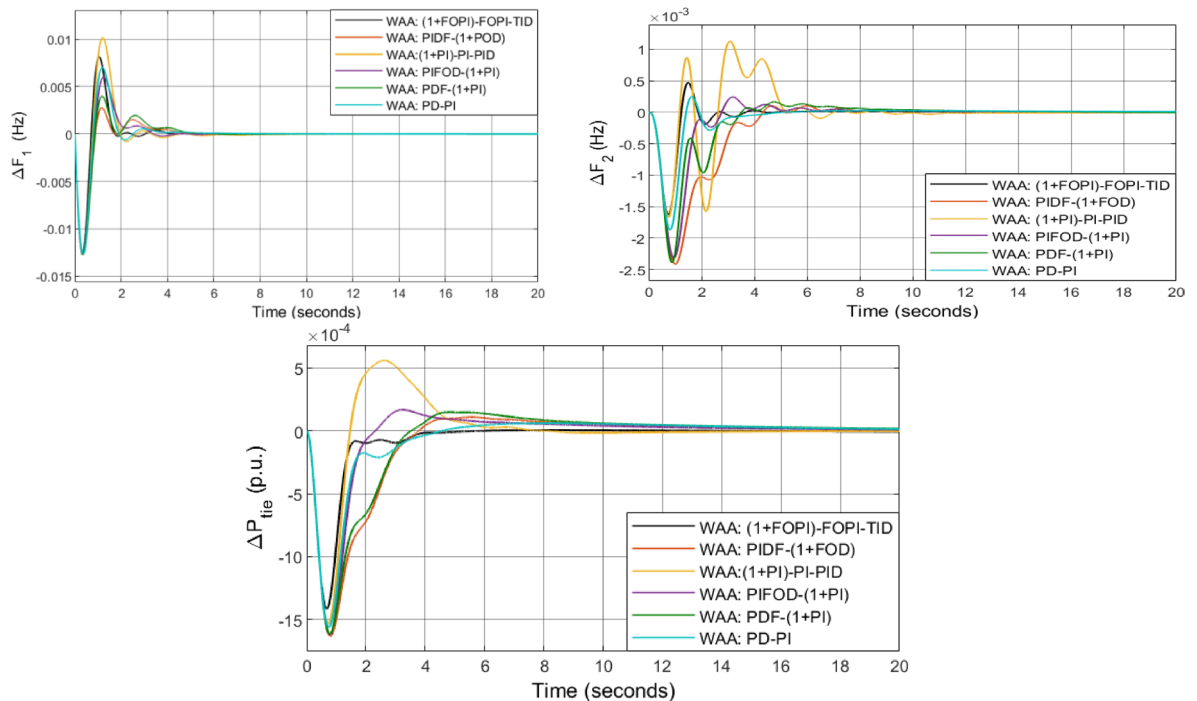


Fig. 9. Transient response with various controllers but same optimizer at case 2.

procedure using transient metrics. Figure 9 illustrates the dynamic responses of a two-area interconnected power system subjected to a load disturbance, presenting the frequency deviations in Area-1 (ΔF_1), Area-2 (ΔF_2), and the tie-line power deviation (ΔP_{tie}) for various WAA-based cascade controller structures. A comparative evaluation is carried out between the proposed WAA-(1+FOPI)-FOPI-TID controller and other existing controllers, including PIDF-(1+FOD), (1+PI)-PI-PID, PIFOD-(1+PI), PDF-(1+PI), and PD-PI.

As demonstrated in Fig. 9 and summarized in Table 4, the proposed (1+FOPI)-FOPI-TID control scheme outperformed all comparative techniques. Table 4 presents a comparative performance evaluation of several WAA-based cascade controllers for Case 2 using key dynamic performance indices, including ITAE, settling time (within a ± 0.0002 band), and maximum undershoot of frequency and tie-line power deviations.

Notably, it achieved an ITAE value of 0.01381—representing a 45.3% improvement over the PIFOD-(1+PI) controller. The scheme also showed significant enhancements in settling times: 47.7% improvement for ΔF_1 , 21.4% for ΔP_{tie} , both compared to PIFOD-(1+PI) CC, and 32.8% improvement for ΔF_2 (compared to PD-PI CC). While no improvement was observed in the percentage undershoot for ΔF_1 , the proposed controller achieved reductions of 3.2% for ΔF_2 and 7.8% for ΔP_{tie} when compared to the (1+PI)-PI-PID CC.

