Frequency Regulation of Interconnected Power System Using Black Widow Optimization

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ABSTRACT A frequency regulation of interconnected power system comprising thermal reheat system and photovoltaic panel systems is disclosed in this research article with Proportional Integral Derivative (PID) controller optimized using Black Widow Optimization Algorithm (BWOA) based on distinct feature of cannibalism of black widow spiders. With rising demand for perfectly optimized power systems, a best optimal solution for controller gains besides merit of faster convergence and avoidance of trapping in local minimal are becoming key requirements for system engineers. In tune with these requirements, we have developed an optimized solution based on BWOA in the power system realm to minimize the fitness function which is Integral Time Absolute Error composing of frequency and tie-line power variations. Superiority of BWOA optimized controller in power system realm is established by comparing and analyzing its simulation results with some other known tuned controllers which uses different optimization algorithms namely firefly algorithm, genetic algorithm, whale optimization algorithm and modified whale optimization algorithm. Results in this paper lays out that BWOA optimized PID controller outperforms other reported controllers in terms of fitness function value, settling time, undershoot/overshoot of the incremental variations in frequency and tie-line power of the interconnected power system. Further, the potency and robustness of the proposed tuned controller are also proven by considering large variation in load demand, real-time constraints namely generation rate constraint and governor dead band in the system. Additionally, the sensitivity analysis of the optimized controlled system is performed to conclude that the proposed BWOA optimized PID controller optimized controller is insensitive to changes in system parameters and eliminates the necessity of resetting of controller parameters. The performance of the proposed control technique is also tested on two-area non-reheat thermal power system with non-linear constraints namely time delay, generation rate constraint and governor deadband.

INDEX TERMS Black widow optimization, load frequency control, PID controller, photovoltaic systems, thermal-reheat.

NOMENCLATURE

A	Gain of PV panel transfer function.
ABC	Artificial Bee Colony.
ACO	Ant Colony Optimization.
B	Frequency bias constant.
BBBC	Big Bang Big Crunch.
BES	Battery Energy Storage.
BWOA	Black Widow Optimization Algorithm.
BWS	Black Widow Spiders.

CRPSO	Craziness Based Particle Swarm Optimization.
CS	Cuckoo Search.
C_T	Time constant of PV plant with MPPT.
D	Derivative.
DE	Differential Evolution.
D_T	Time constant of PV plant with MPPT.
E	Gain of PV panel transfer function.
$e(t)$	Error signal.
ES	Evolutionary Strategies.
FA	Firefly Algorithm.
FPA	Flower Pollination Algorithm.
GA	Genetic Algorithm.
G_{cn}	Transfer function of PID control.

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GRC   Generation Rate Constraint.
GSA   Gravitational Search Algorithm.
I   Integral.
ITAE   Integral Time Absolute Error.
K_{dn} Derivative controller gain value of nth area.
K_{dnmax} Maximum value of derivative controller of nth area.
K_{dnmin} Minimum value of derivative controller of nth area.
K_{in} Integral gain value of nth area.
K_{inmax} Maximum value of integral controller of nth area.
K_{inmin} Minimum value of integral controller of nth area.
K_{pn} Proportional controller gain value of nth area.
K_{pnmax} Maximum value of proportional controller of nth area.
K_{pnmin} Minimum value of proportional controller of nth area.
K_{ps} Power system gain constant.
K_r Gain of turbine.
LFC   Load Frequency Control.
MPPT   Maximum Power Point Tracking.
n area of power system.
N_c Dimension of controller parameters.
N_{p1} Initial population.
N_{p2} New population after cannibalism.
N_{p3} New population after mutation.
OF   Objective Function.
OFS   Offsprings.
P   Proportional.
p_1 & p_2 Widow parents.
PI   Proportional Integral.
PID   Proportional Integral Derivative.
PV   Photovoltaic.
R   Regulation droop.
RESs   Renewable Energy Sources.
sf sharing factor.
SA   Simulated Annealing.
STPP   Solar Thermal Power Plant.
T Total simulation time.
t Time instant.
T_g Time constant of governor in area-2.
T_{ps} Power system time constant.
T_{ptie} Tie-line power coefficient.
T_t & T_r Reheat turbine time constants.
α Procreation constant.
Δf_n Deviation in frequency of nth area.
ΔP_{Ln} Load demand in nth area of the system.
ΔP_{tie} Deviation in tie-line power of interconnected areas.

I. INTRODUCTION

Load frequency control (LFC) is well known in the art to ensure that electric power is delivered at a consistent

frequency and keeps tie-line power within defined limits and is one of the most important auxiliary services in electrical power system operations [1]. Because of growing environmental concerns about conventional power sources, the integration of renewable energy sources (RESs) into the electric power grid has become increasingly crucial in recent years. The solar and wind energy are the two main renewable energy sources that are being integrated for electric power generation to mitigate the concerns with conventional energy sources [2]. In view of the advantages such as low maintenance cost and suitability for distributed power generation and off-grid system, solar photovoltaic (PV) system is one of the propitious renewable energy sources for electric power generation. However, a major concern posed by the solar PV system is the intermittency of input solar power and requirement of large battery energy storage system, due to which stand-alone systems composing of only PV grid are not reliable for providing continuous and reliable delivery of power. A hybrid system is one of the solutions for providing reliable power supply including renewable energy sources. It is to apprise that the hybrid system may also suffer from frequency regulation problem due to intermittent nature of solar power in view of partial shadow areas and sudden variation in load demand which essentially in turn transpires to the need of incorporation of controllers to keep frequency and tie-line power variations within defined limits.

It is critical to design a load frequency control system correctly to reduce frequency and tie-line power oscillations [3]. A detailed literature survey of various control strategies implemented by power system engineers for managing frequency regulation in traditional and deregulated power system with or without inclusion of renewable energy sources is presented in [4]–[7]. The authors in [1], [4], [5] compare different control strategies for LFC of systems integrated with wind turbines, PV systems, battery energy storage (BES) etc. and discussed in details the merits and demerits of controllers based on classical, optimal, soft computing, centralized and decentralized control. The findings of using single reheat turbine instead of two reheat turbines and appropriate values of non-linearities of hydrothermal system are presented in [6]. In addition to review of controllers, the future scope of LFC presented in [7] unveils to explore the integration of RESs and their impact on frequency regulation problem. These studies reveal the importance and scope of advance control techniques for regulating load frequency in a power system with increasing integration of RESs. In this regard, many researchers over the recent past have worked on various types of controllers such as proportional, integral, derivative, proportional integral, proportional integral derivative [8], fuzzy logic, artificial neural network [9], optimal, sub-optimal [10] etc. for regulating frequency in power systems. Bhatt *et al.* in [11], [12] presented the integral controller based LFC of RES integrated power system. The performance of integral (I), proportional integral (PI) and proportional integral derivative (PID) controller is analyzed in [13] for LFC of three-area thermal system integrated

with solar thermal power plant (STPP). Davtalab *et al.* in [14] illustrated the performance of modern control i.e. fuzzy control technique for solar PV integrated thermal power system. The modern control techniques are well suited for non-linear, integrated and complex power system problems. However, these techniques pose the limitations of increased complexity of controller logic and large processing time for large size power systems [15]. On the contrary, the classical control techniques are easy to implement and have simple control logic for large dimension power systems. The concern with the classical control techniques is the requirement of considerable efforts in tuning the controller gain parameters. To overcome this limitation of classical controllers, many researchers have used physics-based algorithms such as simulated annealing (SA) [16], big bang big crunch (BBBC) [17], Gravitational Search Algorithm (GSA) [18] etc.; swarm based algorithms such as artificial bee colony (ABC) algorithm [19], ant colony optimization (ACO), cuckoo search (CS) [20], craziness based particle swarm optimization (CRPSO) [10], [12] etc. and evolutionary algorithms such as genetic algorithm (GA) [21], evolutionary strategies (ES), differential evolution (DE) [22], firefly algorithm (FA) [14], [23], flower pollination algorithm (FPA) [24], whale optimization algorithm (WOA) [27], water cycle algorithm (WCA) [33], grasshopper optimization algorithm (GOA) [36] etc. to solve the frequency regulation problem. The critical review of different controllers and optimization techniques presented in [37] clearly shows that there is abundant scope to solve frequency regulation using more nature inspired and hybridized algorithms. The meta-heuristic algorithms reported in literature suffer from some limitations such as susceptibility to trap in local minima, slow convergence and large processing time for large dimensional problem [13] besides the advantages of giving better optimal solution and possessing attributes of good exploration and exploitation as these algorithms are based on the distinct characteristics of a living being [25]. With the noticeable points of the meta-heuristic techniques, the importance of design of advanced evolutionary algorithm based optimized controller design is evident to handle the imbalance amid generation and load demand to overcome the limitations of being trapped in local optima, sluggish convergence rate and more memory usage. To overcome the limitations of reported algorithms and design optimally tuned controllers, researchers are working continuously to propose new algorithms and obtain the best optimal solutions. In line with this, Hayyolalam *et al.* has recently introduced Black Widow Optimization Algorithm (BWOA) in [25] based on distinctive mating behavior of black widow spiders. The BWOA branches out from the unique mating behavior of the black widow spiders which hold an exclusive stage of cannibalism. The exclusive stage of cannibalism aids in regulating the individual population size and renders the cannibalistic Black Widow Spider (BWS) in achieving the most optimal conditions for their survival. The advantages and competence of the algorithm in terms of not being trapped

in local minima, faster convergence and more optimal results for standard functions and real-world engineering problems motivate the authors of the present work to utilize this optimization technique for addressing the LFC problem.

