Disturbance observer aided optimised fractional-order three-degree-of-freedom tilt-integral-derivative controller for load frequency control of power systems

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Abstract
This work demonstrates a maiden application of a fractional-order based three-degree-of-freedom tilt-integral-derivative controller for escalating the load frequency control performance of power system having wind power generator integrated. The disturbance observer is housed with the proposed fractional-order-three-degree-of-freedom-tilt-integral-derivative controller to efficiently estimate the wind velocity's uncertain profile and subsequently enrich the control law. The mastery of the proposed control algorithm has been tested on multi-area interconnected power systems by performing an extensive comparative study with other prevalent techniques reported in the state-of-art. Harris’ Hawks optimisation is applied to explore the proposed controllers’ optimum gains, exercising an integral error-based criterion. Time response measurements of the studied test systems in the wake of load fluctuation and intermittent output of wind power generator explicitly establish the efficacy of the proposed Harris’ Hawks optimisation tuned disturbance observer-based fractional-order-three-degree-of-freedom-tilt-integral-derivative controller over its other counterparts concerning damping of system oscillations. Furthermore, the developed control system’s robust stability is affirmed using Kharitonov’s stability theorem, considering ±25% variation in system parameters.

1 INTRODUCTION

The study of power system operation and control with high penetration of renewable energy resources (RERs) is becoming complicated and most remarkable for delivering uninterrupted power to consumers. The modern power system network comprising several control areas and specific areas can be represented as a coherent group of generations [1]. Any abrupt change in the loading condition of any control area and/or transients of RERs causes deviation of frequency and interchange tie-line power from their nominal limits. Thus, to ensure the power system’s successful operation, balancing between load-generation and scheduled and actual tie-line power (predominating factor of keeping constant system frequency) is exigent. Load frequency control (LFC) analysis of the power system entails a dynamic and competent approach for delivering good quality of power to end users against the unpredictable load variation and/or RERs transient. LFC’s objective is to ensure that the change of frequency and tie-line interchange power subjected to load variation and/or RERs transient must be within their theoretical limits [2]. The key features of LFC are discussed in ref. [3].

Researchers are endeavouring various control techniques to study the LFC problem of the power system. A brief review of different control methods adopted for LFC is reported in ref. [4]. The most common approach used in the LFC study of power systems is the proportional-integral-derivative (PID) controller or its different variants [5–9]. A PI controller with various energy storage systems is used in ref. [10] for the LFC of power systems in a deregulated environment. Low-inertia of inverter-based power generation systems causes undesirable influence on the system frequency and threatens the system’s dynamic security. A virtual-inertia control based optimal PI controller is presented in ref. [11] to enhance the frequency...
regulation of micro grid with high penetration of RERs. Magdy et al. [12] demonstrated coordinated LFC and superconducting magnetic energy storage technology using an optimal PID controller for power systems frequency regulation. However, the performance of classical controllers may deteriorate with system non-linearities and parametric uncertainties. A comprehensive LFC study of interconnected power systems having diverse power generation resources using an optimal feedback controller is presented in ref. [13]. The state feedback controller’s implementation requires measurement of all system states, which is practically tricky for higher-order power systems due to the sensors’ cost and/or unavailability.

The intelligent controllers based on fuzzy logic and artificial neural network (ANN) are also used as supplementary controllers to study the power system dynamics [14–17]. Though the fuzzy logic-based controllers refine the system outputs compared to conventional controllers, their operation is sensitive to selecting rule base, choice of membership functions, scaling factor and defuzzification method. These parameters are chosen either by trial-and-error way or based on the designers’ experience [14]. The implementation of ANN-based controllers requires an extensive training data set and suffering from substantial computation time. Khooban et al. implemented an adaptive LFC for a micro grid [18]. The design of adaptive controllers relies strictly on the mathematical model of the test system. It is challenging to realise the detailed mathematical model of large-order systems considering parametric uncertainty, non-linearities, temperature variation and system disturbances. Apart from these, the effectiveness of the sliding mode controller [19,20], H∞ based controller [21] etc. have been reported in the literature.

Recently, the integration of fractional-order (FO) calculus into traditional controller appreciable improves the conventional controllers’ tracking and disturbance rejection ability. Because of having better dynamic performance in uncertain situations, FO-based controllers (FOC) have been predominantly observed in the LFC study of power systems [22–25]. In ref. [26], an attempt has been made to study the FO-based integral-double-derivative controller’s performance for simultaneously regulating the area frequency and generator terminal voltage. The LFC of power systems by employing a fuzzy aided FOC is reported in refs. [27,28] and shows the mastery over its other counterparts in minimising the frequency and tie-line power deviation.

The tilt-integral-derivative (TID) controller has a similar structure to the PID controller with non-integer power in proportional gain [29]. The efficacy of the TID controller over conventional controllers in terms of more precise tuning, better disturbance rejection ability, robustness, and minimises the impacts of parameter uncertainties on the system performance has been shown in ref. [29]. Differential evolution (DE) tuned TID controller with derivative filter (TIDF) is applied to a multi-area power system with governor dead-band (GDB) and generation rate constraint (GRC) [30]. The integral-tilt-derivative controller to study interconnected power systems’ dynamics considering non-linearities is discussed in ref. [31]. The advantage of cascaded TID and conventional controllers is outlined in ref. [3] for interconnected power systems. However, these studies do not quantify the mastery of a TID controller considering RERs. Another possible way of improving the damping of system oscillations is by increasing the degree-of-freedom (DOF). In ref. [32], a 2DOF-PID controller is used as a secondary controller to suppress the system oscillations. LFC of power systems using FO based 2DOF-PID controller is reported in ref. [33]. Three-degree-of-freedom (3DOF) controller has been successfully implemented in refs. [34,35] to regulate the frequency of interconnected power systems.

Owing to an increase in system complexity, system reconfiguration, high penetration of RERs, and ever-rising load demand, the design and implementation of novel intelligent control algorithms to study the power system dynamics is always imperative. The literature review unfolds the individual application of FO based controllers [22–25], two/three DOF controllers [32–35], TID controller [30,31] for the LFC of power systems. However, no attempt has been made to design a controller combining the merits of FO calculus, 3DOF and TID controller, for LFC analysis. Thus inspiring from the effectiveness of the controllers mentioned above, a FO based 3DOF-TID controller is designed for LFC of higher-order power systems considering RERs.

Disturbances are extensively present in physical systems and bring adverse effects on its performance. The disturbance observer (DO) quickly estimates the disturbance, and feedforward disturbance cancellation is achieved. In DO based robust control, internal and external disturbances are estimated by using identified dynamics and measurable states of plants, and the robustness of systems is achieved by feed backiing these estimations. An overview of DO based control strategies is given in ref. [36]. The advantages of DO based control techniques in the LFC are shown in refs. [37,38].

It is remarked from surveying the literature that the LFC performance confides on the applied optimisation technique for exploring near-optimum gains of the controller parameters. A growing interest and awareness in the thriving, inexpensive, efficient applications of optimisation techniques, such as, flower pollination algorithm (FPA) [8], biogeography based optimisation [35], grey wolf optimisation (GWO) [39], whale optimisation [40], salp swarm optimisation (SSA) [3], dragonfly algorithm [33], sine-cosine algorithm [41,42] etc. have been recently noticed in the LFC literature. These techniques substantially improve the system performance leaving some shortcomings like high computation time, slow convergence rate, dependence on inputs control parameters etc. Moreover, improving the balance between exploration and exploitation, and escaping the solutions from local optima with considerable computation time, a continuous effort to explore new powerful optimisers has been noticed in the literature. Moreover, the no-free-lunch (NFL) theory states an algorithm, theoretically, cannot be considered a general-purpose universally-best optimiser. The NFL-theory encourages us to explore and apply a more efficient optimiser for addressing the LFC problem. Harris’ Hawks optimisation (HHO) simulates Harris’s cooperative
behaviour and chasing style [43]. HHO optimiser’s effectiveness is shown by comparative analysis with some well-known optimisation techniques [43]. Thus inspiring from the tuning deftness of HHO, this work may endeavour to explore the viability of utilising HHO in designing the suggested DO-based FO-3DOF-TID controller, for the first time, to address the LFC problem. The notable contributions in work are summarised below.

