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A novel honey badger algorithm based load frequency controller design of a two-area system with renewable energy sources☆

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A B S T R A C T

When it comes to the process of ensuring the stability, quality, and reliability of a power system, one of the most crucial components is known as the load frequency controller (LFC). It does this by ensuring that there is a balance between the amount of power that is produced and the amount that is consumed. This paper proposes a novel evolutionary approach, referred to as the Honey Badger Algorithm (HBA), PI/PID controllers should be configured in the best possible way in order to address the LFC problem in the electrical power system. The research takes into account a power system that is integrated between two areas and uses renewable energy sources, such as a wind system and a solar system. The utilization of renewable energy sources has the potential to yield favorable outcomes in frequency control through the provision of prompt and adaptable responses to fluctuations in system frequency, helping to maintain grid stability. The proposed HBA method is utilized to refine the controller parameter values, using a fitness function anchored on the integral of absolute error (IAE) and the integral time multiplied by absolute error (ITAE). The performance of the proposed HBA-based controller has evaluated under 5% step load perturbation (SLP) in area-1. The HBA-based controllers demonstrate greater performance in terms of settling time, overshoot, and fitness value when compared to other well-known optimization algorithms such as Particle Swarm Optimization (PSO), Whale Optimization Algorithm (WOA), and Grey Wolf Optimization (GWO). According to the obtained results, the IAE-based PID controller has the best performance. The HBA-based PID controller is evaluated according to the following performance criteria; the objective function value is 0.4201, the settling time values and overshoot values for the area-1, area-2 and tie-line are 15.6, 33.7 and 27.9 s and −6.6, −0.7 and −0.0071 Hz, respectively. According to the findings, the HBA is both a dependable and effective tool for finding solutions to LFC research problems in multi-source power systems.

1. Introduction

Load frequency control, often known as LFC, is an important part of the operation and upkeep of electrical networks, ensuring the stable and reliable supply of electricity to consumers (Bevrani et al., 2021). The LFC is responsible for regulating generator output to correspond with fluctuating load levels and maintain the system frequency within acceptable limits (Ullah et al., 2021). The conventional approach to LFC is predicated on the use of power plants that are based on fossil fuels and can be controlled and dispatched, such as coal, gas, and hydroelectric (Alomoush, 2010). However, the increasing adoption of clean energy options such as such as solar and wind power, introduces new complexities for LFC (Aldeen and Trinh, 1994). Unlike conventional power plants, renewable energy sources are variable and uncontrollable, making it challenging to ensure grid stability and reliability (Farahani et al., 2012). To address these challenges, researchers have proposed various LFC strategies that integrate renewable energy sources. These strategies include frequency-based control, power-based control, and model predictive control, among others (Guha et al., 2016). Additionally, advances in communication and control technologies such as optimal controller, adaptive controller, conventional controller, meta-heuristic based controller and ANN based controller over the last

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few decades (Shankar et al., 2017).

Using the multi-verse optimization (MVO) algorithm approach, a four-area power system's optimal design of a classical controller was suggested in (Mudi et al., 2019). A genetic algorithm-based design controller's performance is compared to studied MVO-based design controller. Grey wolf optimizer algorithm based classical LFC controller is proposed by Sharma (Yatin and Chandra, 2015) and Guha (Guha et al., 2016) for an interconnected power system. A sequential quadratic programming technique for LFC is also presented by Khodabakhshian (Khodabakhshian et al., 2012). To achieve accurate parameter tuning of conventional controllers in a mixed power system with multiple areas, certain measures must be taken, DE-based LFC was suggested in (Mohanty et al., 2014; Rout et al., 2013). Farhangi et al (Farhangi et al., 2012). propose a novel method for LFC system in a power grid with two areas and generation rate constraints by using a cognitive learning-based smart regulator. The effectiveness of the method that was suggested was analyzed using hydro-neuro fuzzy (HNF), fuzzy logic, and PI controller. An ABC algorithm based LFC for power system which has three area and interconnected power system is investigated respectively in (Paramasivam and Ilangi, 2012; El-Fergany Attia and Abdelaziz Almoataz, 2014; Naidu et al., 2014a; El Yakine Kouba et al., 2015; Mokhlis et al., 2014). Research on the operation of the differential evolution (DE) algorithm and how it pertains to the proportional integral (PI) controller for automated generation control (AGC) of an interconnected power system was conducted by Umesh Kumar and others (Kumar et al., 2013a). In (Banaja et al., 2014; Kumar et al., 2013b; Sahu et al., 2014), a fuzzy PID controller with an analog filtration and a 2-DOF PID controller with DE are studied for the LFC of an interconnected power system (Chandra Saikia et al., 2013; Naidu et al., 2014b). explain the Firefly algorithm and a pattern search filtering strategy utilizing the wavelet transform. That strategy is used in order to eliminate noise from the area control error (ACE) signal. In (Hashim et al., 2021), A fuzzy PID controller using the big bang big crunch optimization technique and an imperialist competitive method used in the construction of a fractional order PID controller are examined.