The following are the important contributions of this research article, which are highlighted in light of the importance of proposed evolutionary based method for optimally fine-tuning the controller gain values to minimize the frequency and tie-line power deviations of two-area power systems:

- Key goal of this research is to present a simple, and superior load frequency regulation controller in comparison to existing controllers.
- A BWOA optimized controller is proposed to regulate incremental variation in frequency and tie-line power of interconnected system composing of thermal reheat turbine and PV panel system.
- The controller's robustness is demonstrated by analyzing the performance of the optimized controller as load demand varies and in the presence of non-linearities namely time delay, generation rate constraint (GRC) and governor deadband in the system.
- Sensitivity analysis demonstrates that the suggested controller is unaffected by variations in system parameters.
- A comparison of the proposed BWOA tuned PI and PID controllers with GA tuned PI, FA tuned PI, WOA tuned PI, and MWOA tuned PID controller described in the current literature establishes the superiority of the suggested BWOA tuned PID controller in LFC.
- Performance analysis of proposed BWOA tuned PID controller on two area thermal non-reheat system with non-linear constraints and comparison with FA tuned PID and hybrid firefly algorithm and Pattern Search (hFA-PS) tuned PID controller reported in literature

The structure of the article is organized as: The mathematical model of the two-region power system is described in Section 2. The implemented fitness function for improving the controller gains is shown in Section 3. Section 4 describes the BWOA suggested algorithm for developing LFC controllers. Section 5 contains the simulations findings, observations and analysis. Section 6 summed up the conclusions of the work.

II. SYSTEM UNDER STUDY

The suggested control technique is tested on a two-region power system that includes a thermal reheat system in one area and a PV plant with maximum power point tracking (MPPT) [23], [26], [32] in the other. Previous research [23], [27] used a two-area power scheme similar to the used in the present article. The values and parameter abbreviations used in this paper are listed in Appendix [23], [27]. Fig. 1 depicts the simulation model of system under investigation. The detailed modeling and transfer functions of PV plant with MPPT and reheat thermal turbine are given in [23], [26]. A & E are the gains related to PV panel transfer function and C_T & D_T are the time constants of PV plant with
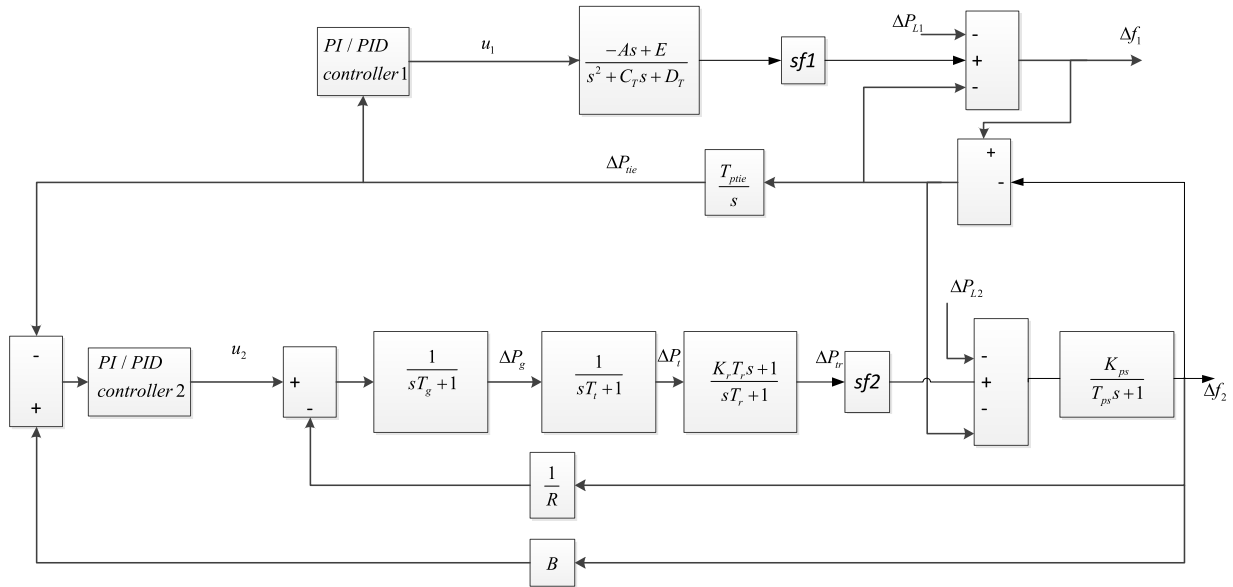
FIGURE 1. Simulation Model of system under investigation [23], [27].

MPPT. T_g is time constant of governor in area-2; K_r is gain of turbine and T_t & T_r are reheat turbine time constants; R is regulation droop, B is frequency bias constant, T_{ptie} is tie-line power coefficient, K_{ps} & T_{ps} are power system gain and time constant respectively. The load demand in n^{th} area of the system is denoted by ΔP_{Ln}.

Under normal operating conditions, the demand is satisfied by the generated power within the respective control areas. However, if the system has additional load demand, this leads in a mismatch between real and projected power exchange, resulting in frequency and tie-line power fluctuations. To mitigate these perturbations, secondary control action is initiated by the controllers. The u_1 and u_2 represents the controller outputs of area 1 and area-2 respectively in the transfer function block diagram. The transfer function, G_{cn}, of PID control [32] of nth area is given as equation (1) and expressed as:

$$G_{cn} = K_{pn} + \frac{K_{in}}{s} + K_{dn}s \qquad (1)$$

where K_{pn}, K_{in} and K_{dn} is proportional (P), integral (I), derivative (D) controller gain values of nth area. The oscillations in frequency and tie-line power due to incremental load requirement in the system must be minimized by suitable controller action which in turn depends on the controller gain values. The optimization technique to optimally tune the controller parameters is explained in the subsequent section.

III. PROBLEM FORMULATION
This study focuses on identification of the optimum PID controller gains for frequency regulation using recently introduced black widow optimization algorithm for diminishing the perturbations in frequency and tie-line power of the interconnected system including RESs. The same objective

function (OF) i.e. integral time absolute error considered in [23], [27], [33] is taken as the fitness function for BWOA algorithm and given as:

$$OF = \int_0^T t\,|e(t)|\,dt = \int_0^T t\left\{|\Delta f_1| + |\Delta f|_2 + |\Delta P_{tie}|\right\}dt \qquad (2)$$

where T is the total simulation time, $e(t)$ is the error signal obtained from summation of deviation in frequency, Δf_n, at time instant t, of nth areas and tie-line power (ΔP_{tie}) of interconnected areas. The fitness function in the RES integrated power system is designed to reduce frequency and tie-line power fluctuations that exists after a long time after the occurrence of disturbance in the system. Using this fitness function, oscillations in system settles faster in comparison to any other fitness function [28]. The system constraints are the minimum and maximum limits of controller gains. Hence, the optimization problem for the present work is defined as:

$$\text{Minimize } OF \text{ subject to } \begin{array}{c} K_{pn\,\min} \leq K_{pn} \leq K_{pn\,\max} \\ K_{in\,\min} \leq K_{in} \leq K_{in\,\max} \\ K_{dn\,\min} \leq K_{dn} \leq K_{dn\,\max} \end{array} \qquad (3)$$

where K_{pnmin}, K_{inmin} and K_{dnmin} are minimum value and K_{pnmax}, K_{inmax} and K_{dnmax} are maximum values of P, I and D controllers respectively. These controller gains in equation (3) are optimized using recently introduced black widow optimization algorithm explained in the next section.

IV. BLACK WIDOW OPTIMIZATION ALGORITHM (BWOA) FOR LFC
The authors developed a bio-inspired Black Widow Optimization Algorithm (BWOA) in [25], [29], which is based on an incomparable property of black widow spider mating. The Black widow is primarily nocturnal, with the female
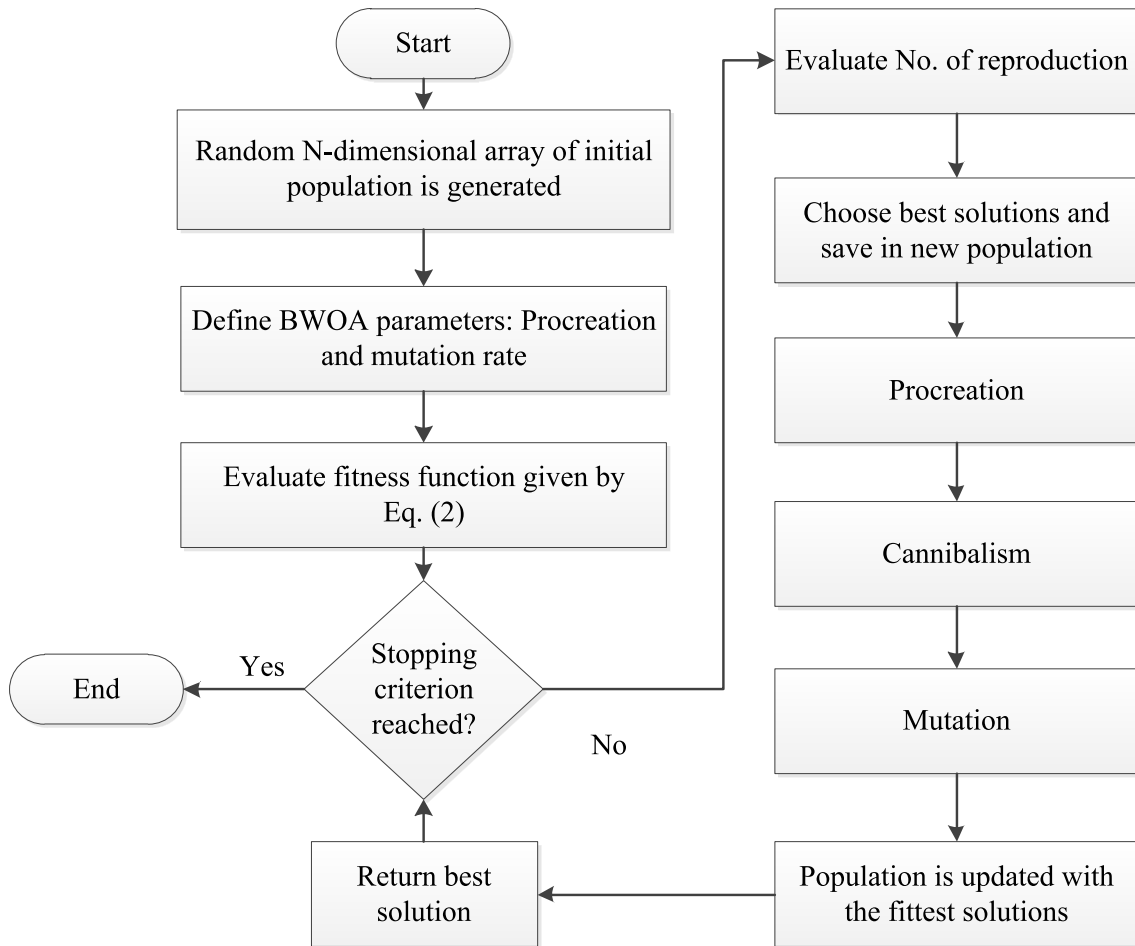
FIGURE 2. Flowchart of BWOA [25], [29].