(i) To design an HHO optimised FO-3DOF-TID controller for LFC of interconnected power systems having wind power generator (WPG) integrated.

(ii) A DO is designed to estimate uncertain wind velocity and, consequently, implement in FO-3DOF-TID control action.

(iii) To carry out the investigation in a realistic scenario, the WPG model is developed considering wind aerodynamic, mechanical coupling shaft, and doubly-fed induction generator (DFIG).

(iv) A comparative study has been performed with some of the prevalent control techniques reported in the literature to highlight the mastery of the suggested controller in the damping system oscillations.

(v) A comparative analysis has been performed to appraise the tuning proficiency of HHO in searching near-optimal settings over GWO, SSA, grasshopper optimisation algorithm (GOA), DE and firefly algorithm (FA).

(vi) To outline the impacts of integrating inherent nonlinearities on the dynamic performance against step load fluctuations and intermittent WPG output.

(vii) To validate the robustness of the developed control system considering ±25% variation in system parameter by employing Kharitonov’s stability method.

The rest of the paper is arranged as follows. The mathematical model of test systems is given in Section 2, following the FO-3DOF-TID controller modelling. Section 3 provides a brief discussion of HHO. Simulation results and comparative analysis are deployed in Section 4. Finally, Section 5 gives the conclusion following future scopes of the work.

2 | MODEL AND METHODOLOGY

2.1 | System investigated

The undertaken model considered for assessment embraces two/three/four/five area interconnected power systems having DFIG driven WPG integrated. The block diagram of the three-area reheat thermal power plant is shown in Figure 1(a). Each control area owns the speed governor with dead-band, steam turbine including GRC and power system. The linear approximated WPG model has wind aerodynamic, the two-mass model of mechanical coupling shaft and DFIG, as illustrated in Figure 1(b). The power rating of control areas is 2000, 4000 and 8000 MW, and the same of WPG is 3.6 MW. The nominal values of the relevant system parameters are provided in the Appendix [28,39,44].

2.2 | Wind aerodynamic model

The aerodynamic model provides the coupling between rotational speed $\omega_r$ and mechanical torque $T_m$ generated by the wind turbine, as depicted in Figure 2. The output power of WPG fluctuates according to the time-varying wind speed and environmental situations. The mechanical power $P_m$ derived from the WPG is proportional to the cube of incoming wind speed $V_w$, as given in Equation (1). The wind turbine extracts specific wind energy from the wind, expressed by the rotor power coefficient, as defined in Equation (2) [45].

$$P_m = 0.5\rho_{air}A_{blade}C_pV_w^3; \quad T_m = (P_m/\omega_r).$$  \hspace{1cm} (1)

$$C_p(\lambda, \beta) = \alpha_1 \left( \frac{\alpha_2}{\lambda_1} - \alpha_3 \beta - \alpha_4 \right) + \alpha_5 \frac{\alpha_6}{\lambda_1} + \alpha_6 \lambda$$

where, $\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}, \quad \frac{\alpha_5}{\lambda_1} = \frac{\alpha_6 R}{V_w}$.

where $\rho_{air}$ indicates the density of air in Kgm$^{-3}$; $A_{blade}(= \pi d^2/4)$ is blade swept area in m$^2$; $d$ is the diameter of the blade in m. The wake effect is the aggregated effect, the number of wind turbines (WT) in a wind farm. The first WT disrupts on the second, then the first two on third, and so on. The wind aerodynamic model is developed, considering the Jensen wake model [46]. The wake speed ($V_{wake}$) for multiple WT can be determined using Equation (3).

$$V_{wake} = V_w \left[ 1 - \sum_{i=1}^{n} \left( 1 - \sqrt{1 - \left( \frac{F_T}{\rho \pi r^2 V_w^2} \right)^2} \right) \left( \frac{r}{r + k\Delta x} \right)^2 \right].$$  \hspace{1cm} (3)

where $F_T$ defines thrust force, $k$ is a decreasing coefficient ($k = 0.05$ for offshore WT and $k = 0.075$ for onshore WT), $\Delta x$ is the distance between two consecutive wind turbines. In this work, we consider $n = 2$ for analysis. The power output of aerodynamic model has been approximated as

$$P_m = 0.001 V_{wake}^3$$  \hspace{1cm} (4)

2.3 | Mechanical coupling shaft

The mechanical torque (output of the aerodynamic model) is transferred to the rotor of the DFIG through a mechanical
coupling shaft. A two-mass model is considered to represent the mechanical shaft. The low-speed WT is coupled to a high-speed generator through a gear-box. The flexible shaft connecting the low-speed turbine and high-speed generator can be expressed using spring and damper [47]. Equation (5) provides the differential equation model of the mechanical shaft.

\[
\begin{align*}
\dot{\omega}_r &= -\left(\frac{B_r}{J_r}\right)\omega_r + \left(\frac{B_{sh}}{J_r}\right)\omega_g - \left(\frac{1}{J_r}\right)T_{sr} + \left(\frac{1}{J_r}\right)T_m \\
\dot{\omega}_g &= \left(\frac{B_{sh}}{2J_g}\right)\omega_r - \left(\frac{B_g+B_{sh}}{J_g}\right)\omega_g + \left(\frac{1}{N_{g}/J_g}\right)T_{sr} - \left(\frac{1}{J_g}\right)T_g \\
\dot{T}_{sr} &= K_{sh}\omega_r - \left(\frac{K_{sh}}{N_g}\right)\omega_g
\end{align*}
\]  

(5)

where \(T_g\) is air-gap torque of induction generator; \(J_r\) and \(J_g\) are the inertia parameters of WT and generator, respectively; \(B_r\) and \(B_g\) are the damping coefficients of rotor of WT and generator, in order; \(B_{sh}\) is the damping coefficient of coupling shaft; \(T_{sr}\) indicates the internal torque of the model; \(N_{g}\) is the gear train ratio.
2.4 | Dynamic modelling of doubly-fed induction generator

The performance of interconnected power systems has been assessed by integrating DFIG driven WPG, as shown in Figure 1(b). The linear approximated model of the DFIG, as used in ref. [44], is considered for the present study. In Figure 1(b), \(T_c\) and \(T_w\) are the time constants of frequency sensor and washout filter, respectively; \(K_g\) is regulation droop constant; \(H_g\) is inertia constant of induction generator; \(T_e\) is time constant of WT; \(K_p,WT\) and \(K_i,WT\) are the gains of speed controller of WT, respectively; \(\Delta \omega_{ref}\) is the incremental change in generator speed subjected to wind velocity. The variation in output power \(P_w\) subjected to \(\Delta \omega_{ref}\) measuring frequency deviation of an area \((\Delta f)\) can be calculated from Equation (6).

\[
P_w = -\left( \frac{G_m(i) G_{WT}(i)}{1 + G_m(i) G_{WT}(i)} \right)
\]

where \(G_m(i) = (T_e/[R_g (1 + s T_w)(1 + s T_e)])\).

\[
\Delta \dot{f} = -\left( \frac{G_g(i) G_{WT}(i)}{1 + G_g(i) G_{WT}(i)} \right) \Delta \omega_{ref}
\]

The gains of speed controller \((K_p,WT, K_i,WT)\) of WPG are optimally computed using HHO. The optimised gains are provided in Appendix.