As a result, the proposed (1+FOPI)-FOPI-TID CC appears to be a potential solution for improving LFM performance in various PSIs. The transient responses of the proposed WAA: (1+FOPI)-FOPI-TID CC and other controllers were further examined under 4% SLC in area 1, as shown in Fig. 10. The WAA: (1+FOPI)-FOPI-TID CC outperformed all competing controllers under 4% SLC in area 1, confirming its superiority and demonstrating MSTA stability with nonlinearities.

Case 3: Performance analyses under random load perturbation

The dynamic analysis of the proposed WAA: (1+FOPI)-FOPI-TID CC was conducted using a random step load (RSL) 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 as depicted in Fig. 11. Figure 12 depicts the transient responses of a two-area interconnected power system under successive load disturbances, illustrating the frequency deviations in Area-1 (ΔF_1), Area-2 (ΔF_2), and the tie-line power deviation (ΔP_{tie}) for different WAA-based cascade controller schemes. The highlighted zoomed-in regions emphasize the initial disturbance intervals, allowing a clear comparison of dynamic performance.

It is apparent from Fig. 12 that, when compared to other controllers in the existing literature, the WAA: (1+FOPI)-FOPI-TID CC demonstrates consistent dynamic performance under randomized loading patterns in area 1. It shows reduced undershoot and overshoot, along with faster convergence, highlighting its robustness and effectiveness in handling dynamic variations Fig. 13.

Case 4: sensitivity analysis/robustness

A sensitivity analysis was conducted to evaluate the robustness of the WAA optimized (1+FOPI)-FOPI-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_g , B , R , and T_{12} are varied by approximately $\pm 25\%$, as outlined in Table 5 under $\Delta P_{L1} = 1\%$ SLP at area 1. Table 5 and Fig. 14 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 approach under modifications of system parameters was found to be