In this study, we have demonstrated the efficiency and superiority of the HBA method for optimizing controllers in load frequency control problems. This method has not been extensively explored in the literature, making our work a valuable addition to the field. Our study provides a comprehensive comparison of different optimization methods, including PSO, GWO, and WOA, with a focus on the advantages offered by the HBA method. Furthermore, we have presented detailed simulation results that showcase the performance of HBA-based controllers in various load variation scenarios. The provided information is crucial for academics and practitioners who are interested in enhancing the performance of generating units in response to load variations.

- For the purpose of determining whether or not the Honey Badger Algorithm (HBA) is successful at its intended task, a power system consisting of two areas is used. This system incorporates a wide array of energy sources, including wind, solar, hydro, gas, and reheat thermal units.
- The HBA use a fitness function based on either the integral of absolute error (IAE) or the integral time multiplied absolute error (ITAE). By utilizing these fitness functions, The HBA demonstrates a high level of efficacy in navigating and exploring the solution area and determine the appropriate settings for the gains of the controller.
- This study evaluates the effectiveness of HBA-based PI/PID controllers in comparison to other population-based meta-heuristic optimization techniques, including PSO, GWO, and WOA-based PI/PID controllers. The performance is assessed based on the minimum settling time and convergence performance. It is proved that proposed HBA based controllers show superior performance over PSO, WOA, and GWO based ones.
- The efficacy of the HBA-based controller has been assessed through the evaluation of its control performance under varying load conditions of + 10%, + 5%, −5%, and −10%. The findings of the study indicate that the utilization of HBA based controllers yields superior performance and effectively stabilizes the variations in tie-line power and frequency within reasonable time constraints across all examined load variation scenarios.
- According to the findings of the research, the HBA that was offered is a viable alternative to the LFC studies' traditional approach to finding a solution.

The following provides an overview of this work's organizational structure; Section 2 describes the steps involved in defining the LFC issue. Section 3 offers a heuristic algorithm; the HBA has been described. Section 4 outlines the utilization of the HBA methodology in the context of LFC. The fifth section of the document presents a case study along with an overview of renewable energy sources. The findings of the simulation, as well as a comparison analysis and performance criterion, are reported in Section 6. Last but not least, the conclusion is presented in Section 7, along with some recommendations for further research.

2. Load frequency control problem

The Load Frequency Control (LFC) is a crucial operation in power systems, which endeavors to sustain equilibrium between power supply and demand. The area control error (ACE) signal in load frequency control (LFC) represents the difference between the planned and actual power exchange between two areas within a connected power network and the following is a description of the ACE signal for a system with two areas (Guha et al., 2016);

$$ACE_1 = B_1 \Delta f_1 - \Delta P_{tie} \quad (1)$$

$$ACE_2 = B_2 \Delta f_2 - \Delta P_{tie} \quad (2)$$

Where ACE_1 and ACE_2 are the area control error of area-1 and area-2, B_1 and B_2 are the frequency bias coefficients, Δf_1 and Δf_2 are the frequency deviation of the area-1 and area-2, ΔP_{tie} is the tie-line power variation. The Proportional-Integral-Derivative (PID) controller is a commonly employed control methodology for the purpose of regulating the Area Control Error (ACE) signal and ensuring that the system frequency remains within acceptable thresholds. To optimize the performance of the PID controller, the controller gains (K_p, K_i, K_d) must be appropriately tuned. Several fitness functions have been proposed to identify the ideal gain parameters, including the integral of absolute error (IAE) and the integral time multiplied absolute error (ITAE). These fitness functions aim to increase the PID controller's stability and robustness while simultaneously reducing the amount of error that exists between the actual and intended responses of the system. To enhance the operational efficiency of a PID controller, it is necessary to adjust the gain parameters to their optimal values, it is necessary to perform tuning, IAE and ITAE based objective functions are taken into consideration. The expression of the objective function for the IAE can be represented as demonstrated in Eq. (3).

$$J_{IAE} = \int_0^T \{|\Delta F_1| + |\Delta F_2| + |\Delta P_{12}|\} dt \quad (3)$$

And the objective function for the ITAE is given in Eq. (4).

$$J_{ITAE} = t * \int_0^T \{|\Delta F_1| + |\Delta F_2| + |\Delta P_{12}|\} dt \quad (4)$$