2.5 | Fractional-order-based three-degree-of-freedom-tilt-integral-derivative controller

In this work, an FO-3DOF-TID controller has been maid-enly designed and applied on three/four/five area interconnected power systems to study their dynamic performance in the wake of sudden load fluctuation and uncertain WPG output. The availability of extra three tuning non-integer parameters, such as tilt parameter \(n\), fractional power of integrator \(\beta\), and differentiator \(\lambda\) along with other normal parameters of the 3DOF-PID controller, substantially promotes authors to study its control mastery in LFC of power systems. The main objective of deploying the suggested controller, as a supplementary controller, in the LFC loop is to improve the disturbance rejection ability, enhance set-point tracking, and shape the closed-loop control system’s dynamic performance. The DOF in a control system is defined as a number closed-loop transfer function (T.F) that can be handled individually [34]. The model of FO-3DOF-TID controller is shown in Figure 3, where \(k_p, k_i, k_d\) and \(k_{ff}\) are the proportional, integral, derivative, and feedforward weights, in order; \(N\) is the gain of derivative filter; \(PW\) and \(DW\) are the proportional and derivative weights, respectively. The overall T.F of Figure 3, considering one input at a time, computed as given in Equation (7). In Equation (7), \(E(i)\), \(Y(i)\), \(D(i)\) and \(U(i)\) are error input, measurement signal, disturbance input and control input, respectively.

\[
\begin{align*}
U(i) &= k_p \frac{1}{n} PW + k_i \frac{1}{\beta} \left( \frac{\lambda^2 N}{\lambda^2 + N} \right) DW \\
Y(i) &= k_p \frac{1}{n} + k_i \frac{1}{\beta} + k_d \left( \frac{\lambda^2 N}{\lambda^2 + N} \right) \\
D(i) &= -k_d \left[ k_p \frac{1}{n} + k_i \frac{1}{\beta} + k_d \left( \frac{\lambda^2 N}{\lambda^2 + N} \right) \right]
\end{align*}
\]

![FIGURE 3 Block diagram of the proposed fractional-order-three-degree-of-freedom-tilt-integral-derivative controller](image)

The proposed LFC problem has been formulated as a regulatory control problem to optimise controller settings and minimise the area control error (ACE). Equation (8) shows the objective function chosen for parameter optimisation using HHO. The reasons for selecting the integral square error criterion are: (i) Mathematically convenient for analytical and computational purposes, (ii) penalises large error resulting fast time response with small peak overshoot and fewer oscillations and (iii) accelerate the convergence rate of the algorithm.

\[
J = \int_0^T \left[ (B \Delta f_j)^2 + (\Delta P_{ref,j})^2 \right] dt = \sum_j^J 1, 2, 3 & j \neq i
\]
Subjected to boundary constraints:

\[
\begin{align*}
    & k_{p,\text{min}} \leq k_p \leq k_{p,\text{max}}, \quad k_{d,\text{min}} \leq k_d \leq k_{d,\text{max}}; \quad \nu_{\text{min}} \leq \nu \leq \nu_{\text{max}}; \quad n_{\text{ff},\text{min}} \leq n_{\text{ff}} \leq n_{\text{ff},\text{max}}; \\
    & k_{\text{ff},\text{min}} \leq k_{\text{ff}} \leq k_{\text{ff},\text{max}}; \quad \lambda_{\text{min}} \leq \lambda \leq \lambda_{\text{max}}; \\
    & \beta_{\text{min}} \leq \beta \leq \beta_{\text{max}}, \quad \lambda_{\text{min}} \leq \lambda \leq \lambda_{\text{max}}.
\end{align*}
\]

where $B_f$ is frequency bias constant; $\Delta f_i$ is frequency error of $f^\beta_i$-control area; $\Delta P_{\text{tie},i}$ indicates tie-line power error between $i$-th and $j$-th control areas; $k_{p,\text{tid,min}}$ and $k_{p,\text{tid,max}}$ are minimum and maximum gains of PID-controller, respectively; $n_{\text{min}}$ and $n_{\text{max}}$ are minimum and maximum values of tilt parameter, respectively; $N_{\text{min}}$ and $N_{\text{max}}$ are minimum and maximum values of filter cut-off frequency, respectively; $k_{\text{ff},\text{min}}$ and $k_{\text{ff},\text{max}}$ are minimum and maximum values of feedforward gain, respectively; $\beta_{\text{min}}$ and $\beta_{\text{max}}$ are minimum and maximum values of fractional power of integrator, respectively; $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$ are minimum and maximum values of fractional power of differentiator, in order.

The PID parameters are optimally explored between $(0,2)$, tilt parameter is selected within $(2,3)$, filter gain is set between $(0,200)$, $k_{\text{ff}}, \beta$ and $\lambda$ are chosen within $(0,1)$. Owing to the random initialisation of HHO, the optimisation process runs for 20 times, and the best solutions after these 20 runs have been marked as final solutions.

### 2.6 Disturbance Observer

To enrich the controller performance and adequately estimate the uncertain wind velocity, DO is designed and implemented in the FO-3DOF-TID control action. DO takes the inverse of plant model (with a low-pass filter) to estimate the disturbances (i.e., external perturbations and/or unmatched parameters uncertainties) and directly uses this information to refine the control law. The use of DO in the closed-loop control system makes the system more robustly stable [48]. The schematic model of DO is shown in Figure 4. The dynamical model of the test system can be expressed in state-variables form as

\[
\begin{align*}
    \dot{x}(t) &= Ax(t) + Bu(t) + \xi(t) \\
    y(t) &= Cx(t)
\end{align*}
\]

where $x$ is the state of plant; $u$ is control input; $d$ is disturbance input; $A$, $B$ and $C$ are the system, input, and output matrices with proper dimension, respectively; $\xi(t) = Gd(t)$, $||\xi|| < a$, $a$ is a small positive number; $G$ is disturbance matrix.

The design of DO with an assumption that all the states are available for measurement, $\xi(t)$ is also taken as a state variable [37]. The augmented system model of Equation (9) can be expressed as

\[
\begin{bmatrix}
    \dot{x}(t) \\
    \dot{\xi}(t)
\end{bmatrix} =
\begin{bmatrix}
    A & I \\
    0 & 0
\end{bmatrix}
\begin{bmatrix}
    x(t) \\
    \xi(t)
\end{bmatrix} +
\begin{bmatrix}
    B & 0
\end{bmatrix} u +
\begin{bmatrix}
    0 \\
    \xi
\end{bmatrix}.
\]

Hence, the model of DOB can be constructed as [37]

\[
\begin{bmatrix}
    \ddot{x}(t) \\
    \ddot{\xi}(t)
\end{bmatrix} =
\begin{bmatrix}
    A - \Lambda_1 I \\
    0 - \Lambda_2 I
\end{bmatrix}
\begin{bmatrix}
    x(t) \\
    \xi(t)
\end{bmatrix} +
\begin{bmatrix}
    B \Lambda_1 \\
    B \Lambda_2
\end{bmatrix} u -
\begin{bmatrix}
    \Lambda_1 x(t) \\
    \Lambda_2 x(t)
\end{bmatrix}.
\]

where $\dot{x}$ and $\dot{\xi}$ are the estimated state and disturbance, respectively; $\Lambda_1$ and $\Lambda_2$ are the observer gain matrices to be chosen appropriately to ensure the observer error system (as defined in Equation (12) by subtracting Equation (10) from Equation (11)) is asymptotically stable, that is, eigenvalues of $[A - BL] \neq 0$. The matrices $\Lambda_1$ and $\Lambda_2$ can be chosen by using Equation (13). To ensure good estimation and faster convergence of DO, the values of $\Lambda_1$ and $\Lambda_2$ are derived by the pole-placement method [37].