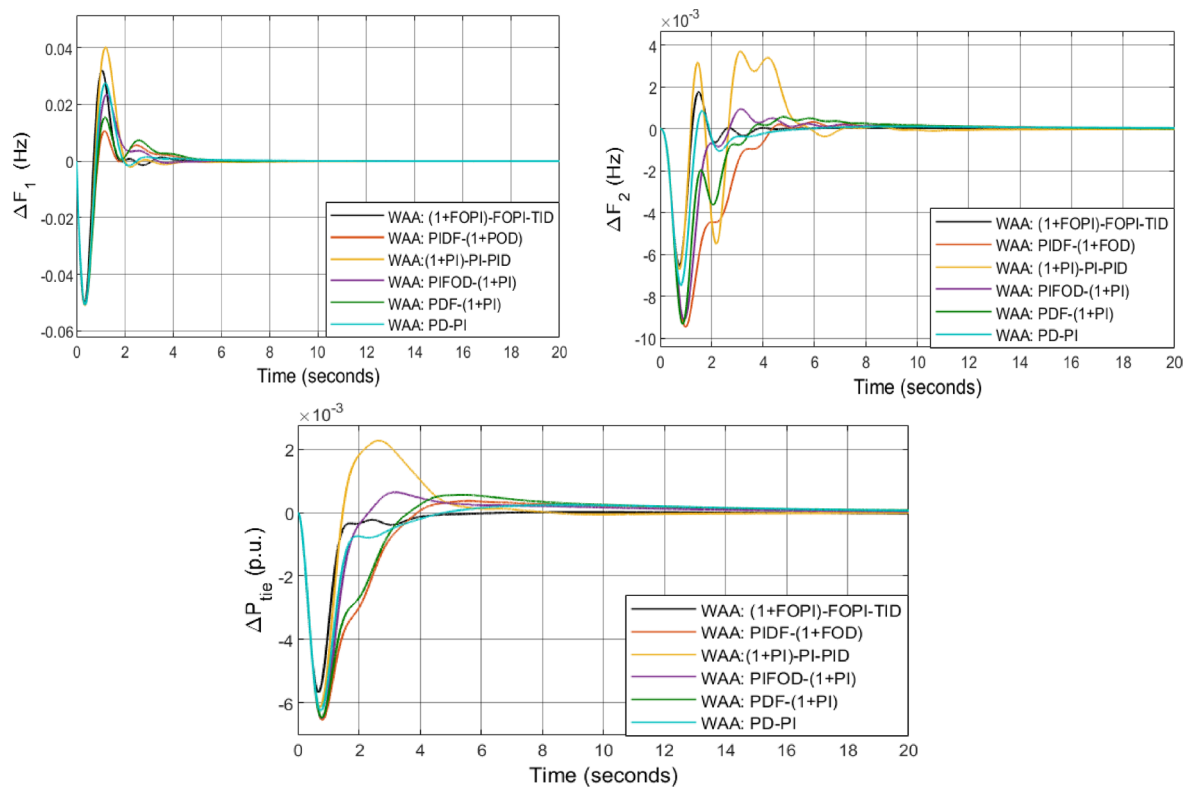


Fig. 10. Transient reactions for case 2 with 4% SLC at area 1: (a) ΔF_1 , (b) ΔF_2 , and (c) ΔP_{tie} .

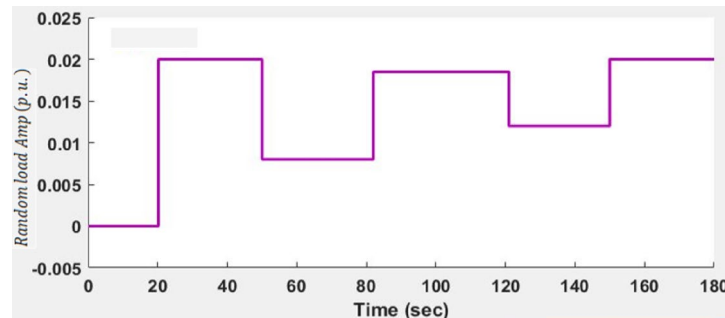


Fig. 11. Random step loads ΔP_{L1} in area 1.

negligible. The analysis reveals that even with significant variations of up to 25% in parameters, the proposed scheme 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.

Case 5: Resonance Cyber Attack (ResA)

In this case, the ResA is simulated by introducing load disturbances at arbitrary frequency values, without any prior knowledge of the system's operational state. Figure 14, illustrates a cyber-attack injection signal applied to the power system model, represented as a bounded high-frequency square-wave disturbance varying between ± 0.1 p.u. over the simulation duration. This signal is used to emulate false data injection or malicious control signal manipulation, periodically perturbing system measurements or control inputs to evaluate the robustness of the load frequency control scheme under cyber-physical threats.

The cyber-attack signal is synthetically generated within the simulation environment using a periodic switching (square-wave) function with fixed amplitude and duty cycle.

The dynamic response of the system to this attack is analyzed using various control strategies, with corresponding results illustrated in Fig. 15. Among the compared controllers, the WAA: (1 + FOPI)-FOPI-TID configuration demonstrates the most robust performance, exhibiting the lowest RoCoF amplitude in area 1 (0.0654) and maintaining a relatively moderate amplitude in area 2 (1.3276) summarized in Table 6. This indicates superior disturbance rejection and frequency stability under cyber-attack conditions.