remaining hidden during the day and spinning her web at night. The female widow spends the majority of her adult life in the same location. When a female black widow wants to mate, she sprays pheromone on selected parts of her net to attract the male. The first male to enter the web reduces the attractiveness of females to rivals by reducing their web size. During or after mating, the female swallows the male, then transfers the eggs to her egg sock. The offspring engages in sibling cannibalism after hatching the egg [38]. They do, however, remain on their moms' web for a short while, and they may even swallow the mother. The fit and powerful individuals survive as a result of this cycle and thus, the global optimum of the goal function is the best.

In terms of faster convergence, not being trapped in local optima, and decent balance between exploration and exploitation of the search space, the proposed algorithm outperforms other evolutionary algorithms. BWOA is used in this paper to overcome the frequency regulation problem by optimizing the PI and PID controller gain parameters. The flowchart of BWOA is depicted in Fig. 2. The step-by-step mapping of the algorithm used to solve LFC's engineering optimization problem [25], [29] is given below:

A. INITIALIZATION

BWOA initializes the population Np_1 of widow spiders randomly having dimension $Np_1 \times N_c$ which contains the values of controller parameters within defined limits. N_{p1} is population size and N_c denote number of controller gains. For each array of widow, objective function/function given by equation (2) is evaluated.

B. PROCREATION

The survival of the fittest individuals and the creation of better offspring are the basis of evolutionary algorithms. In BWOA, the off springs (OFS) are produced by mating of two widow parents, p_1 and p_2, with consideration of procreation constant α. The off springs produced [25], [29] are given as equation (4) and (5) and expressed as:

$$OFS_1 = \alpha \times p_1 + (1 - \alpha) \times p_2 \qquad (4)$$
$$OFS_2 = \alpha \times p_2 + (1 - \alpha) \times p_1 \qquad (5)$$

C. CANNIBALISM

Cannibalism is the process of eating up and destroying father spider by the mother spider and weaker spider off springs by
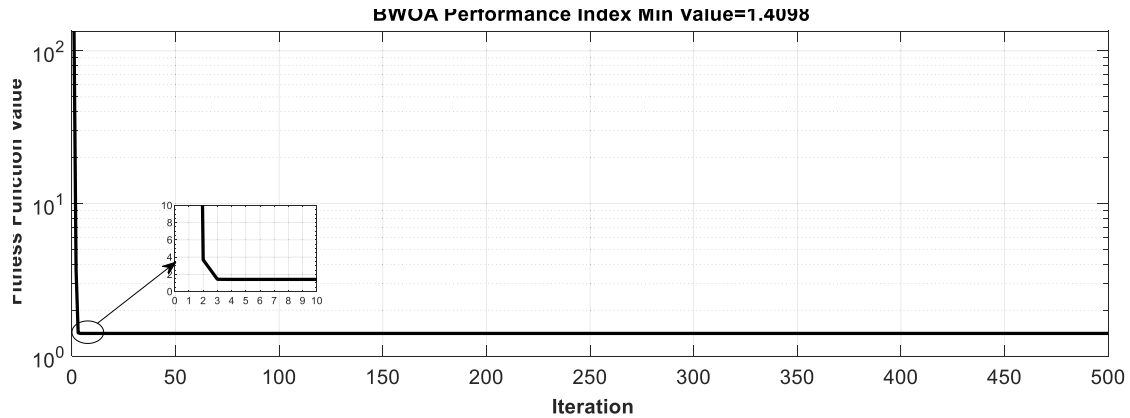
FIGURE 3. Convergence curve of BWOA.

the stronger spider off springs. Based upon the cannibalism rate, the population having better objective function value is stored into new population, N_{P2} and rest of the population is destroyed.

D. MUTATION
The chromosome of some randomly chosen widow spiders from initial population are mutated to generate new population, N_{P3}.

E. UPDATING AND MUTATION
The population generated at step (c) and (d) are merged to form new population and the fitness function value is assessed for each of the solution in the new population and best optimal solution is returned after sorting the population based upon their fitness function value.

In the present study, the abovementioned BWOA algorithm is implemented to fine tune the PI and PID controller gains. The detailed discussion of results obtained is presented in the next section.

V. SIMULATION RESULTS
Optimized controllers are used to control the load frequency of a two-area interconnected power system made up of a thermal reheat turbine and a PV grid system. The values of the controllers are optimally tuned in the present work using recently introduced BWOA. The simulation of the system is performed on MATLAB R2019a on Dell Laptop with 64-bit Operating System, processor Intel®Core^{TM} i5-8265U and 8 Giga Byte RAM. The parameters of the algorithms namely rate of procreation, rate of cannibalism and rate of mutation are set to be 0.6, 0.44 and 0.4 respectively [25] and population size is considered to be 30. These values are chosen because the best optimal solution is obtained for problems solved in [25] using these values when the algorithm is run multiple times for different values of algorithm parameters. The algorithm returns the optimal solution in a very few iterations. However, to demonstrate the not being trapped in local optima, the present paper uses the

500 iterations as stopping criterion for BWOA. Further, for the comparative analysis of the proposed optimized controller with reported tuned controllers, the same saturation limits of the controller gains considered in [23] i.e. between -2 to 2 is considered in the current work. The system parameters of [23], [27] are factored in for the present work and shown in the Appendix. The convergence of the proposed algorithm to solve LFC problem is shown in Fig. 3. It is clear that the fitness function value saturates to 1.4098 which is less than the value obtained using GA [23], FA [23], WOA [27] and MWOA [27] reported in Table 1 and also, it is achieved only in 3 iterations which proves its faster convergence. The proposed controller superiority and competency is exhibited by considering the following scenarios:

(a) Performance comparison of proposed BWOA optimized controller with other optimization algorithms
(b) Impact of high load demand on system performance
(c) Sensitivity analysis of optimized controlled interconnected power system
(d) Effect of non-linearities on system performance

A. PERFORMANCE COMPARISON OF PROPOSED BWOA OPTIMIZED CONTROLLER WITH OTHER OPTIMIZATION ALGORITHMS
This section presents the simulated response of a RES integrated power system with PV panels. In both regions of the system, a demand of 0.1 p.u. load is imposed. The same system is controlled using GA optimized PI [23], FA optimized PI [23], WOA optimized PI [27], MWOA optimized PID [27], BWOA optimized PI and BWOA optimized PID controller. The simulation results of variation in frequency of both regions and tie-line power of an optimally controlled power system using optimized PI controller are shown in Fig. 4 to Fig. 6 and using PID controllers in Fig. 7 to Fig. 9. When both areas in the system are subject to sudden demand of 0.1 p.u. load, it is evident from the dynamic responses and results reported in Table 1 that the system with BWOA tuned PID controller mitigates the perturbations in system frequency and tie-line
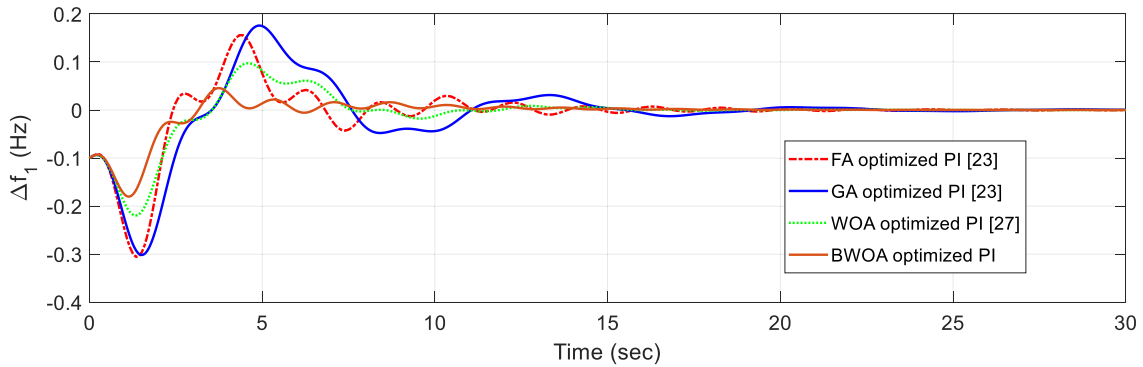
FIGURE 4. Response of incremental variation in frequency of region 1 with different optimally tuned PI controllers.
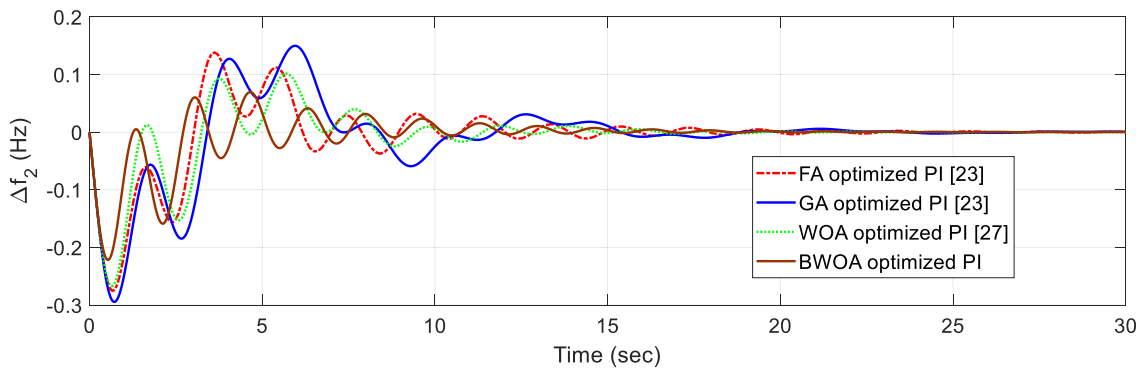