\[
\begin{bmatrix}
    \ddot{x} \\
    \ddot{\xi}
\end{bmatrix} =
\begin{bmatrix}
    A - \Lambda_1 I \\
    0 - \Lambda_2 I
\end{bmatrix}
\begin{bmatrix}
    x(t) \\
    \xi(t)
\end{bmatrix} +
\begin{bmatrix}
    B \Lambda_1 \\
    B \Lambda_2
\end{bmatrix} u -
\begin{bmatrix}
    \Lambda_1 x(t) \\
    \Lambda_2 x(t)
\end{bmatrix}.
\]

To perform the study on a realistic platform, the wind velocity changes from 5.6 to 13.8 m $s^{-1}$, as illustrated in Figure 5(a) (black colour). For comparison, the estimated wind velocity profile employing DO is also portrayed in Figure 5(a). Figure 5(b) shows the wind power output, subsequently projected to test systems for assessing its dynamic performance. The result depicted in Figure 5(a) concludes that the developed DO tracks the uncertain wind velocity and offers satisfactory output.
3.1 Exploration phase

Hawks explore the prey location in the search area by using their powerful eyes. If the prey location is not detected, they occasionally wait, observe, and monitor to catch the prey (randomly perching) by following two distinct strategies [43].

The hawks may perch (considering equal chance \( q \)) towards prey based on (i) the positions of other family members and the rabbit (\( q < 0.5 \)), and (ii) random tall trees (\( q \geq 0.5 \)), which is modelled in Equation (14) [43].

\[
X_{i+1}^{t} = \begin{cases} 
X_{i}^{t} - \text{rand} \times \left[ 2 \times \text{rand} \times X^{t} \right] & q \geq 0.5 \\
X_{\text{rabbit}}^{t} - \text{rand} \times \left[ \text{rand} \times (ub - lb) \right] & q < 0.5 
\end{cases}
\]

where \( X_{i}^{t} \) and \( X_{i+1}^{t} \) are the positions of hawks at \( t \)th and \((t+1)\)th instants, in order; rand is the randomly generated number within \((0,1)\); \( \text{rand} \) is the randomly selected hawks position from the current population; \( X_{\text{rabbit}}^{t} \) is the position of rabbit at \( t \)th instant; \( ab \) and \( lb \) are the upper and lower bounds of control variables, respectively; \( X_{\text{av}}^{t} \) shows the average position of current population of hawks. In Equation (14), the part corresponding to \( q \geq 0.5 \) generates solutions based on the random location of hawks and other family members, and the part corresponding to \( q \geq 0.5 \) produces outputs based on the difference between the best-so-far and average position of hawks plus randomly-scaled components [43]. The transformation from exploration to exploitation phase in HHO can be modelled by using Equation (15). Exploration happens when \( |E| \geq 1 \) and exploitation occurs with \( |E| < 1 \) [43].

\[
E = 2E_{0} \left( 1 - \frac{t}{T} \right) \quad :E_{0} \in (-1, 1) .
\]

3.2 Exploitation phase

During exploitation, Harris’ hawks perform surprise pounce to attack the prey. However, the prey intelligently plays some escaping strategies to overcome the threatening situation [43].

3.2.1 Soft besiege

If \( r \) is the parameter for identifying the chance of successfully escaping (\( r < 0.5 \)), and not successful escaping (\( r \geq 0.5 \)) before the attack, hawks perform hard and soft besieges to gets closer to the rabbit. When \( r \geq 0.5 \) and \( |E| \geq 0.5 \), hawks softly encircle the rabbit (though rabbit tries to escape by performing random jumps) to finally catch it. Mathematically, this phase can be modelled by using Equation (16).
RESULTS AND DISCUSSION

When \(|E| \geq 0.5\) but \(r < 0.5\) (before the surprise pounce) rabbit has enough energy to escape. In ref. [43], the Levy flight concept has been introduced that basically model escaping prey and leapfrog during soft besiege. Thus, Equation (16) can be modified, considering the Levy flight concept, as

\[
Y = (X_{rabbit}^{t'} - X^{t'}) - E|X_{rabbit}^{t'} - X^{t'}| \quad Y = Y + S \times LF(dim) \quad (22)
\]

where dim is the number of control variables; \(S\) is a random vector of dimension \(1 \times \text{dim}\); and \(LF\) is the Levy flight constant computed by using Equation (18) [43].

\[
\text{LF}(x) = 0.01 \times \frac{\mu}{|\nu|^{1/\beta}} \times \left( \frac{\Gamma(1+\beta) \sin(\pi \beta/2)}{\Gamma(0.5(1+\beta)) \times \beta \times 2^{0.5\beta-1}} \right)^{1/\beta} \quad (23)
\]

where \(\mu\) and \(\nu\) takes random values between \((0,1)\). Finally, the solution is updated by using Equation (19) [43].

\[
X^{t+1} = \begin{cases} 
Y & \text{if fit}(Y) < \text{fit}(X^{t'}) \\
Z & \text{otherwise} 
\end{cases} \quad (24)
\]

3.2.2 Hard besiege

During this phase (i.e. when \(r \geq 0.5\) and \(|E| < 0.5\)), rabbit has low energy and hawks hardly encircles it. This phase can be modelled by using Equation (20).

\[
X^{t+1} = X_{rabbit}^{t'} - E|X_{rabbit}^{t'} - X^{t'}| \quad (25)
\]

when \(r < 0.5\) and \(|E| < 0.5\), hawks perform hard besiege to encircle and kill the prey. Similar to soft besiege, hawks updates their location by using Equation (21). However, in this case, hawks try to reduce the distance from their average location with escaping prey [43].

\[
X^{t+1} = \begin{cases} 
Y & \text{if fit}(Y) < \text{fit}(X^{t'}) \\
Z & \text{if fit}(Z) < \text{fit}(X^{t'}) 
\end{cases} \quad (26)
\]

The value of \(Y\) and \(Z\) is computed from Equation (22).

\[
Y = X_{rabbit}^{t'} - E|X_{rabbit}^{t'} - X^{t'}| \quad Z = Y + S \times LF(dim) \quad (27)
\]

4 RESULTS AND DISCUSSION

The time response analysis of multi-area interconnected power systems with/without WPG has been assessed to quantify the suggested FO-3DOF-TID controller’s mastery. The impacts of GRC, GD, and communication delay on the system performance have been analysed under the control action of the proposed controller. The following assumptions have been taken to carry out the simulation study:

a) The small-signal stability model (transfer function form) of interconnected power systems has been developed.

b) The rational models of GDB and communication delay are considered to show its impacts on the system outputs.

c) To develop the DO, it is approximated that all system states are available for measurement and disturbance signal is bounded, that is,

\[
d(t) = \sup_{\tau \geq 0} |d(t)| \quad (28)
\]