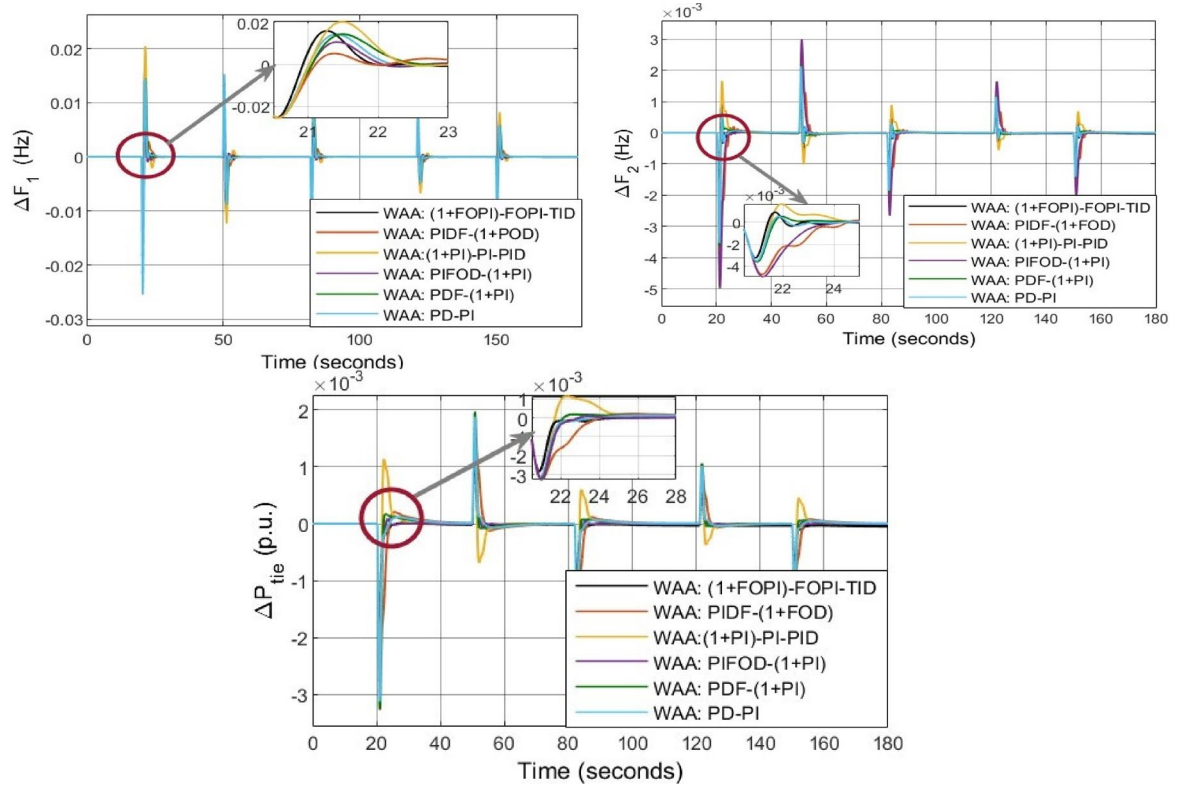


Fig. 12. Transient response with various algorithm techniques.

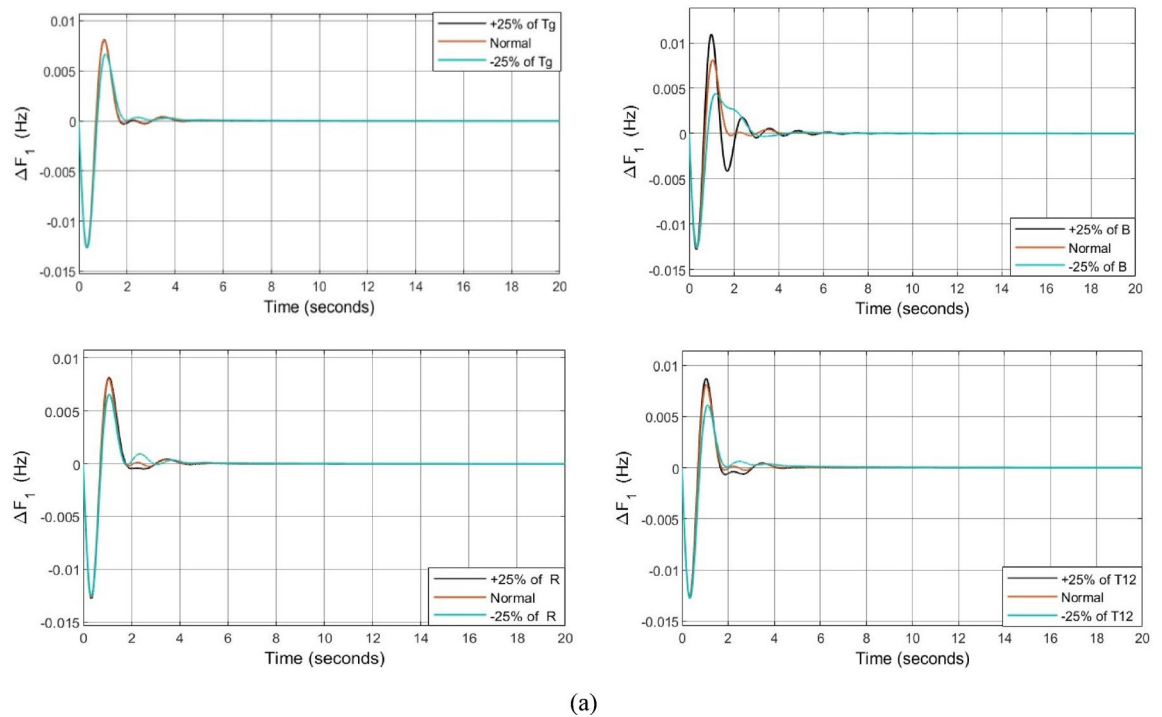


Fig. 13. (a): Variation of T_g , B , R , and T_{12} PS parameters for ΔF_1 . (b): Variation of T_g , B , R , and T_{12} PS parameters for ΔF_2 . (c): Variation of T_g , B , R , and T_{12} PS parameters for ΔP .