The process of optimizing the gain parameters of the PID controller is accomplished by utilizing objective functions. However, the limit ranges of the gain parameters of the PID controller are defined as constraints. The parameter values of the controller must be within the specified minimum and maximum limits. The expression for the limit ranges of the gain parameters of the PID controller can be formulated as follows:

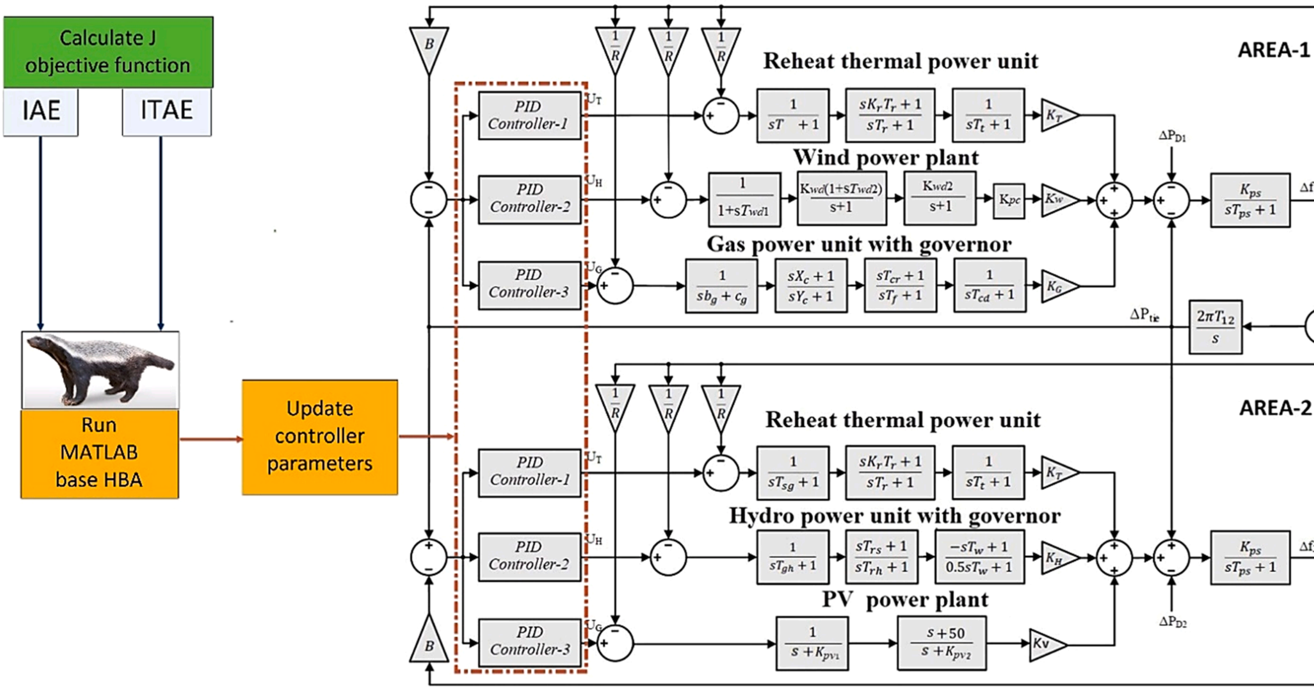

Fig. 1. Optimization process of LFC system using proposed HBA technique.

$$\begin{cases} K_{p,\min} & \le K_p & \le K_{p,\max} \\ K_{i,\min} & \le K_i & \le K_{i,\max} \\ K_{d,\min} & \le K_d & \le K_{d,\max} \end{cases} \tag{5}$$

Particularly significant in load frequency control (LFC) difficulties is the tuning of the PID controller gain settings. This is because the controller plays a crucial role in managing the ACE signal and preserving the frequency stability of the power system. Improper tuning of the gain values can lead to slow or unstable system response, and can even cause oscillations or system failure. In practice, the gain values are typically adjusted using trial-and-error methods, which can be time-consuming and may not guarantee optimal performance. The meta-heuristic methods such as honey badger algorithm (HBA) technique have been proposed as an alternative approach for tuning the PID controller gain parameters. These algorithms can optimize the PID controller gain values based on a fitness function and search for the optimal values in a shorter time.

Table 1
Nominal values of two area renewable integrated multi source power system parameter.