The model of test systems has been developed in the SIMULINK domain, while the optimisation codes of HHO are

| Optimisation techniques | \(k_p\) | \(k_i\) | \(k_d\) | \(k_{fit}\) | PW | DW | \(N\) | \(n\) | \(\beta\) | \(\lambda\) | Fitness value (\(x10^{-5}\)) |
|------------------------|--------|--------|--------|--------|-----|-----|------|------|-------|-------|-----------------|
| HHO                   | 0.4383 | 1.6472 | 0.6172 | 0.6364 | 0.3816 | 0.1869 | 5.8096 | 2.9134 | 0.1576 | 0.5972 | 1.0238         |
| Area-2                | 0.7587 | 1.1332 | 0.4157 | 0.7094 | 0.7655 | 0.4898 | 1.8056 | 2.6324 | 0.9706 | 0.8003 |               |
| Area-3                | 0.4321 | 1.0695 | 1.8492 | 0.7547 | 0.7952 | 0.4456 | 65.153 | 2.5469 | 0.4854 | 0.1419 |               |
| SSA                   | 1.3088 | 0.5845 | 1.5031 | 0.5629 | 0.5133 | 0.6336 | 160.06 | 2.3224 | 0.6023 | 0.5190 | 1.1239         |
| Area-2                | 1.0919 | 1.2899 | 0.2026 | 0.6644 | 0.8563 | 0.2615 | 3.4800 | 2.3802 | 0.8015 | 0.5682 |               |
| Area-3                | 1.4456 | 0.4453 | 0.2169 | 0.8625 | 0.9241 | 0.6977 | 36.194 | 2.9706 | 0.2215 | 0.1618 |               |
| GOA                   | 1.3026 | 1.2300 | 1.5746 | 0.9269 | 0.9776 | 0.4454 | 51.1212 | 2.4522 | 0.1355 | 0.3214 | 1.4836         |
| Area-2                | 0.6149 | 0.7202 | 1.5554 | 0.3643 | 0.2155 | 0.8114 | 1.1535 | 2.5397 | 0.1039 | 0.2495 |               |
| Area-3                | 0.5390 | 0.2086 | 1.8259 | 0.2918 | 0.1730 | 0.5744 | 71.4551 | 2.9672 | 0.4745 | 0.9818 |               |
| SSA                   | 1.5447 | 1.7470 | 1.7181 | 0.7094 | 0.5794 | 0.3396 | 90.3704 | 2.2153 | 0.1229 | 0.7169 | 1.6096         |
| Area-2                | 0.7124 | 0.2274 | 0.6028 | 0.6540 | 0.5733 | 0.1903 | 0.3096 | 2.3190 | 0.2854 | 0.2640 |               |
| SSA                   | 1.0033 | 1.2035 | 1.8802 | 0.4981 | 0.6773 | 0.8109 | 72.9430 | 2.3673 | 0.7226 | 0.5167 |               |

TABLE 1 Comparative study among different optimisation techniques (for test system-1 considering 1% step load perturbation in area-1)
separately written in .m-file. The simulations were executed on an Intel Core i3 processor 2.4 GHz, 6 GB memory. The performance of HHO, along with controllers, is assessed considering the convergence rate, the lowest minimum objective function value and minimum time response measurements. The entire study has been performed in four different phases, as stated below.

a) Initially, the competence of the adopted HHO in searching near-optimal gains of the controller is established over GWO, SSA and GOA, as the computation efficiency of these algorithms already confirm in refs. [3,24,39].
b) The performance of test systems is analysed considering constant load perturbation, without integrating WPG.
c) Performance analysis of interconnected power systems having WPG integrated against constant load and uncertain wind power output (Figure 5(b)).
d) The robust stability margin is derived from the closed-loop control system against ±25% variation in system parameters.

4.1  Competence assessment of adopted optimisation technique

Initially, the dynamic performance of FO-3DOF-TID controlled unequal three-area interconnected reheat-thermal power plant (test system-1) against 1% step load perturbation (SLP) at \( t = 2 \) s in area-1 is investigated. To assess the tuning efficacy of HHO, the results are compared with some well-known optimisation methods, for example, SSA, GOA, GWO, DE [49] and FA [50]. The optimised gains of the FO-3DOF-TID controller are explored using HHO, SSA, GOA and GWO algorithms and given in Table 1. The dynamic performances of test system-1 are compared in Figure 6.

As depicted in Table 1, the minimum objective function value shows the superiority of HHO over SSA, GOA and GWO algorithms. The convergence characteristic of Figure 6(d) yields faster convergence of HHO. Improvement of objective function value with HHO is noted as 9% (SSA), 31% (GOA) and 36% (GWO). Table 2 presents the time response measurements of Figure 6(a),(b) in terms of overshoot (OS), undershoot (US) and settling (ST). It is apparent from Table 2 and Figure 6(a),(b) that HHO tuned FO-3DOF-TID controller exhibits better system outputs in comparison to SSA, GOA and GWO tuned FO-3DOF-TID controllers in terms of ST and peak magnitude of system oscillations. Hence it may conclude that HHO is competent to obtain better near-optimal frequency and power deviations of the studied test system. In the subsequent investigation, HHO is only considered to optimised the controller settings.

4.2  Dynamic performance analysis of test system-1

In this section, the mastery of the suggested FO-3DOF-TID has been appraised by analysing the dynamic performances of
### TABLE 2
Transient measurements of test system-1 (for comparative study among optimisation techniques)

| Optimisation techniques | \( \Delta f_1 \) | \( \Delta f_2 \) | \( \Delta f_3 \) | \( \Delta P_{\text{tie,12}} \) | \( \Delta P_{\text{tie,23}} \) | \( \Delta P_{\text{tie,13}} \) |
|------------------------|---------|---------|---------|---------|---------|---------|
|                        | OS (\( \times 10^{-4} \)) | US (\( \times 10^{-4} \)) | ST      | OS (\( \times 10^{-5} \)) | US (\( \times 10^{-5} \)) | ST      |
| HHO                    | 12.04  | 18.04  | 5.91    | 0.98    | 4.32    | 5.13    |
| SSA                    | 16.36  | 20.36  | 6.07    | 1.83    | 6.16    | 6.18    |
| GWO                    | 3.08   | 25.08  | 15.98   | 0.0     | 15.94   | 9.32    |
| GOA                    | 14.88  | 20.88  | 7.39    | 12.5    | 7.57    | 7.45    |

Note: Boldfaces show best results.

### FIGURE 7
Comparative study among different controllers, (a) frequency deviation in area-1, (b) frequency deviation in area-3, (c) tie-line power deviation between area-2 and area-3, (d) control input in area-1.
TABLE 3 Optimised controller parameters of test system-1 by employing HHO considering 1% step load perturbation in area-1

| Controllers | $k_p$ | $k_i$ | $k_d$ | $k_{ff}$ | PW | DW | $N$ | $n$ | $\beta$ | $\lambda$ | Objective function ($x10^{-3}$) |
|-------------|-------|-------|-------|---------|-----|-----|-----|-----|--------|--------|----------------------------------|
| FO-3DOF-TID |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 0.4383| 1.6472| 0.6172| 0.3816  | 0.1869| 5.8096 | 2.9134| 0.1576| 0.5972  | 1.0238 |                                  |
| Area-2      | 0.7587| 1.1332| 0.4157| 0.7655  | 0.4898| 1.8056| 2.6324| 0.9706| 0.8003  |        |                                  |
| Area-3      | 0.4321| 1.0695| 1.8492| 0.7952  | 0.4456| 65.153 | 2.5469| 0.4854| 0.1419  |        |                                  |
| 3DOF-PID    |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 0.6775| 1.2690| 0.6313| 0.8235  | 0.9502| 5.4178 | –    | –    | 1.1207  |        |                                  |
| Area-2      | 0.6881| 0.4952| 0.2489| 0.6947  | 0.0344| 6.2605 | –    | –    |        |        |                                  |
| Area-3      | 0.4866| 0.8923| 1.2883| 0.3171  | 0.4387| 5.0818 | –    | –    |        |        |                                  |
| 2DOF-PID    |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 0.9262| 1.3172| 0.8791| 0.1712  | 0.2769| 39.585 | –    | –    | 1.2674  |        |                                  |
| Area-2      | 0.3689| 0.8126| 0.7089| 0.7060  | 0.0462| 1.4521 | –    | –    |        |        |                                  |
| Area-3      | 1.5107| 0.4552| 1.5724| 0.0318  | 0.0971| 41.623 | –    | –    |        |        |                                  |
| FOPID       |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 1.4880| 1.6852| 1.8264| –       | –    | 79.409 | –    | –    | 0.4218  | 0.6557 | 1.3091                          |
| Area-2      | 0.8783| 1.3677| 1.8554| –       | –    | 47.698 | –    | –    | 0.9157  | 0.0357 |                                  |
| Area-3      | 0.0512| 0.4234| 0.6958| –       | –    | 0.3532 | –    | –    | 0.7922  | 0.8491 |                                  |
| TID         |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 0.6993| 0.7148| 1.3173| –       | –    | 76.477 | 2.8147| –    | 1.3258  |        |                                  |
| Area-2      | 0.3436| 0.7527| 1.3669| –       | –    | 38.498 | 2.9058| –    |        |        |                                  |
| Area-3      | 0.2909| 0.8049| 0.1047| –       | –    | 1.3201| 2.1270| –    |        |        |                                  |
| PID         |       |       |       |         |     |     |     |     |        |        |                                  |
| Area-1      | 0.3131| 0.8132| 1.8902| –       | –    | 60.0403| –    | –    | 1.4836  |        |                                  |
| Area-2      | 0.7514| 0.6064| 0.2941| –       | –    | 1.2083| –    | –    |        |        |                                  |
| Area-3      | 1.4980| 0.5947| 1.6618| –       | –    | 104.61| –    | –    |        |        |                                  |