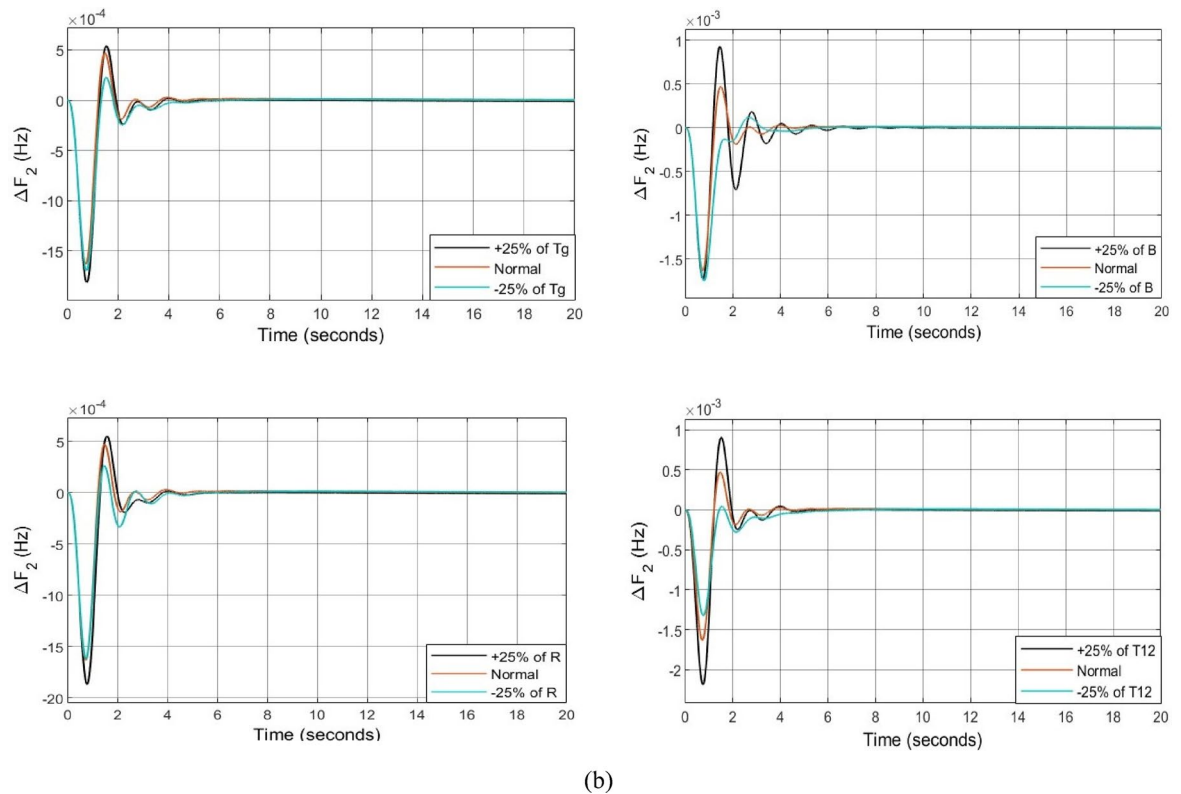


Fig. 13. (continued)

The WAA: PDF-(1 + PI) controller ranks second, with a slightly higher RoCoF amplitude in area 1 (0.0880) and a comparable value in area 2 (1.7652), suggesting effective damping characteristics. In contrast, the (1 + PI)-PI-PID controller performs the poorest, recording the highest RoCoF amplitude in area 2 (1.7025), alongside a relatively elevated value in area 1 (0.1158). Similarly, the WAA: PIFOD-(1 + PI) controller shows inadequate performance in area 2 with an amplitude of 1.5391, further emphasizing its reduced resilience to cyber-attacks.

The RoCoF profiles, presented in Fig. 1, align with these observations, while most controllers effectively limit RoCoF within acceptable thresholds in area 1 and area 2 exhibits higher susceptibility to instability.