Parameter	Value	Parameter	Value	Parameter	Value
f	60Hz	$R = R_1 = R_2$	2.4Hz/pu	T_t	0.3s
$P_{r1} = P_{r2}$	1000MW	$B = B_1 = B_2$	0.432$puMW/Hz$	T_{gh}	0.2s
P_L	1000MW	K_G	0.130438pu	T_{rs}	5s
GRC	±0.05%	K_{ps}	68.95$Hz/pu\ MW$	T_{rh}	28.75s
b_g	0.05 s	K_r	0.3s	T_w	1s
c_g	1	K_w	0.138	T_{ps}	11.49
X_c	0.6 s	K_H	0. 326,084 pu	T_{12}	0.0433
Y_c	1 s	K_T	0.543478 pu	T_{wd1}	0.041
K_V	-18	K_{wd1}	1.25	T_{wd2}	0.6
K_{pv1}	0.502525	K_{wd2}	1.30	T_{cr}	0.01 s
K_{pv2}	99.4975	T_{sg}	0.08s	T_f	0.23 s
K_{pc}	0.8	T_r	10s	T_{cd}	0.2 s

3. Honey badger algorithm

This study presents a novel approach referred to as the Honey Badger Algorithm (HBA) is suggested to find the PID controller's gain variables optimum value for the LFC issue. In 2021, Hashim et al. introduced the HBA algorithm (Hashim et al., 2021). The concept draws inspiration from the social conduct of honey badgers. The honey badger employs two methods to procure sustenance: it either employs olfactory senses to track and gather the scent of its prey, or it does it by following the honey guide bird, which helps it find a source of food. Both of these circumstances fall under the categories of "digging mode" and "honey mode", respectively. It uses its excellent sniffing abilities in the first mode to determine the general target's location. It then circles the target to choose the best location to begin digging. During the subsequent stage, the individual follows the honey guide bird with the expectation that it will successfully locate the beehive. The foods indicated here are the answer to optimization issues (Hashim et al., 2021). The mathematical models of HBA include both discovery and utilization stages. The following expression is used to initialize the respective positions of honey badger with n population;

$$x_j = LB_i + r_1(UB_i - LB_i), r_1 \in [0, 1] \tag{6}$$

where UB_i and LB_i shows maximum and minimum boundaries of the solution domain, x_j is jth position of the honey badger and designates a possible answer in a group of size n. The abundance of target and the separation between the ith and jth honey badgers determines intensity (I). I_j is the smell potency of the target and given as follows;

$$I_j = \frac{r_2 S}{4\pi d_j^2}, r_2 \in [0, 1] \tag{7}$$

$$S = (x_j - x_{j+1})^2 \tag{8}$$

$$d_j = x_{prey} - x_j \tag{9}$$

where S is analogous to the intensity of the source or centralization intensity while d_j is the displacement between the jth prey and badger. The density factor (α) controls time-dependent irrationality. In the following equation, the density parameter lowered throughout cycles to lessen randomness:

$$\alpha = C \quad x \quad \exp\left(\frac{iter}{\max_{iter}}\right) \tag{10}$$

where $\max_{iter}$ signifies the upper limit of iterations., and C is a fixed amount greater than 1 (the standard value is 2). The HBA optimization algorithm uses the flag (F), which changes the search way and gives staff members more opportunities for exploring the region, to fleeing from local solution area. The procedure of updating the HBA position (x_{new}) has "digging phase" and "honey phase".

Digging phase. The honey badger exhibits a cardioid-shaped digging pattern during its excavation activities. The following equation simulates the approximate cardioid motion as:

$$x_{new} = x_{prey} + F\beta I x_{prey} + F r_3 \alpha d_j |\cos(2\pi r_4)[1 - \cos(2\pi r_5)]| \tag{11}$$

The variable x_{prey} denotes the optimal location of the prey that has been acquired thus far, specifically, the global optimum. $\beta \geq 1$ denotes the honey badger's foraging proficiency. Where r_3, r_4, and r_5 are three unique digits that were produced at random between [0,1]. Lastly F is a flag that alters the search strategy, and is selected as follows:

$$F = \begin{cases} 1 & if \quad r_6 \leq 1/2 \\ -1 & otherwise \end{cases} \quad r_6 \in [0,1] \tag{12}$$

Honey phase. The following equation models the scenario in which the honey badger exhibits a behavior of trailing the honeyguide bird to locate a beehive.

$$x_{new} = x_{prey} + \alpha d_j r_7 F, r_7 \in [0,1] \tag{13}$$

where, x_{new} and x_{prey} indicate, respectively, the new positions of the HB and the prey. It is clear from Eq. (13) that the HBA makes advantage of the distance knowledge (d_j) to direct its search toward the optimum prey position x_{prey}. The three factors that determine the HBA the most are the population or the number of solutions (n), the maximum number of iterations ($\max_{iter}$), and the number of state variables (d). The HBA optimization method ensures powerful capacity of regionally explore through honey attraction and directs the populace's members to approach the most talented candidate. Additionally, the density factor allows the method to do a globally searches and maintains the different groups to ensure that local optimum ways are not used.