4.3 Dynamic performance analysis of four-area power system (test system-2)

To show the HHO based FO-3DOF-TID controller’s effectiveness, the study has been extended to a four-area interconnected reheat thermal power plant widespread in the literature [3,8].
### TABLE 4  Transient specifications of test system-1 (for comparative study among different controllers)

| Controllers | $\Delta f_1$ | $\Delta f_2$ | $\Delta f_3$ | $\Delta P_{tie,12}$ | $\Delta P_{tie,23}$ | $\Delta P_{tie,13}$ |
|-------------|-------------|-------------|-------------|----------------|----------------|----------------|
|             | OS         | US         | ST         | OS ($x10^{-5}$) | US ($x10^{-5}$) | US ($x10^{-5}$) |
| HHO FO-3DOF-TID | 0.0020 | 0.0080 | 4.60 | 6.04 | 0.0018 | 5.91 | 3.52 | 0.0013 | 5.26 | 9.87 | 4.32 | 5.13 | 4.5 | 4.77 | 4.22 |
| 3DOF-PID | 0.0024 | 0.0172 | 6.11 | 0 | 0.0033 | 6.22 | 0.219 | 0.0026 | 6.19 | 0 | 19 | 6.60 | 9.79 | 0 | 6.7 | 9.02 | 0 | 6.49 |
| 2DOF-PID | 0.0021 | 0.0123 | 6.58 | 0 | 0.0029 | 6.44 | 0 | 0.0024 | 6.26 | 0 | 17 | 6.87 | 8.59 | 0 | 7.11 | 8.52 | 0 | 6.61 |
| FOPID | 0.0016 | 0.0080 | 7.15 | 4.88 | 0.0018 | 7.91 | 5.12 | 0.0018 | 8.35 | 2.96 | 13 | 8.26 | 6.48 | 1.12 | 6.24 | 6.09 | 0.185 | 8.64 |
| TID | 0.0029 | 0.0198 | 9.96 | 3.72 | 0.0061 | 8.83 | 8.35 | 0.0057 | 8.79 | 5.49 | 43 | 8.98 | 22 | 2.31 | 9.23 | 21 | 0.348 | 8.75 |
| PID | 0.0028 | 0.0083 | 14.64 | 48.4 | 0.0030 | 16.69 | 50.1 | 0.0031 | 16.68 | 35.6 | 23 | 16.68 | 12 | 17.5 | 16.68 | 11 | 1.81 | 16.68 |
| DE TID [49] | 0.1005 | – | 28.96 | 4230 | – | 19.01 | 4660 | – | 20.59 | 5320 | – | 26.11 | 206 | – | 17.19 | 369 | – | 19.94 |
| FA PID [50] | 0.1095 | – | 26.56 | 6550 | – | 26.72 | 6470 | – | 26.55 | 9470 | – | 24.03 | 260 | – | 19.66 | 325 | – | 20.70 |

Note: Boldfaces show best results.

**FIGURE 8** Comparative study among different controllers following step load perturbation and wind power perturbation in area-1, (a) frequency deviation in area-1, (b) frequency deviation in area-3, (c) tie-line power deviation between area-2 and area-3, (d) control input in area-1.
The MW capacity of test system-2 is area-1: 2000 MW, area-2: 4000 MW, area-3: 8000 MW and area-4: 16,000 MW. Nominal system parameters are taken from [3,8] and provided in the Appendix. Likewise, test system-1, the dynamic performance of test system-2, has been inspected in two phases, that is, initially with SLP at $t = 2$ s, and then simultaneously applying SLP and RWPP. HHO is used to optimise the controller gains, and the final values are shown in Table 5. The closed-loop outputs of test system-2 yield by FO-3DOF-TID controller are compared with the results of 3DOF-PID, 2DOF-PID, FOPID and FPA tuned cascade PI-PD [8] controllers in Figure 10. Table 6 gives the peak OS, US and ST of Figure 10. The results of Table 6 and Figure 10 help to conclude that the suggested controller offers a worth-appreciating performance for test system-2 in terms of damping of system oscillations. The results obtained with the HHO tuned FO-3DOF-TID controller approaches the final value speedily with fewer swings.
Table 5 that the FO-3DOF-TID controller provides the lowest objective function value compared to other controllers. But, in some cases, as seen from Table 6, the peak magnitude of system responses derived with the FO-3DOF-TID controller is more compared to its other counterparts. It is obvious to note that the minimisation of ST and OS/US is simultaneously not possible, hence trade-offs between ST and OS/US to be quantified systematically.

To demonstrate the efficacy of the FO-3DOF-TID controller in regulating frequency and tie-line power error, the dynamic performances of test system-2 having WPG integrated are analysed. The system performance has been inspected considering GDB, GRC, and communication delay in ACE transmission. Figure 11 illustrates the deviation of frequency and tie-line power subject to RWPP and 1% SLP at $t = 2$ s in area-1. The optimum controller gains presented in Table 5 are considered for simulation. For better comparison, the results obtained with 3DOF-PID, 2DOF-PID and FOPID controllers are also painted in Figure 11. As ocular from Figure 11, the proposed FO-3DOF-TID controller significantly enhances system performances with minimum peak magnitude and highest damping of system oscillations. Moreover, the FO-3DOF-TID controller is worthy of tackling the effects of power system non-linearities and communication delay in ACE signal transmission. Hence it may conclude that the proposed HHO tuned FO-3DOF-TID controller is superior in regulating frequency and tie-line power error of test system-2 after penetration of WPG into area-1 in comparison to prevalent control methodologies reported in LFC literature.