Conclusion

This study presents a novel (1 + FOPI)-FOPI-TID cascade control strategy, optimized using a WAA, for the frequency regulation of heterogeneous two-area PSIs incorporating reheat thermal, gas, hydro, and nuclear generation units. The system model integrates critical nonlinearities, including GRC, BD, GDB, and CTD, as well as cyber-attack scenarios to evaluate real-world robustness. Extensive dynamic simulations, including random step load perturbations, are conducted to assess the effectiveness of the proposed control scheme. Comparative evaluations with contemporary control configurations, such as WAA: PIFOD-(1 + PI) and WAA: PD-PI CCs, demonstrate the superior dynamic performance of the proposed method. Specifically, the (1 + FOPI)-FOPI-TID controller achieved a 45.3% improvement in ITAE and reduced frequency settling times by 47.7% (ΔF_1) and 32.8% (ΔF_2) in the first and second areas, respectively, under test case 2. Moreover, sensitivity analysis confirms the robustness of the proposed controller, maintaining consistent performance despite substantial parameter variations. Under cyber-attack scenarios, the controller exhibited minimal RoCoF amplitudes in both areas, further underscoring its resilience Fig. 16.

In summary, while the fractional-order cascade structure is more complex than classical controllers, its fixed-parameter implementation post-tuning is feasible for real-time application, and the design-time optimization cost is justified by the achieved performance and robustness benefits. This research contributes significantly to the advancement of load frequency control strategies through the development of robust, WAA-based CC architecture. The WAA: (1 + FOPI)-FOPI-TID approach not only enhances system stability and dynamic responsiveness but also ensures operational resilience under nonlinearities and cybersecurity threats.

Future work will focus on implementing the controller on real-time hardware (like OPAL-RT) to empirically validate its computational performance, alongside the integration of fault-detection mechanisms capable of rapidly identifying and diagnosing malicious intrusions before they can destabilize the power system.

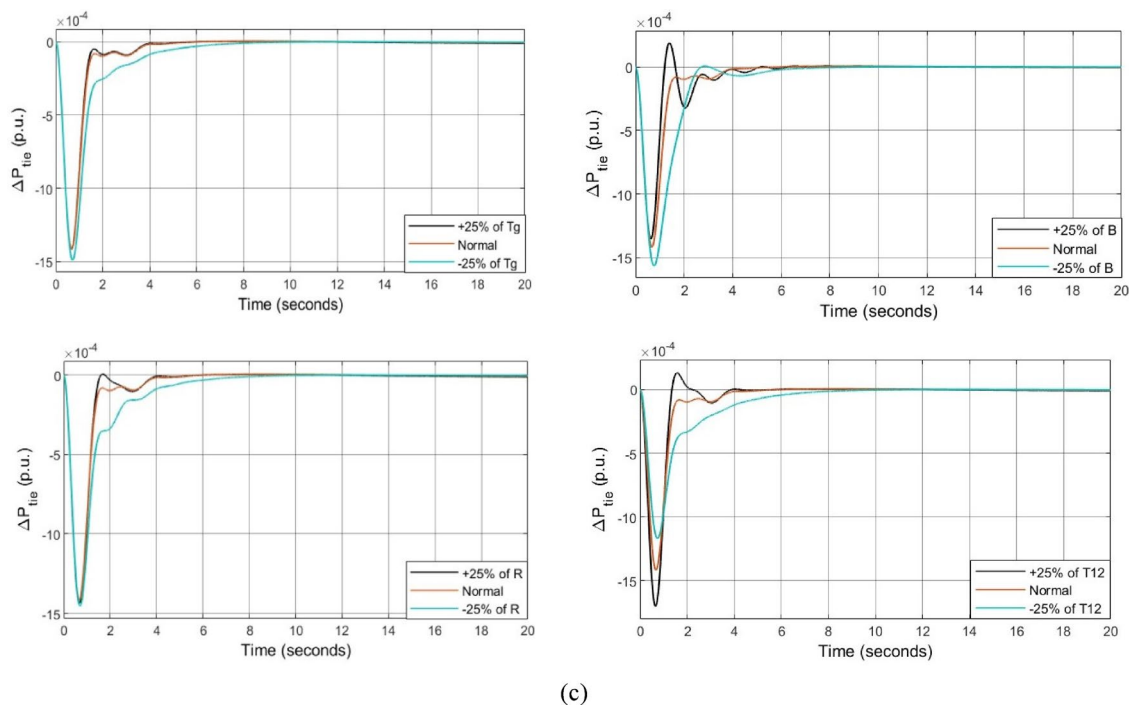


Fig. 13. (continued)