The following is the pseudocode representation of the Honey Badger Algorithm (Hashim et al., 2021).

Set parameters t_{max}, N, β, C.
The population is initialized by assigning random places to individuals.
Assess each honey badger position's fitness x_i using objective function and assigning values of f_i, $i \in [1, 2, \ldots, N]$.
Hold on to the optimal position x_{prey} and allocate fitness to f_{prey}.
do (**where** $t \leq t_{max}$)
  Adjust the decrementing factor α → Eq. (10).
  do (**for** $i = 1$ to N)
    Determine the magnitude of the intensity I_i → Eq. (7-8-9).
    then (**if** $r < 0.5$) → r is random number [0 ,1]
      Update x_{new}'s position → Eq. (11).
    else
      Update x_{new}'s position → Eq. (13).
    end, if
    Evaluate the new position and set to f_{new}.
    then (**if** $f_{new} \leq f_i$)
      Set $x_i = x_{new}$, $f_i = f_{new}$.
    end, if
    then (**if** $f_{new} \leq f_{prey}$)
      Set $x_{prey} = x_{new}$, $f_{prey} = f_{new}$.
    end, if
  end, for
end, where the stopping requirements have been met.
Return x_{prey}

4. Application of HBA technique to LFC problem

In the following paragraphs, we will discuss how the HBA approach was used to solve the LFC issue. The proposed approach involves the novel adaptive technique's development and execution using the HBA technique to optimize gain values of the PID controller for effective LFC. The fitness function is determined using the IAE and the ITAE by using Eqs. (4) and (5) to assess the efficacy of the PID controller. Through iterative evaluation of the fitness function, the HBA technique seeks to identify the optimal gain values within the designated search space. Fig. 1 shows the proposed approach of the LFC system for the test system.

5. Case study

The present study employed a two-area power system to assess the efficacy of the HBA-derived regulator proposed for the LFC structure. Fig. 1 depicts this two-area system's layout. As seen in Fig. 1, there are three generation units in Area-1, which are the reheat thermal power unit, wind power plant and gas power unit with governor. And also Area-2 consists of three generation units which are reheat thermal power unit, hydro power unit with governor and photovoltaic (PV) power plant. This test system has two distinct forms renewable power sources, PV and wind power plant.

- Wind power plant*:* According to the system's simplicity and the small signal's stability, the derivative of the wind turbine's output power with respect to time may be approximately described in this study as follows using a first-order transfer function.

Table 2
The parameter settings values of the methods.

Methods	Problem Dimension	c_1	c_2	ω	v_L	v_H	α_{max}	p	N	Iter_max
PSO	18 (PID), 12 (PI)	1.5	1.5	0.9	-1	1	-		30	10
GWO	18 (PID), 12 (PI)	-	-	-	-	-	2	0.5	30	10
WOA	18 (PID), 12 (PI)	-	-	-	-	-	2	0.5	30	10
HBA	18 (PID), 12 (PI)	-	-	-	-1	1	-	-	30	10

Table 3
Comparative performance of ITAE / IAE value for PI controllers based on methods.

Controllers	Obj (J)	Settling time			Peak Overshoot		
		Δf_1 (s)	Δf_2 (s)	ΔP_{tie} (s)	Δf_1 (Hz)	Δf_2 (Hz)	ΔP_{tie} (pu)
HBA tuned PI; IAE	0,5947	16,500	39,300	33,600	-10,500	-1100	-0,0100
GWO tuned PI; IAE	0,7684	25,300	50,000	50,000	-11,700	-1185	-0,0133
PSO tuned PI; IAE	0,8269	28,700	40,400	48,200	-11,700	-2000	-0,0155
WOA tuned PI; IAE	0,9096	18,000	50,000	50,000	-12,600	-1250	-0,0149
PSO tuned PI; ITAE	5,1734	17,200	35,300	37,600	-12,100	-2,700	-0,0153
GWO tuned PI; ITAE	5,6347	24,900	45,000	36,200	-12700	-2020	-0,0163
HBA tuned PI; ITAE	7,3452	21,200	49,100	42,300	-11,900	-1670	-0,0140
WOA tuned PI; ITAE	21,4650	50,000	50,000	50,000	-14,400	-3000	-0,0228

Table 4
Comparative performance of ITAE / IAE value for PID controllers based on methods.