FIGURE 5. Response of incremental variation in frequency of region 2 with different optimally tuned PI controllers.
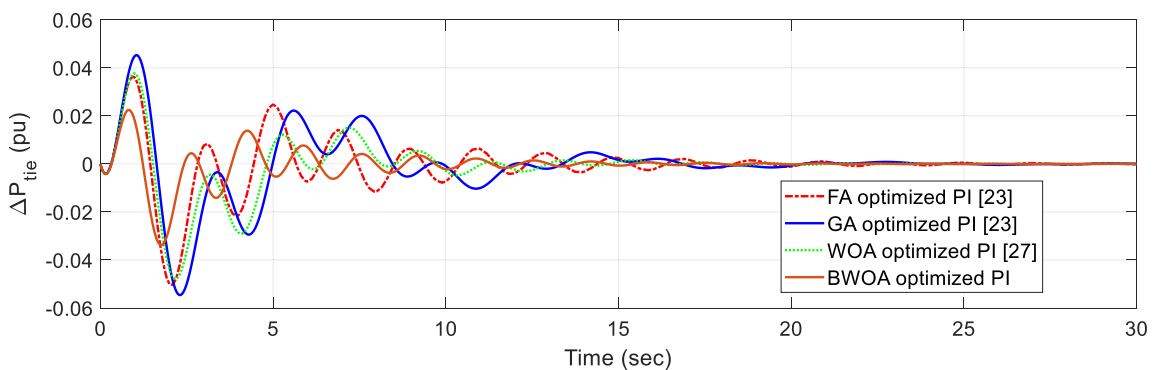

FIGURE 6. Response of incremental variation in tie-line power with different optimally tuned PI controllers.

power more effectively in comparison to GA, FA, WOA, MWOA and BWOA tuned PI/PID controllers reported in literature [23], [27] in light of undershoot, overshoot and settling time. The variations in frequency and tie-line power responses depicted in Fig. 4 to Fig. 9 and Table 1 revealed that the overshoot, undershoot and settling time of the oscillations in the system reduces considerably with BWOA optimized PID controller in comparison to other responses obtained from the reported algorithms.

It is observable from the results reported in Table 1, that the system with BWOA tuned controller shows significant improvement in comparison to performance using GA, FA, WOA and MWOA optimized controllers. It is clear that although the overshoot in frequency of both areas is more than the system response with MWOA optimized controller, but the proposed controller has considerable improvement in reducing the undershoot and settling time of the responses. Hence, it is deduced that the BWOA optimized PID controller outperforms the other reported controllers. Table 2 shows the controller gains and fitness function value obtained using the BWOA technique. It is clear that the fitness function value obtained using BWOA algorithm is less than the other
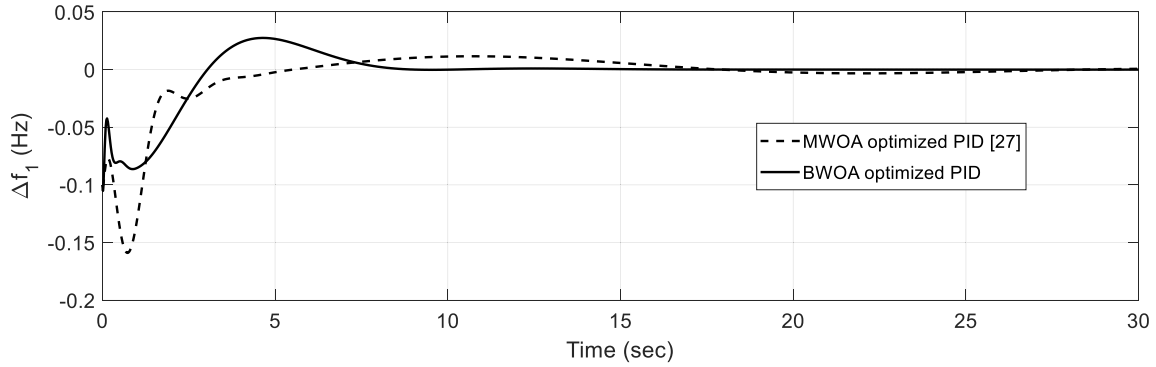
FIGURE 7. Response of incremental variation in frequency of region 1 with different optimally tuned PID controllers.
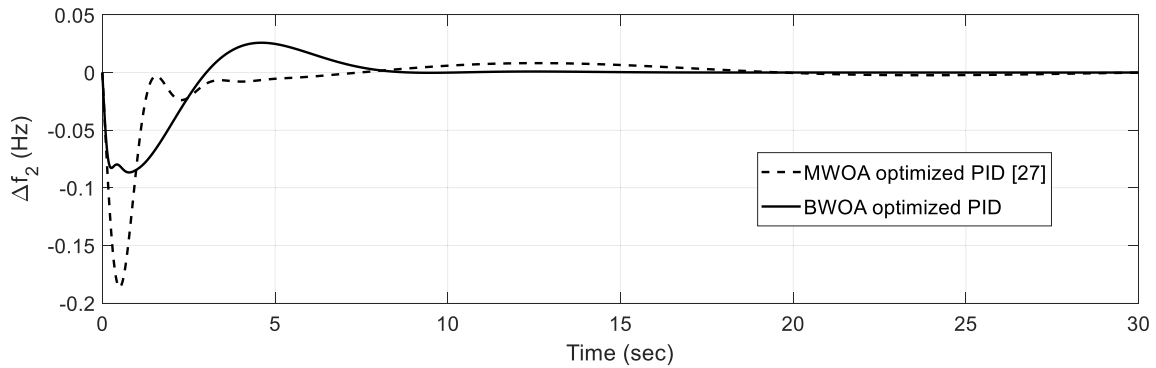

FIGURE 8. Response of incremental variation in frequency of region 2 with different optimally tuned PID controllers.
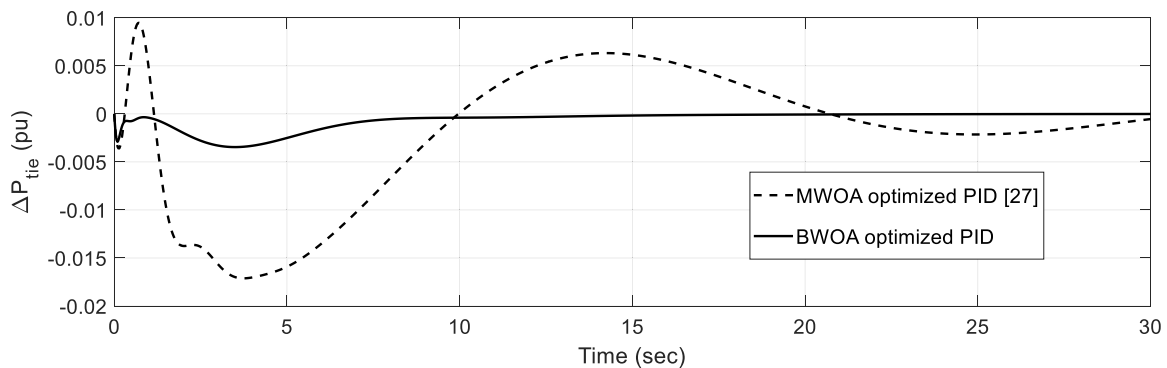

FIGURE 9. Response of incremental variation in tie-line power with different optimally tuned PID controllers.

reported values of fitness function with GA [23], FA [23], WOA [27], MWOA [27] and BWOA tuned PI controller. The fitness function obtained with BWOA is improved by 88.37%, 81.02%, 65.79% and 9.64% with respect to the values obtained using GA [23], FA [23], WOA [27] and MWOA [27] respectively.

B. IMPACT OF HIGH LOAD DEMAND ON SYSTEM PERFORMANCE

Large load disturbances that are sudden in occurrence ranging from 0.1 p.u. to 0.4 p.u. are used to demonstrate the

sturdiness of the BWOA optimized PID controlled two-area system with PV grid panels. The simulation results in Fig. 10 to Fig. 12 demonstrate that the propounded controller successfully mitigates the influence of sudden load disturbances and quickly settles incremental variation in frequency and tie-line power.