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_g	+ 25	0.01481	1.924	2.312	1.355	13.0	1.804	14.09
	Nominal	0.01381	1.693	1.752	1.355	13.0	1.625	14.13
	- 25	0.01691	2.169	2.333	2.376	13.0	1.687	14.87
B	+ 25	0.02249	3.883	2.432	2.333	13.0	1.713	13.49
	Nominal	0.01381	1.693	1.752	1.355	13.0	1.625	14.13
	- 25	0.02027	3.595	1.479	2.163	13.0	1.744	15.60
R	+ 25	0.01661	2.831	1.908	1.312	13.0	1.860	14.31
	Nominal	0.01381	1.693	1.752	1.355	13.0	1.625	14.13
	- 25	0.01736	2.788	2.333	2.461	13.0	1.612	14.50
T_{12}	+ 25	0.01652	3.782	2.354	1.227	13.0	2.178	16.98
	Nominal	0.01381	1.693	1.752	1.355	13.0	1.625	14.13
	- 25	0.01962	3.970	2.454	3.014	13.0	1.320	11.70

Table 5. Percentage variations in hybrid PS parameters.

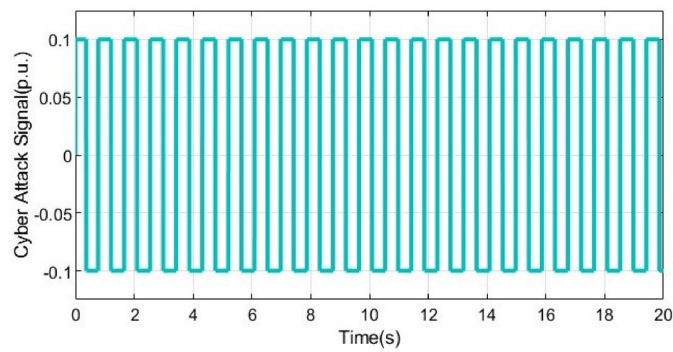


Fig. 14. Cyber-attack signal model applied to the PS.

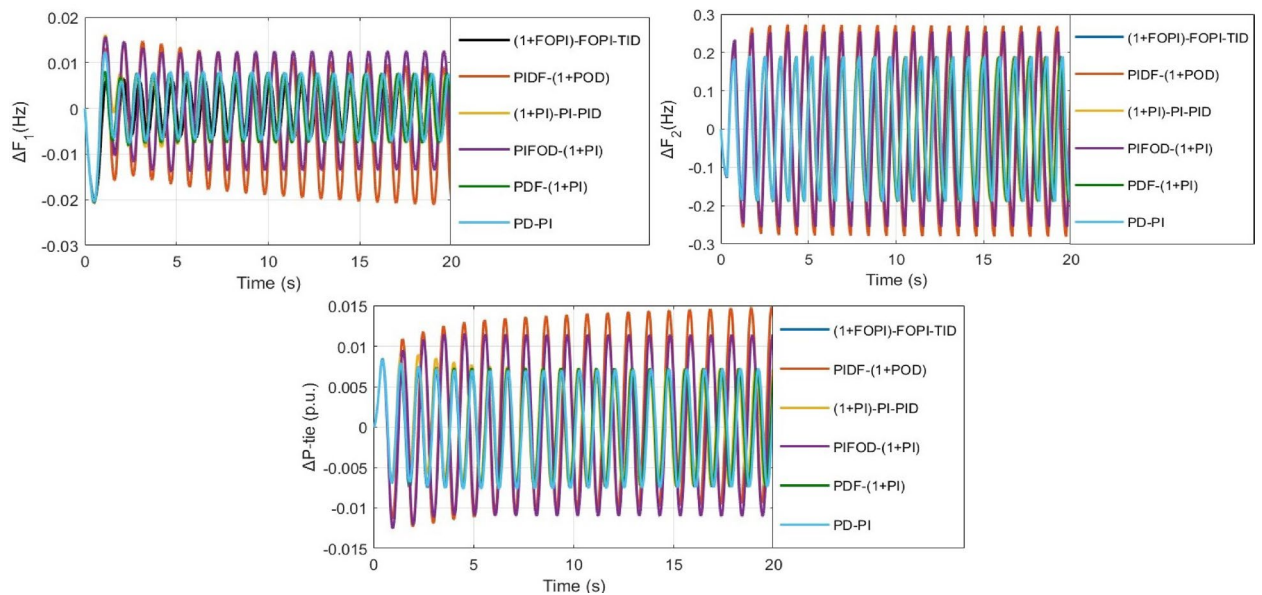


Fig. 15. Controller performances under the cyber-attack: ΔF_1 , ΔF_2 , and ΔP_{tie} .