### 4.4 Dynamic performance analysis of five-area power system (test system-3)

In this section, the dynamic performance of an unequal five-area thermal power system having WPG integrated has been investigated [30,51]. The controller parameters are optimised by applying the HHO algorithm. To quantify the FO-3DOF-TID controller’s efficiency, the system outputs are compared with the results of 3DOF-PID, FOPID and DE tuned TIDF [30] controllers. The variation of frequency and tie-line power
**TABLE 6**  Different characteristics of dynamic responses of test system-2 subject to 1% step load perturbation in area-1

| Parameters | HHO: FO-3DOF-TID | HHO: 3DOF-PID | HHO: 2DOF-PID | HHO: FOPID | HHO: TID | HHO: PID |
|------------|------------------|---------------|----------------|-------------|----------|----------|
|            | OS \((×10^{-4})\) | US \((×10^{-4})\) | ST \((×10^{-4})\) | OS \((×10^{-4})\) | US \((×10^{-4})\) | ST \((×10^{-4})\) | OS \((×10^{-4})\) | US \((×10^{-4})\) | ST \((×10^{-4})\) |
| \(\Delta f_1\) | 16 | 124 | 8.45 | 20 | 132 | 9.78 | 22 | 134 | 10.07 | 24 | 132 | 10.98 | 16 | 116 | 11.36 | 15 | 135 | 12.89 |
| \(\Delta f_2\) | 13 | 75 | 10.02 | 17 | 87 | 11.50 | 14 | 84 | 10.69 | 16 | 83 | 12.69 | 16 | 75 | 13.66 | 13 | 91 | 14.41 |
| \(\Delta f_3\) | 8.93 | 67 | 9.649 | 9.32 | 76 | 11.58 | 9.68 | 79 | 10.6 | 7.469 | 74 | 11 | 10 | 57 | 12.84 | 6.49 | 77 | 14.69 |
| \(\Delta f_4\) | 8.96 | 67 | 9.61 | 9.77 | 74 | 10.76 | 9.57 | 77 | 10.62 | 7.35 | 71 | 11.43 | 11 | 59 | 12.85 | 6.07 | 79 | 14.84 |
| \(\Delta P_{tie,12}\) | 4.04 | 71 | 17 | 4.36 | 79 | 16.41 | 8.83 | 80 | 17.42 | 4.19 | 77 | 17.58 | 4.04 | 64 | 18.72 | 4.23 | 82 | 17.97 |
| \(\Delta P_{tie,23}\) | 24 | 2.21 | 15.74 | 27 | 3.84 | 15 | 27 | 2.56 | 15.32 | 27 | 3.76 | 16.17 | 24 | 4.46 | 17.22 | 29 | 2.44 | 18.63 |
| \(\Delta P_{tie,34}\) | 23 | 1.44 | 17.17 | 26 | 1.87 | 16.34 | 27 | 1.44 | 17.89 | 26 | 9.17 | 19.23 | 23 | 1.49 | 19.73 | 26 | 2.418 | 5.04 |
| \(\Delta P_{tie,14}\) | 23 | 1.34 | 17.83 | 26 | 7.94 | 19.7 | 26 | 1.21 | 18.36 | 25 | 1.39 | 17.99 | 23 | 1.36 | 19.68 | 26 | 1.82 | 19.43 |

Note: Boldfaces show best result.
following load and uncertain wind power perturbation is shown in Figure 12. The optimum gains of FO-3DOF-TID controller and minimum objective function value are given in Table 7. It is apparent from Figure 12 the outputs of test system-3 having WPG integrated is unbounded under the control action of the DE tuned TIDF controller.

In contrast, the suggested FO-3DOF-TID controller is competent to handle system non-linearities and uncertain wind power perturbation. This study further highlights the FO-3DOF-TID controller’s effectiveness in the damping system oscillations over its other counterparts. Due to page restriction, the optimised gains of other studied controllers are not shown. As the results obtained with DE tuned TIDF controller are unbounded, these do not portray in Figure 12(a)–(c).

### 4.5 Dynamic performance analysis of two-area multi-unit multi-sources power system (test system-4)

The effectiveness of HHO tuned FO-3DOF-TID controller has been further assessed for a two-area multi-unit multi-source power system with thermal, hydro and diesel power generators. The test system is taken from ref. [52], and its nominal parameters are shown in the Appendix. The HHO is applied to optimise FO-3DOF-TID controller parameters considering 1% SLP at $t = 2$ s in area-1 and presented in Table 8. The outputs of test system-4 obtained with HHO based FO-3DOF-TID controller are plotted and compared with SSA tuned 3DOF-PID, 2DOF-FOPID and 3DOF-FOPID controllers [52] in Figure 13(a), (b). The comparative analysis reveals the superiority of HHO based FO-3DOF-TID controller in terms of damping of oscillations.

The frequency and tie-line power deviation subjected to load and RWPP considering WT’s wake effect is shown in Figure 13(c), (d). For comparison, the results without the weak effect are also shown in Figure 13(c), (d). It is apparent from the results that the wake effect in wind turbines deteriorates system

| Parameters | Area-1 | Area-2 | Area-3 | Area-4 | Area-5 |
|------------|--------|--------|--------|--------|--------|
| $k_p$      | 0.3473 | 0.8869 | 0.2143 | 0.3288 | 0.5313 |
| $k_i$      | 0.6622 | 0.9920 | 0.3979 | 0.7368 | 0.7300 |
| $k_d$      | 0.6355 | 0.6779 | 0.7978 | 0.9125 | 0.6320 |
| $k_{ff}$   | 0.9219 | 0.7609 | 0.5254 | 0.3408 | 0.7177 |
| $N$        | 19.8869 | 16.8385 | 146.244 | 36.715 | 37.361 |
| $\sigma$   | 2.5678 | 2.7523 | 2.1773 | 2.3349 | 2.9334 |
| $\beta$    | 0.4977 | 0.0445 | 0.3327 | 0.0887 | 0.4241 |
| $\lambda$  | 0.1189 | 0.3052 | 0.3775 | 0.3337 | 0.9704 |
| PW         | 0.4830 | 0.7762 | 0.0456 | 0.6133 | 0.4115 |
| DW         | 0.5520 | 0.8087 | 0.5242 | 0.5672 | 0.3457 |
outputs resulting increase of peak overshoot and weak damping of oscillations. However, the developed HHO optimised FO-3DOF-TID controller is competent to preserve the system stability.

4.6 | Kharitonov’s theorem and robustness study

The imprecision in system modelling may come from (i) structured uncertainty (or parametric uncertainty) and (ii) unmodeled system dynamics. These uncertainties have adverse effects on system performance and even causes instability. Robustness is the ability of a control system to deal with system stability and offer consistent performance despite system imprecision. This section investigates the robust closed-loop stability of the studied test systems by using Kharitonov’s theorem.

Routh-Hurwitz criterion helps to determine the closed-loop stability a control system when the characteristic polynomial has fixed coefficients. However, when the physical parameters are not known or merely known within a specified range, the robustness of interval systems can be derived by using Kharitonov’s theorem [53]. Kharitonov’s proposes a robust stability method for the interval system with structured uncertainties. According to this theorem, four Kharitonov’s polynomials are constructed from the characteristic polynomial of interval systems. These Kharitonov’s polynomials represent four vertices of Kharitonov’s rectangle for a fixed frequency $s = j\omega$ ($\omega \in \mathbb{R}$) [54,55]. Let the characteristic polynomial of an $n$th-order interval system be defined as given in Equation (23).