C. SENSITIVITY ANALYSIS OF OPTIMIZED CONTROLLED INTERCONNECTED POWER SYSTEM

The sensitivity analysis in electrical power system is very important to predict the response of the system in case if any

**TABLE 1.** Specifications of dynamic responses with optimized controller.

Parameters		GA optimized PI [23]	FA optimized PI [23]	WOA optimized PI [27]	MWOA optimized PID [27]	BWOA optimized PI	BWOA optimized PID	%age improvement of BWOA-PID w.r.t GA-PI	%age improvement of BWOA-PID w.r.t FA-PI	%age improvement of BWOA-PID w.r.t WOA-PI	%age improvement of BWOA-PID w.r.t BWOA-PI	%age improvement of BWOA-PID w.r.t MWOA-PID
Δf_1	OS	0.1758	0.1565	0.0974	0.0116	0.0328	0.0275	84.36%	82.43%	71.77%	16.16%	-137.07%
	US	-0.3017	-0.3063	-0.2196	-0.1590	-0.1203	-0.1052	65.13%	65.65%	52.09%	12.55%	33.84%
	ST	26.73	26.44	26.30	17.99	17.19	8.26	69.10%	68.76%	68.59%	51.95%	54.09%
Δf_2	OS	0.1498	0.1376	0.1017	0.0082	0.0243	0.0258	82.78%	81.25%	74.63%	-6.17%	-214.63%
	US	-0.2945	-0.2756	-0.2671	-0.1863	-0.1337	-0.0867	70.56%	68.54%	67.54%	35.15%	53.46%
	ST	23.64	23.60	25.54	19.69	18.66	8.88	62.44%	62.37%	65.23%	52.41%	54.90%
ΔP_{tie}	OS	0.0453	0.0364	0.0377	0.0095	0.0038	0.0000	100.00%	100.00%	100.00%	100.00%	100.00%
	US	-0.0546	-0.0505	-0.0479	-0.0171	-0.0089	-0.0035	93.59%	93.07%	92.69%	60.67%	79.53%
	ST	27.73	26.45	21.07	29.52	18.53	8.41	69.67%	68.20%	60.09%	54.61%	71.51%

TABLE 2. Controller parameters and fitness function values.

Parameters	GA optimized PI [23]	FA optimized PI [23]	WOA optimized PI [27]	MWOA optimized PID [27]	BWOA optimized PI	BWOA optimized PID
K_{p1}	-0.5663	-0.8811	-0.4563	-0.1070	-0.66708	-2.0000
K_{i1}	-0.4024	-0.5765	-0.2254	-0.0906	-0.54768	-0.3033
K_{d1}	---	---	---	-0.6112	---	-2.0000
K_{p2}	-0.5127	-0.7626	-0.8967	-1.8938	-2.0000	-2.0000
K_{i2}	-0.7256	-0.8307	-0.9865	-1.8935	-0.84696	-2.0000
K_{d2}	---	---	---	-0.2505	---	-1.0483
Fitness Function Value	12.124	7.4259	4.1211	1.5602	3.5086	1.4098
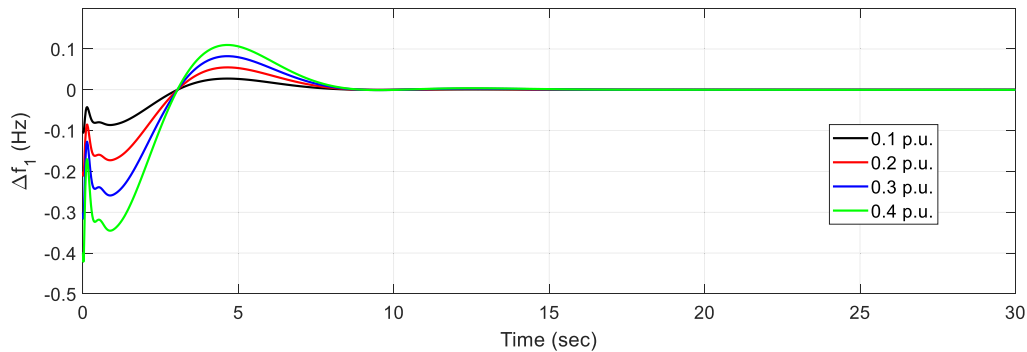
FIGURE 10. Response of incremental variation in frequency of region 1 with large load disturbances.
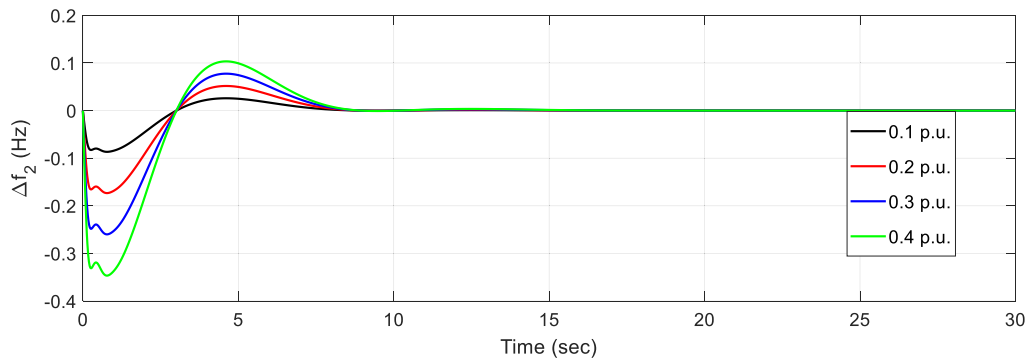
FIGURE 11. Response of incremental variation in frequency of region 2 with large load disturbances.

uncertainty occur in the system and contributes significantly in proper system planning. For example, if there is any

requirement to change in the turbine or solar PV panel, then the designed controller must be compatible with the new
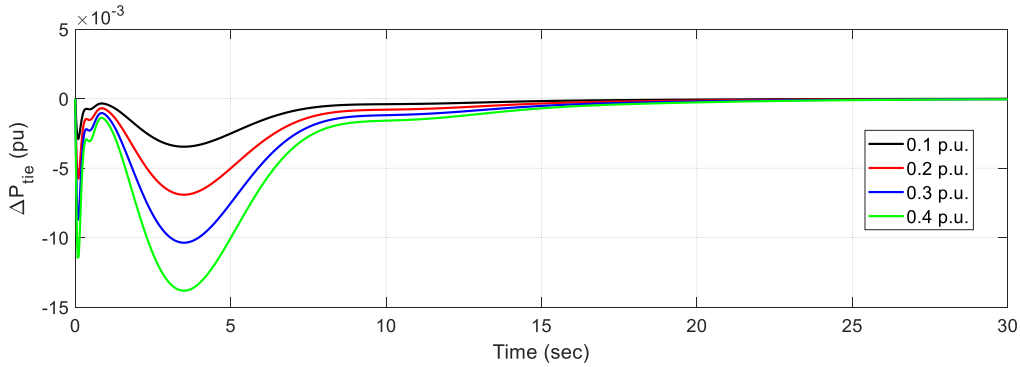
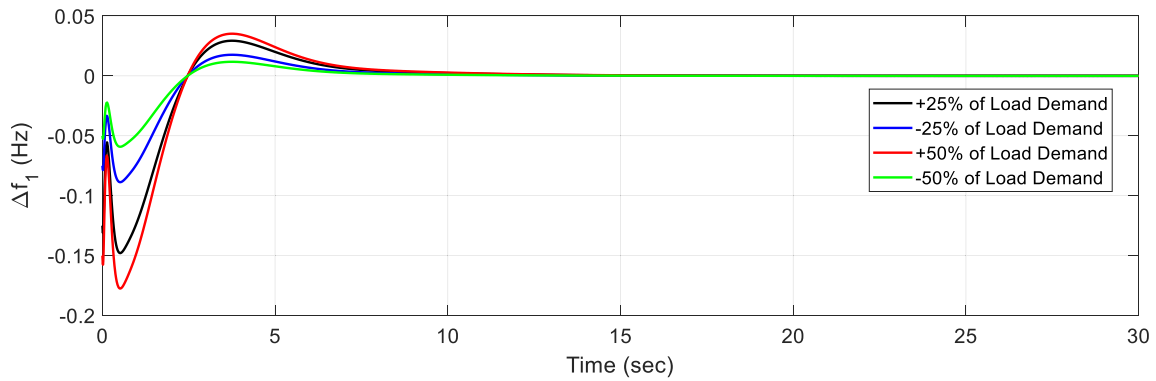**FIGURE 12.** Response of incremental variation in tie-line power with large load disturbances.

FIGURE 13. Response of incremental variation in frequency of region 1 with change in load demand.
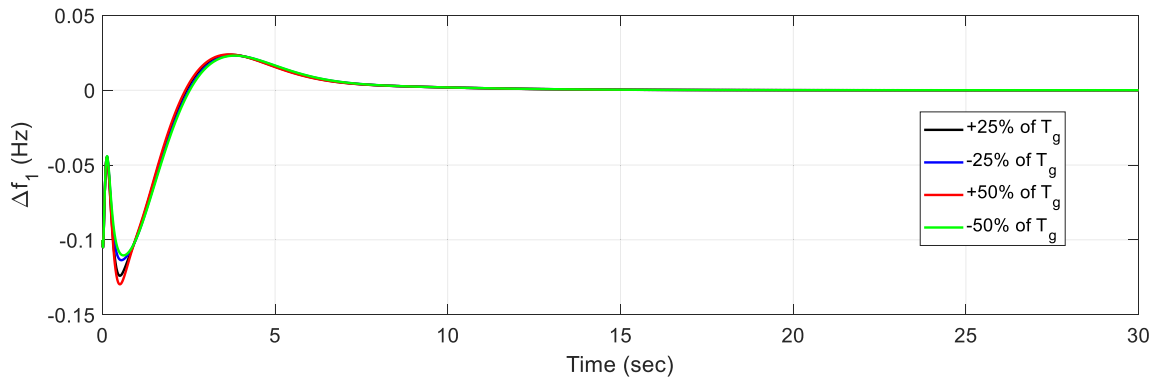

FIGURE 14. Response of incremental variation in frequency of region 1 with change in governor time constant.

installed power system component. Keeping this in view, the sensitivity analysis of BWOA tuned PID controlled PV grid integrated system is performed by considering variation in the system parameters. A substantial range of variation i.e. from -50% to 50% in load demand, governor time constant, time constant of turbine, power coefficient of tie-line, PV panel time constants C_T and D_T is considered for analyzing the performance of controller. It is explicable from the simulation results that there is no need to reset the controller gains even if there is change in the system parameters. The responses are only displayed for frequency variation of region-1 in Figs. 13 to 18, and the specification

of responses for incremental frequency variation of region-2 and tie-line power is reported in Table 3. The suggested controller operates satisfactorily and is able to stabilize the system oscillations, as shown by the simulation results in Fig. 13 to Fig. 18 and the values presented in Table 3.