Controllers	Obj (J)	Settling time			Peak Overshoot		
		Δf_1 (s)	Δf_2 (s)	ΔP_{tie} (s)	Δf_1 (Hz)	Δf_2 (Hz)	ΔP_{tie} (pu)
HBA tuned PID; IAE	0,4201	15,600	33,700	27,900	-6600	-0700	-0,0071
WOA tuned PID; IAE	0,5219	20,95	43,70	38,70	-7800	-0854	-0,0087
PSO tuned PID; IAE	0,4450	19,400	40,800	37,800	-9600	-0820	-0,0880
GWO tuned PID; IAE	0,5592	18,600	39,900	36,900	-9100	-0740	-0,0100
WOA tuned PID; ITAE	2,0980	20,200	42,600	38,600	-9800	-1070	-0,0098
PSO tuned PID; ITAE	2,2073	18,600	40,200	36,200	-8200	-0850	-0,0860
HBA tuned PID; ITAE	2,4345	19,200	46,100	38,100	-11,800	-1100	-0,0146
GWO tuned PID; ITAE	2,8312	19,300	40,500	37,500	-9900	-0990	-0,0105

$$G_{wind}(s) = \frac{K_{WD}}{1 + sT_{WD}} \tag{14}$$

- PV power plant: The PV system can be represented by a linear mathematical model, derived from a first-order transfer function. This model suggests that the electrical output of the PV system varies linearly based on the amount of solar radiation it absorbs, provided the ambient temperature remains unchanged. The model can be expressed as:

$$G_{PV}(s) = \frac{K_{PV}}{1 + sT_{PV}} \tag{15}$$

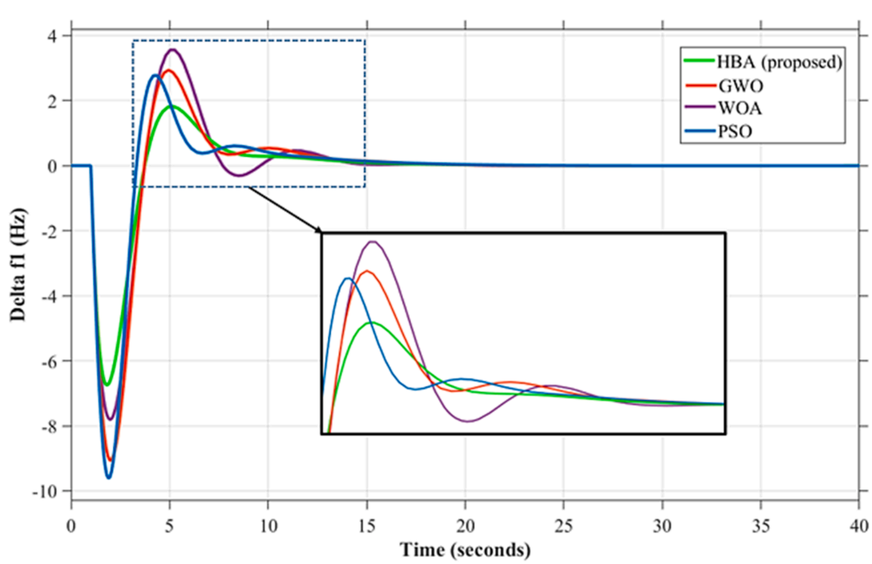

Fig. 2. Frequency deviation in Area-1 (Hz).

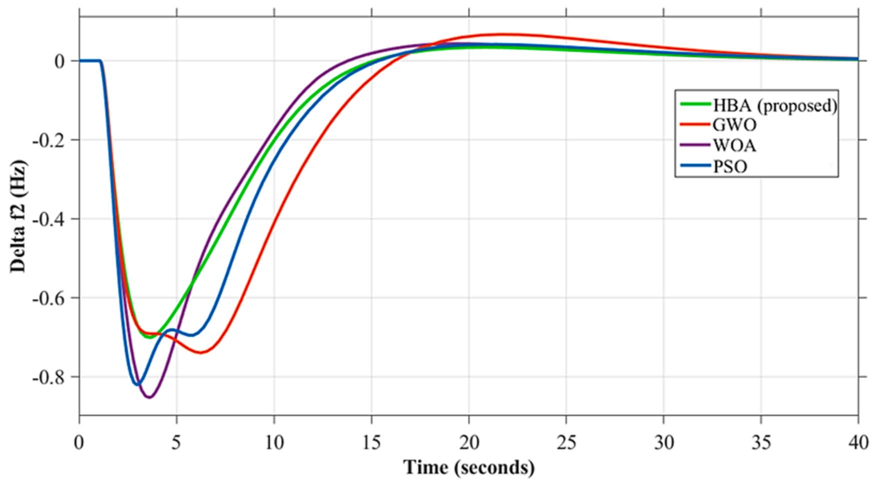

Fig. 3. Frequency deviation in Area-2 (Hz).