$$p(s) = \sum_{k=0}^{n} d_k s^k \quad d_k \in [d^-_k, d^+_k]$$

where $d_k$'s are the coefficients of characteristic polynomial, $d^-_k$ and $d^+_k$ are the lower and upper uncertainty levels of $d_k$,

| Parameters | Thermal | Hydro | Diesel | Objective function value |
|------------|---------|-------|--------|--------------------------|
| $k_p$      | 1.8822  | 1.5238| 1.7890 | $4.33 \times 10^{-5}$    |
| $k_i$      | 1.6103  | 0.1165| 1.8737 |                          |
| $k_d$      | 1.9684  | 0.3246| 1.0042 |                          |
| $k_{ff}$   | 1.6294  | 1.8116| 1.2647 |                          |
| $N$        | 97.9529 | 89.1172| 37.3745|                          |
| $n$        | 2.3171  | 2.9502| 2.0344 |                          |
| $\beta$    | 0.2540  | 0.1951| 0.5570 |                          |
| $\lambda$  | 0.3152  | 0.9708| 0.2838 |                          |
| $PW$       | 0.8435  | 0.0714| 0.3424 |                          |
| $DW$       | 0.5538  | 0.0923| 0.1943 |                          |
The robust stability of Equation (23) can be ascertained by using zero exclusion principle stated as [55]: For $\omega > 0$, if the interval polynomials $p(j\omega)$ have an invariant degree, that is, $R_{\mathcal{R}} > 0$, and at least one stable member in $p(j\omega, p_0)$, the polynomial $p(i)$ is stable if and only if the origin $(0,0)$ is excluded by the Kharitonov's rectangles for $\omega > 0$. Initially, ±25% variation in system parameters is considered for testing the developed closed-loop control system's robust stability. The characteristic polynomial of test system-1 with GRC, GDB and communication delay is calculated, as shown in Equation (25). The rationalised communication delay model has been obtained using 2nd order Padé approximation, and the same is shown in the Appendix. The four Kharitonov's polynomials are calculated from Equation (25) and given in Equation (26).

$$j^{16} + 7j^{15} + 49j^{14} + 262j^{13} + 1071j^{12} + 3429j^{11} + 8625j^{10}$$
$$+ 16875j^9 + 22516j^8 + 29628j^7 + 26195j^6 + 17408j^5$$
$$+ 8493j^4 + 2905j^3 + 636j^2 + 75j + 3 = 0$$

(31)

The plot of Kharitonov's rectangles corresponding to Equation (26) in the complex frequency plan is shown in Figure 14(a). In Figure 14(a), the Kharitonov's rectangles do not include the origin $(0,0)$ while $\omega$ is varying in the range $(0,50)$. As seen in Figure 14(a), the phase of four Kharitonov's polynomials strictly increases with an increase of $\omega$ that may result in the rectangular value set moves in the counter clockwise direction about the origin. The use of the zero exclusion principle of Kharitonov's theorem substantially establishes the robust stability of the developed control system for ±25% variation of system parameters from the nominal value. A similar conclusion can be drawn from Figure 14(b), (c) for test system-2 and 3, respectively. It is apparent from the results of Figure 14 that the studied test system with the proposed FO-3DOF-TID controller is robust owing to the validation of the zero exclusion principle of Kharitonov's stability theorem.

### Table 9: Pros and cons of the proposed control method

| Attributes                              | TID [30,31] | FOPID [32] | Cascade controller [8] | Two/three DOF-PID [32-35] | FO-3DOF-TID |
|-----------------------------------------|-------------|------------|------------------------|---------------------------|-------------|
| Speed of response                       | Sluggish    | Sluggish   | Relatively good because of two control loops | Better                    | Faster (because of higher degree) |
| Stability margin                        | Low         | Low        | Low                    | Moderate                  | High        |
| Disturbance rejection ability           | Poor        | Poor       | Moderate               | Moderate                  | High        |
| Insensitive to parameters uncertainty   | Low         | Low        | Low                    | High                      | High        |
| Number of tuning parameters             | Less        | Less       | Medium                 | Medium                    | More        |
| Computational burden                    | Less        | Less       | Medium                 | Medium                    | High        |
5 | CONCLUSION

This work demonstrates the maiden application of an FO-3DOF-TID controller for LFC of interconnected power systems considering inherent non-linearities. The dynamic performance of four widely used interconnected power systems (two/three/four/five area) with/without WPG has been examined to establish the proposed control method’s supremacy. The model of WPG is developed considering wind aerodynamic, mechanical coupling shaft, and DFIG. DO is designed and implemented in FO-3DOF-TID control action to improve system performance. The efficiency of the designed DO in tracking uncertain wind velocity has been confirmed. A novel optimisation method, namely, HHO, is applied for the first time in LFC to explore its optimum gains. An extensive comparative study between the suggested FO-3DOF-TID controller and other prevalent controllers, that is, 3DOF-PID, 2DOF-PID, FOPID, TID and PID controllers, has been carried out. The comparative results reveal the supremacy of the FO-3DOF-TID controller over its other counterparts in terms of damping system oscillations. Finally, Kharitonov’s stability analysis has confirmed the robustness of studied power systems in the presence of GRC, GDB and time delay. The proposed method’s pros and cons compared with existing control algorithms used in different works for frequency regulation of interconnected power systems have been tabulated in Table 9. In the real-time study, all system states’ measurement is not possible or expensive to measure; a minimal observer-based controller having DO integrated may be considered a future extension of the present study.

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A | APPENDIX

Nominal values of three/four/five area interconnected power systems are listed as follows [34, 44, 51].

\[
T_{sg} = 0.08 \text{ s}, \quad T_{tt} = 0.3 \text{ s}, \quad T_{ps} = 20 \text{ s}, \quad K_{ps} = 20 \text{ Hz pu}^{-1} \text{ MW}, \quad R = 2.4 \text{ Hz pu}^{-1} \text{ MW}, \quad B = 0.425 \text{ pu MW Hz}^{-1} \quad T_{12} = 0.0866 \text{ pu}, \quad T_{r} = 10 \text{ s}, \quad K_{r} = 0.5, \quad \text{GRC} = 3/\text{min}; \quad \text{GDB} = 0.036 \text{ Hz}.
\]

MW capacity of test system-3: area-1: 2000 MW, area-2: 4000 MW, area-3: 8000 MW, area-4: 10,000 MW and area-5: 12,000 MW.

Parameters of test system-4 [52]: \(X_{G} = 0.6, \quad T_{CR} = 0.01, \quad \bar{e}_{G} = 1, \quad \bar{h}_{G} = 0.05, \quad Y_{G} = 1, \quad T_{I} = 0.23, \quad T_{CD} = 0.2, \quad T_{GH} = 0.2, \quad T_{RS} = 5, \quad T_{RHI} = 28.75, \quad T_{w} = 1.\)

DFIG parameters:

\[
H_{k} = 3.5 \text{ pu MW s}, \quad R_{k} = 3 \text{ Hz pu}^{-1}, \quad T_{2} = 0.08 \text{ s}, \quad T_{c} = 6 \text{ s}, \quad T_{a} = 0.4, \quad K_{i,WT} = 1.326, \quad K_{p,WT} = 2.013.
\]

Wind aerodynamic parameters:

\[
\rho = 1.296 \text{ kg m}^{-3}, \quad V_{w} = 16 \text{ m s}^{-1}, \quad \lambda = 8495 \text{ m}^2, \quad \lambda_{opt} = 8.68, \quad D = 104 \text{ m}, \quad \beta_{0} = 1^{\circ}, \quad \alpha_{1} = 0.5176; \quad \alpha_{2} = 116; \quad \alpha_{3} = 0.4; \quad \alpha_{4} = 5; \quad \alpha_{5} = 21; \quad \alpha_{6} = 0.0068.
\]

Mechanical coupling shaft:

\[
J_{r} = 4.29 \text{ s}, \quad J_{g} = 0.9 \text{ s}, \quad B_{r} = B_{g} = 0, \quad B_{sh} = 1.5 \text{ pu}, \quad K_{tg} = 296.7 \text{ pu}, \quad N_{g} = 20.
\]

Second-order Pade approximation of communication delay:

\[
G_{\text{delay}}(s) = \frac{1 - \frac{\sigma_{d}^{2}}{2} + \frac{\sigma_{d}^{2}}{12}s^{2}}{1 + \frac{\sigma_{d}^{2}}{2} + \frac{\sigma_{d}^{2}}{12}s^{2}}, \quad \tau_{d} = 3.2 \text{ s}
\]