D. SYSTEM PERFORMANCE WITH NON-LINEARITIES
In real-time power systems, nonlinearities such as governor dead band and generation rate constraint (GRC) exist, thus it's critical to assess the optimized controller performance while taking these limitations into account [30], [31]. In the present work, governor deadband of 0.036Hz, GRC of
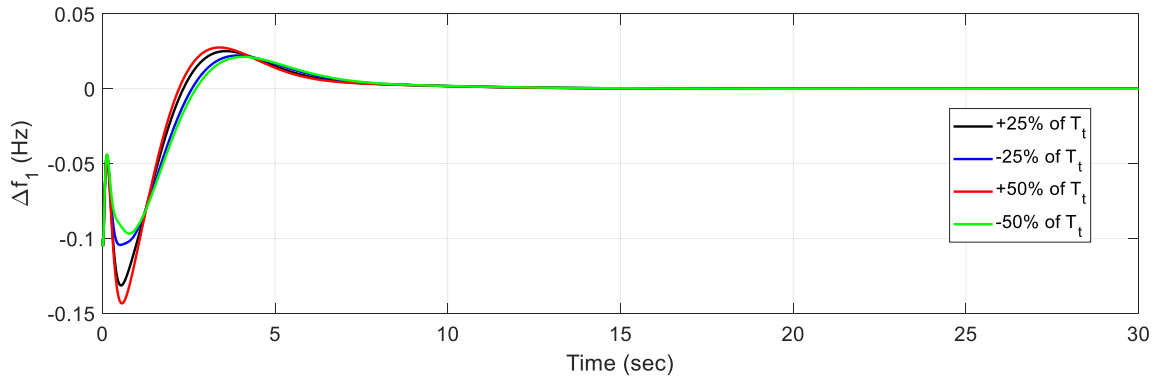
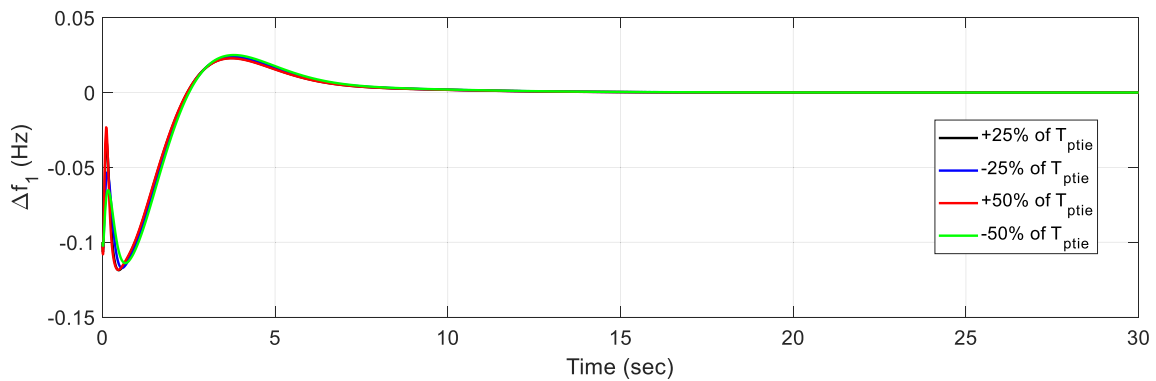**FIGURE 15.** Response of incremental variation in frequency of region 1 with change in time constant of turbine.

FIGURE 16. Frequency variation in region 1 with changes in power coefficient of the tie-line.
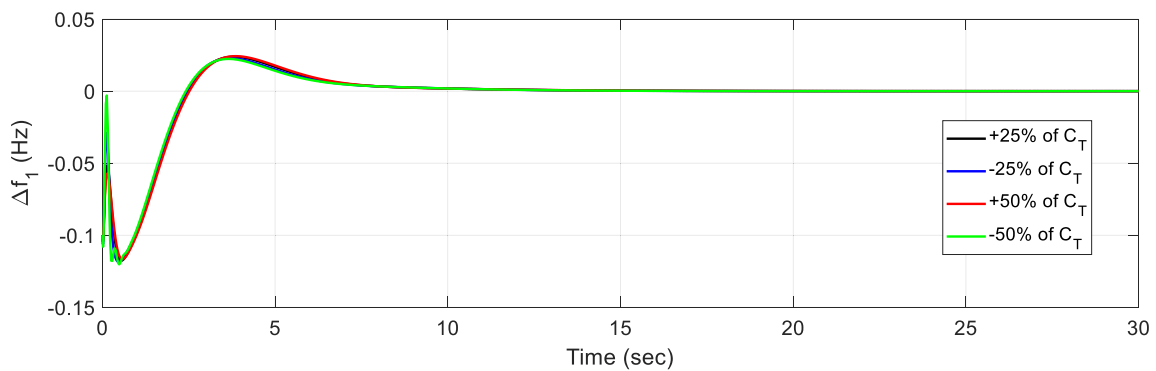

FIGURE 17. Response of incremental variation in frequency of region 1 with change in C_T.

3% p.u. MW/min and time delay of 50ms is considered for simulation [30], [31], [35]. Fig. 19 to Fig. 21 show the simulation results of the system when non-linearities are taken in to account with load disturbance of 0.1 p.u. in both areas. It is evident from the results that the BWOA optimized PID controller successfully handles the non-linearities in the system.

E. CASE STUDY: NON AVAILABLITY OF PV GENERATION

The source of photovoltaic system in area-1 of the power system under consideration is intermittent, non-dispatchable and hence, it becomes necessary to evaluate the performance of the BWOA optimized PID controller to regulate the frequency in case of load sharing of PV system in area-1 and thermal turbine in area-2. The following cases are considered in the present work to support the superiority of the proposed control scheme:

(a) 10% participation of PV system and 90% load sharing by thermal system
(b) 40% participation of PV system and 60% load sharing by thermal system

The sharing factor of PV system and thermal are set to 0.1 and 0.9 respectively in Case study-1. In case study-2, the sharing factor of PV system and thermal are set to 0.4 and 0.6 respectively. The dynamic responses of deviations
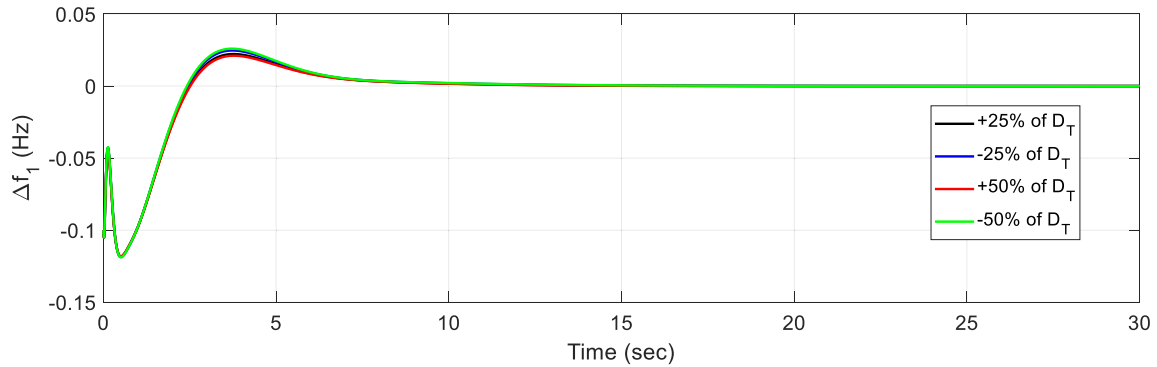
FIGURE 18. Response of incremental variation in frequency of region 1 with change in D_T.