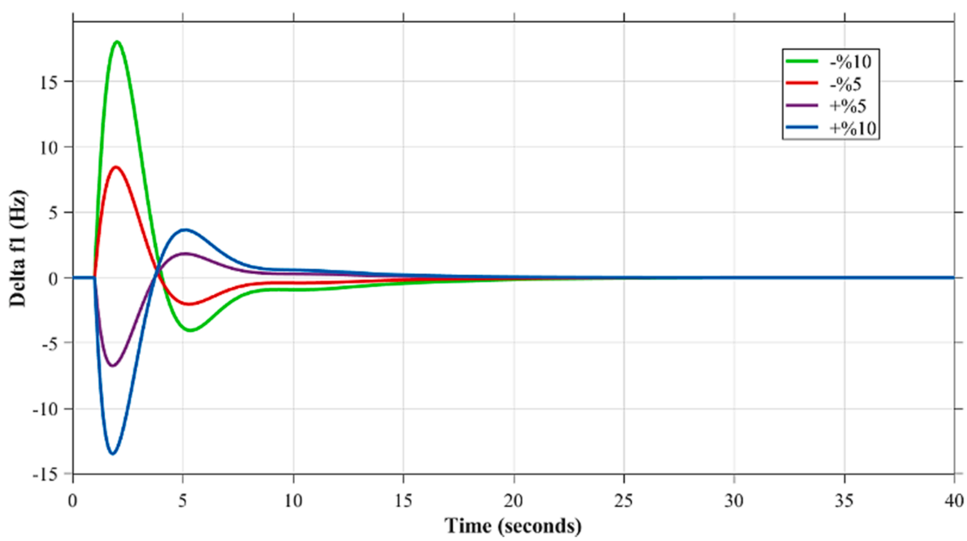

Fig. 4. Change of the tie-line power (pu).

Table 1 lists the numerical values for each parameter of the two-area test system that is being examined.

In order to conduct an investigation for the dynamic characteristics of the performance of the testing system while it is being exposed to both standard and + 10%, + 5%, −5%, and −10% load variation circumstances, the concerned power system model that has been extensively

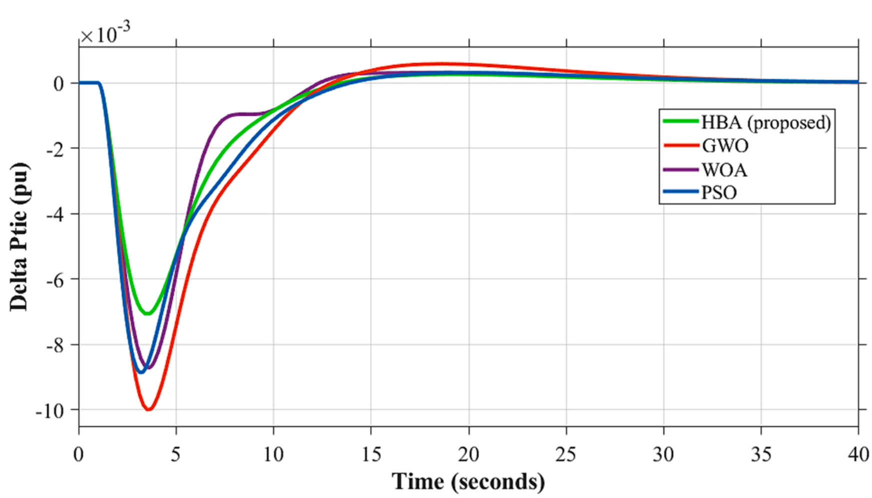

Fig. 5. Changes of area-1 frequency with optimum gains of HBA based PID controller with load variation scenarios.

utilized in the literature (Guha et al., 2016; Shankar et al., 2017; Yatin and Chandra, 2015) has been revised using renewable sources The values that have been predetermined for the system variables are detailed in Table 1. Here, each area has a 1000 MW rating and also each generator in area-1 and area-2 is taken to be coherent. The controllers of system include the speed governor, reheat steam turbine, wind and PV system, and other sub-controller devices. As seen in Table-1, T_{wd1} and T_{wd2} are the wind speed controller's time constants, T_{ps} is the power system unit's time constant, K_{ps} is the power system unit's gain, T_t is the steam turbine's time constant, T_g is the speed governor's time constant, B_1 and B_2 are the areas' respective frequency bias parameters, and R_1 and R_2 are the speed governor's speed regulation parameters for areas 1 and 2. T_{12} is the synchronizing time constant of tie-line, Δf_1 and Δf_2 are deviation of frequency and ΔP_D is the both areas 1 and 2 experienced load change.