Controller	Max. Amplitude (Area 1)	Max. Amplitude (Area 2)
WAA: (1 + FOPI)-FOPI-TID	0.0654	1.3276
WAA: PD-PI	0.0967	1.3835
WAA: (1 + PI)-PI-PID	0.1158	1.7025
WAA: PIFOD-(1 + PI)	0.0930	1.5391
WAA: PDF-(1 + PI)	0.0880	1.7652
PIDF(1 + FOD)	0.0959	1.5442

Table 6. RoCoF (Hz/s) for different controllers. Significant values are in [bold].

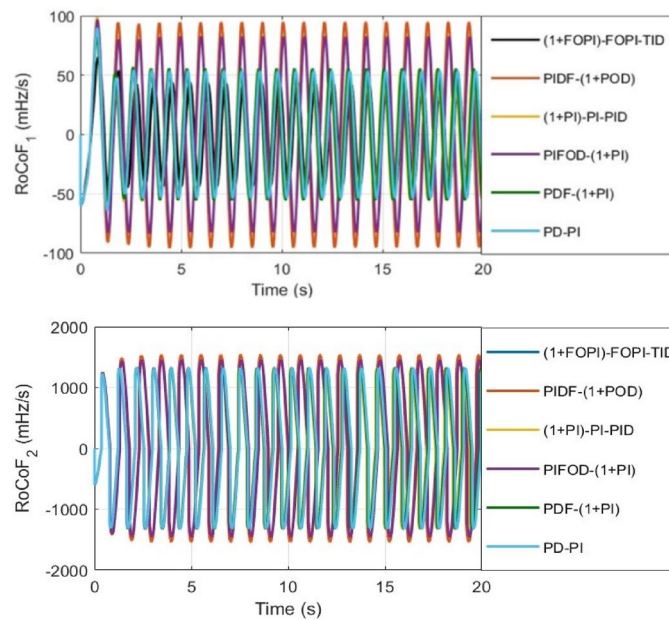


Fig. 16. RoCoF results of PS areas for cyber-attack for Area-1 and Area-2.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Appendix

Multi-unit multi area PS parameters^{1,56,57}

$B_1 = B_2 = 0.4312 \text{ p.u.} \frac{\text{MW}}{\text{Hz}}$; $R_1 = R_2 = R_3 = 2.4 \text{ p.u.} \frac{\text{MW}}{\text{Hz}}$; $T_{sg1} = T_{sg2} = 0.08 \text{ s}$;
 $T_{l1} = T_{l2} = 0.3 \text{ s}$; $K_{r1} = K_{r2} = 0.3$; $T_{r1} = T_{r2} = 10 \text{ s}$; $K_{PS1} = K_{PS2} = 68.9566 \text{ Hz/p.u.}$;
 $T_{12} = 0.0433 \text{ p.u.}$; $a_{12} = -1$; $T_{w1} = T_{w2} = 1 \text{ s}$; $T_{RS1} = T_{RS2} = 5 \text{ s}$; $T_{RH1} = T_{RH2} = 78.75 \text{ s}$;
 $T_{GH1} = T_{GH2} = 0.2 \text{ s}$; $X_C = 0.6 \text{ s}$; $Y_C = 1 \text{ s}$; $c_g = 1 \text{ s}$; $b_g = 0.05 \text{ s}$; $T_{F1} = T_{F2} = 0.23 \text{ s}$;
 $K_T = 0.543478$; $K_H = 0.326084$; $K_G = 0.130438$; $K_{DC} = 1$; $T_{DC} = 0.2 \text{ s}$; $T_{CR1} = T_{CR2} = 0.01 \text{ s}$;
 $T_{CD1} = T_{CD2} = 0.2 \text{ s}$; $T_{PS1} = T_{PS2} = 11.49 \text{ s}$. **MSTA gains:**
 $K_T = 0.543478$, $K_H = 0.326084$, and $K_G = 0.130438$.

Nuclear power plant gains:

$T_N = 0.05$, $K_{RN} = 0.2$, $T_{N2} = 0.25$, $T_{RHN} = 10 \text{ s}$, $T_{RHN2} = 10 \text{ s}$, $T_{RHN3} = 0.25$, $T_{N3} = 0.05 \text{ s}$, and $K_N = 0.25$

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Author contributions

Author contribution: M.A. developed the idea and manuscript, M.B. and J.N.W. supported with the technical work; M.R.A. and J.O. read through the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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