TABLE 3. Sensitivity analysis optimized controlled two-area power system.

| Parameter Variation	% change	Δf_1			Δf_2			ΔP_{tie}		
		OS	US	ST	OS	US	ST	OS	US	ST
Load Demand	25	0.0344	-0.1314	9.17	0.0323	-0.1083	10.03	0.0000	-0.0043	18.97
	-25	0.0206	-0.0786	9.22	0.0194	-0.0650	9.11	0.0000	-0.0026	16.18
	50	0.0413	-0.1577	9.12	0.0387	-0.1300	10.07	0.0000	-0.0052	20.00
	-50	0.0138	-0.0526	9.62	0.0129	-0.0433	9.27	0.0000	-0.0017	14.40
Governor Time constant	25	0.0277	-0.1050	9.12	0.0260	-0.0884	8.99	0.0000	-0.0035	17.69
	-25	0.0273	-0.1050	9.98	0.0257	-0.0859	10.03	0.0000	-0.0034	17.69
	50	0.0279	-0.1050	9.88	0.0262	-0.0936	9.93	0.0000	-0.0035	17.69
	-50	0.0272	-0.1050	9.33	0.0255	-0.0853	10.05	0.0000	-0.0034	17.69
Turbine Time Constant	25	0.0287	-0.1050	9.96	0.0269	-0.0929	9.97	0.0000	-0.0036	17.71
	-25	0.0266	-0.1050	9.73	0.0249	-0.0828	9.97	0.0000	-0.0034	17.69
	50	0.0301	-0.1050	9.91	0.0283	-0.1022	9.93	0.0003	-0.0037	17.71
	-50	0.0258	-0.1050	10.42	0.0242	-0.0804	9.89	0.0000	-0.0033	17.66
Tie-line coefficient	25	0.0272	-0.1066	9.96	0.0259	-0.0866	10.00	0.0000	-0.0034	17.71
	-25	0.0279	-0.1038	9.92	0.0258	-0.0867	9.09	0.0000	-0.0035	17.65
	50	0.0270	-0.1081	9.99	0.0259	-0.0866	10.00	0.0000	-0.0038	17.72
	-50	0.0289	-0.1025	9.63	0.0256	-0.0869	9.92	0.0000	-0.0035	17.56
C	25	0.0279	-0.1043	10.23	0.0258	-0.0868	10.11	0.0000	-0.0038	16.57
	-25	0.0270	-0.1064	11.12	0.0259	-0.0865	9.88	0.0000	-0.0031	18.61
	50	0.0283	-0.1037	10.48	0.0257	-0.0870	10.21	0.0000	-0.0043	16.70
	-50	0.0265	-0.1080	11.62	0.0259	-0.0864	9.75	0.0001	-0.0028	19.38
D	25	0.0264	-0.1052	10.00	0.0249	-0.0868	10.27	0.0000	-0.0039	19.96
	-25	0.0285	-0.1052	9.93	0.0268	-0.0865	9.64	0.0000	-0.0030	14.80
	50	0.0254	-0.1052	10.13	0.0240	-0.0869	19.75	0.0000	-0.0043	21.69
	-50	0.0296	-0.1052	9.90	0.0277	-0.0864	9.46	0.0002	-0.0029	19.27
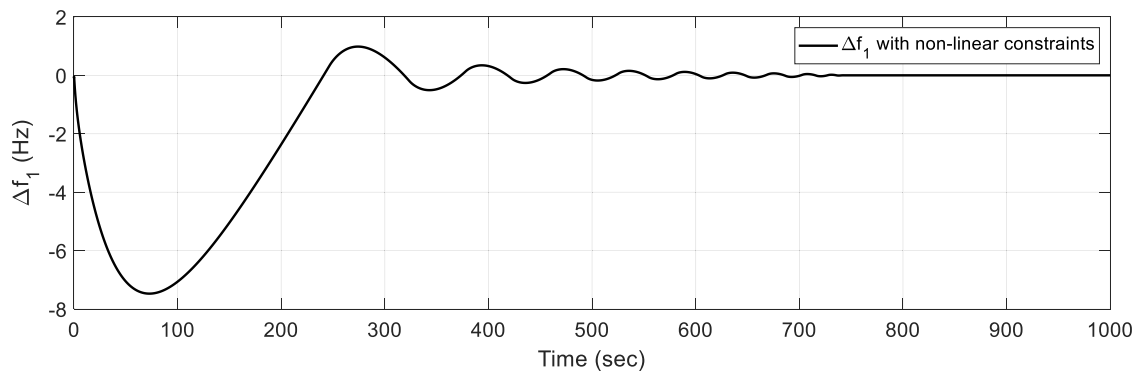
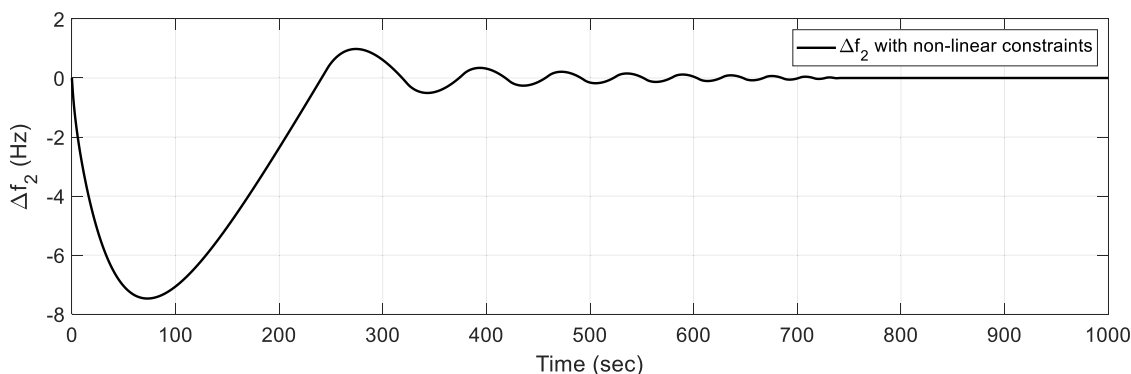**FIGURE 19.** Region 1 Frequency deviation with non-linearities.

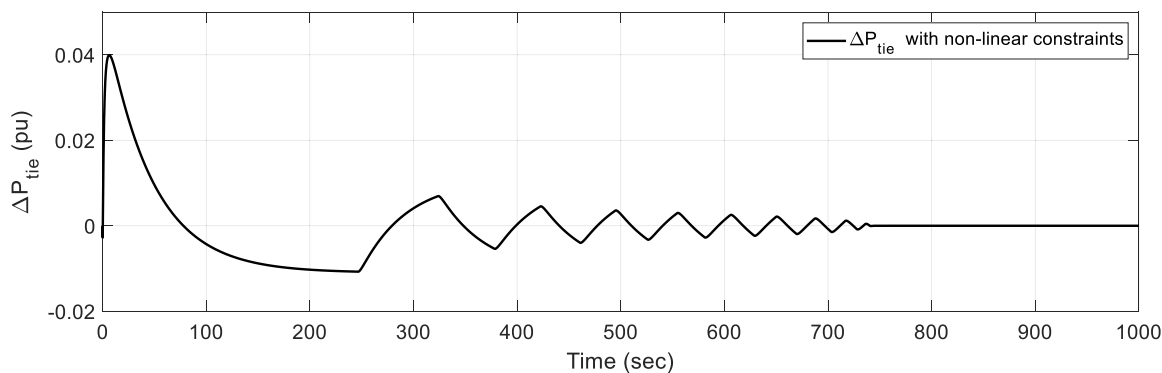**FIGURE 20.** Region 2 Frequency deviation with non-linearities.

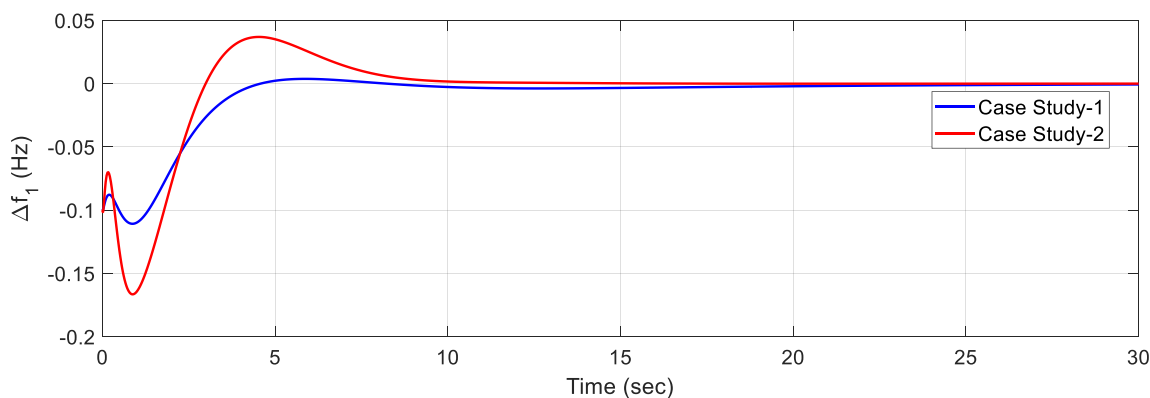**FIGURE 21.** Tie-line power variation with non-linearities.

FIGURE 22. Response of incremental variation in frequency of region 1 for Case study-1 and Case study-2.

in frequency and tie-line power for both case studies are presented in Fig. 22 to Fig. 24. It is clearly evident that BWOA tuned controller effectively regulate the frequency even if there is variation in load sharing of area-1 due to intermittent nature of PV system.

F. PERFORMANCE ANALYSIS OF BWOA OPTIMIZED PID CONTROLLED TWO-AREA THERMAL SYSTEM
The performance of the proposed BWOA optimized PID controlled is analyzed for two-area power system comprising