6. Simulation results

The interconnected two-area test system was simulated using the MATLAB/Simulink software. In the simulation's first second, a 5% load disturbance was made and the ability of the controllers to stabilize the frequency was examined. Both PI and PID's regulator settings are tuned for the efficiency metrics IAE and ITAE. The gain parameters of the PI/PID controllers used for LFC problem are optimized by PSO, GWO, WOA and HBA methods, respectively. Table 2 displays the values that are used for establishing the parameters for each procedure.

There are six generation units in the test system, therefore six PI or PID controllers are used to control these generation units against load changes. In this case, the optimization problem is 12-dimensional for the PI controller and 18-dimensional for the PID controller. The performance criteria values obtained when using a PI controller are shown in Table 3.

According to Table 3, the proposed HBA method provides the best objective function value with a value of 0.5947, when using IAE-based PI controller. The settling time of the proposed HBA frequency provides the shortest time for each criterion (Delta f_1, f_2 and P_{tie}). The proposed HBA method has the least overshoot value, which indicates that the frequency has the least oscillation. The results obtained when using the PID controller for the LFC problem are given in Table 4.

According to Table 4, the proposed HBA method provides the best objective function value with a value of 0.4201, when using IAE-based PID controller. As can be seen from Tables 3 and 4, in comparison to ITAE and PI methods, the IAE technique gives an enhanced strategy. Likewise, the PID method does as well. In this case, the IAE-based PID controller results of the algorithms are graphically shown in Figs. 2, 3, 4. In the first second of the simulation, a load change of 0.05 pu occurs in Area-1. The frequency change in Area-1 due to this load change is shown in Fig. 2. According to Fig. 2, it is the proposed HBA method shown in green that gives the best control response to load change. It has the fastest settling time of 15.60 s and the least overshoot with 6.60 Hz frequency amplitude. The change in frequency within Area-2 depending on the load change is shown in Fig. 3. According to Fig. 3, it is the proposed HBA method shown in green that gives the best control response to load change. It has the fastest settling time of 33.70 s and the least overshoot value with a frequency amplitude of 0.700 Hz. And finally, the power deviation between the two-area due to the load variation is as seen in Fig. 4. According to Fig. 4, it is the HBA approach that has been suggested shown in green that gives the best control response to load change. It has the fastest settling time of 27.90 s and the least overshoot value with a frequency amplitude of 0.0071 Hz. The suggested HBA-based controller's effectiveness as a controller has also evaluated under + 10%, + 5%, −5%, and −10% load variation scenarios. The obtained scenario results are in Fig. 5.

The findings indicate that the HBA technique, as described, yields the most optimal objective function values for PI and PID controllers based on the IAE. In addition, the HBA method provided the fastest settling times and the lowest overshoot values, allowing the frequency to show the least oscillation. The simulation findings provide empirical evidence that the controllers based on exhibit superior performance in effectively stabilizing the frequency and line power fluctuations within acceptable time constraints across various load variation situations. This research offers a significant insight into the literature by demonstrating the effectiveness and distinct advantage of the HBA method in optimizing controllers, which are pivotal in managing generation units amid load variations.

7. Conclusion

In this research paper, we put forth the HBA as an innovative technique designed explicitly for the fine-tuning of PI/PID controller parameters. The primary intent behind this methodology is to address the challenges associated with LFC particularly in interconnected power systems enriched with renewable energy sources, often complicated by regional nuances. To ascertain the efficacy of this novel approach, it was juxtaposed against prominent optimization techniques like the PSO, WOA, and GWO. Upon comparative analysis, the data unequivocally indicated that control systems steered by HBA outperformed the rest, excelling notably in critical performance metrics such as settling time, maximum rise, and overall fitness value.

The study determined that the utilization of the proposed HBA method in the IAE-based PID controller yielded superior control performance, as evidenced by its achievement of the highest objective function value and optimal settling time and overshoot. The results of the simulation further shown that the HBA approach can successfully stabilize the frequency as well as the tie-line power under a variety of load fluctuation situations. The proposed HBA method is therefore considered to be a reliable and efficient solution method for LFC studies in multi-source power systems.

Finally, the study highlights the importance of the load frequency control in maintaining the stability, reliability, and quality of a power system, particularly during renewable energy sources become more widely used. The suggested methodology, known as HBA, offers a fresh and proficient approach tailored for refining controller parameters in the context of the LFC challenge. By utilizing this strategy, there exists a promising potential to not only amplify the overall efficiency of the power system but also considerably boost its resilience and robustness against unforeseen disturbances and variations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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