of thermal non-reheat turbine with GRC in each area. The transfer function model of system and parameters are taken and referred from reference [34]. BWOA optimized controller is used to regulate the frequency regulation of thermal area system having rated power of 2000MW and nominal load of 1000MW [34]. The controller gains lie within the range of −1 to 1 [34]. The performance of the proposed BWOA tuned PID controller is compared with firefly algorithm (FA) and hybrid Firefly Algorithm and Pattern Search (hFA–PS) tuned PID controller [34].
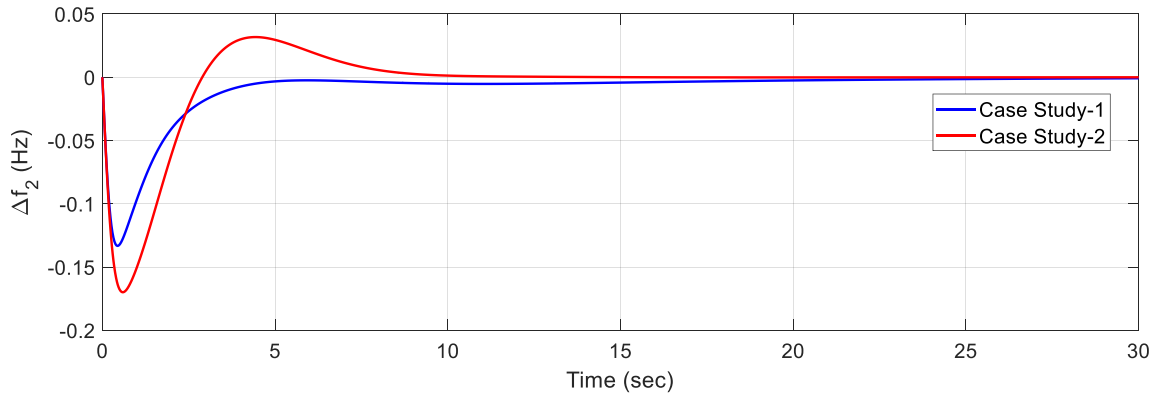
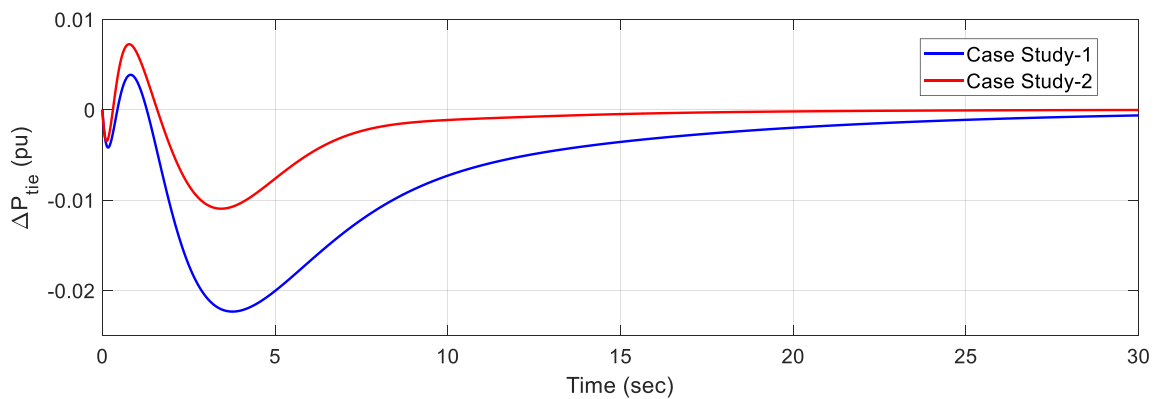**FIGURE 23.** Response of incremental variation in frequency of region 2 for Case study-1 and Case study-2.

FIGURE 24. Response of incremental variation in tie-line power for Case study-1 and Case study-2.
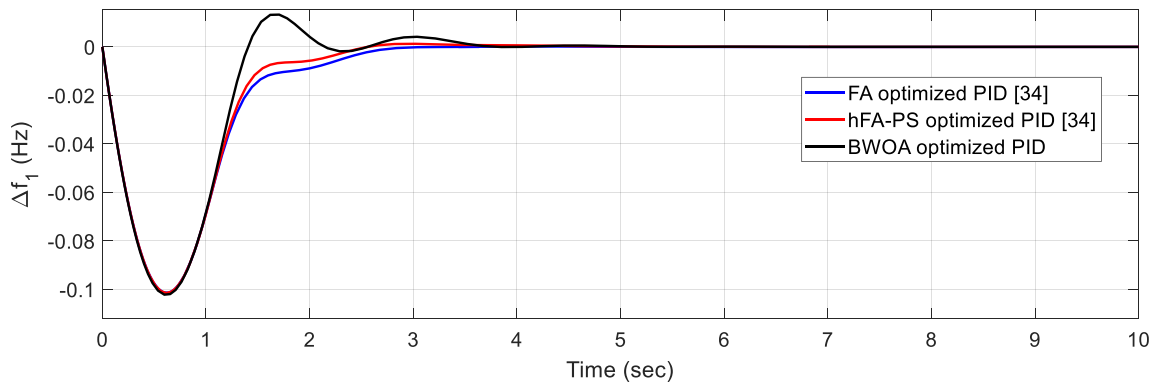

FIGURE 25. Response of incremental variation in frequency of region 1 with different optimally tuned PID controllers.

The specifications of dynamic responses using optimized controllers with step increase of 5% in load demand of area-1 and GRC of ±0.05 is presented in Table 4 and dynamic responses of variations in frequency and tie-line power are shown in Fig. 25 to Fig. 27. The tuned controller parameters and fitness function values are reported in Table 4.

The simulation responses shown in Fig. 25 to Fig. 27 and results reported in Table 4 and Table 5 depict that although there is no much significant improvement in overshoot

and undershoot of the responses, BWOA optimized PID controller outperforms the FA optimized PID and hFA-PS tuned PID controller in terms of settling time and fitness function value of deviations in frequency and tie-line power. The settling time of deviations in frequency of area-1, area-2 and tie-line power has been improved by −9.03%, 25.10% and 21.40% respectively and fitness function improved by 29.88% using BWOA tuned PID controller as compared to FA tuned PID controller [34]. The improvement of -20.71%, 18.44%, 15.50% and 18.33% is observed using BWOA
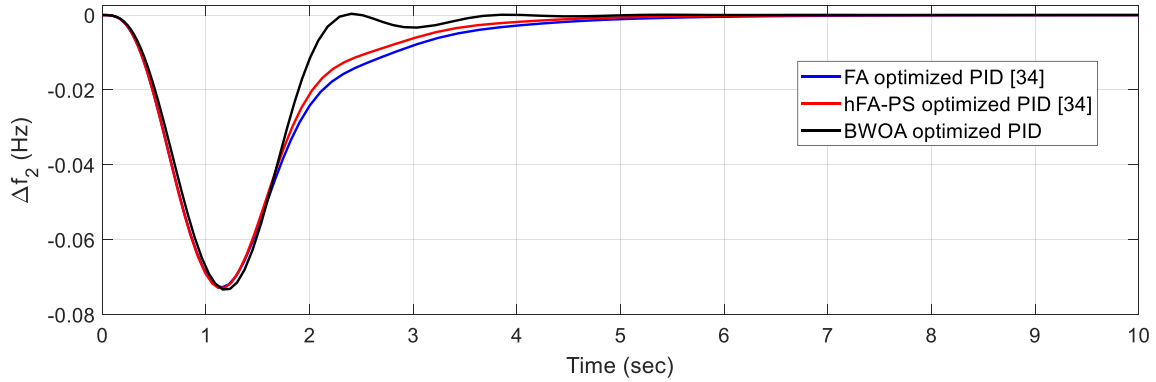
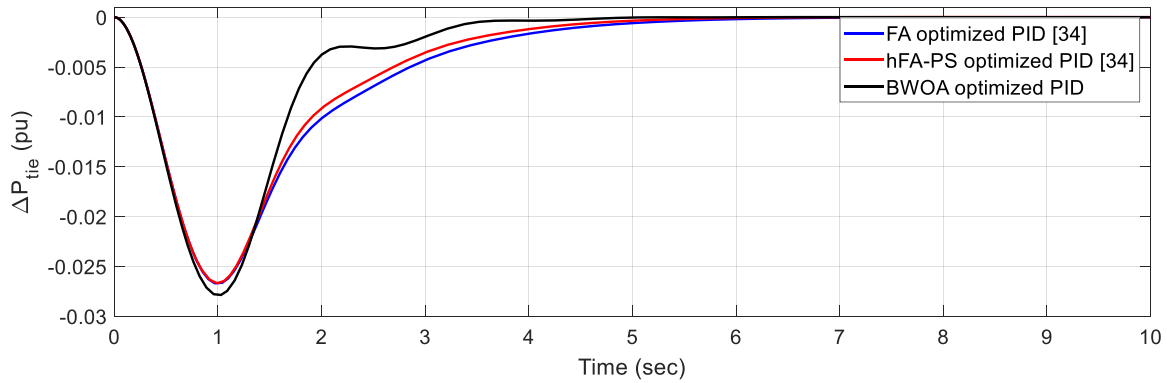**FIGURE 26.** Response of incremental variation in frequency of region 2 with optimally tuned PID controllers.

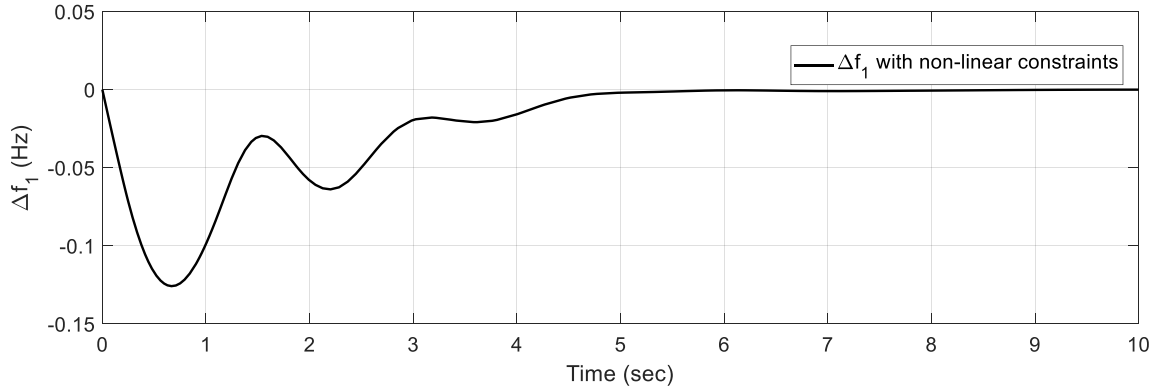**FIGURE 27.** Response of incremental variation in tie-line power with optimally tuned PID controllers.

FIGURE 28. Region 1 Frequency deviation of two-area thermal system with non-linearities.

TABLE 4. Specifications of dynamic responses with optimized controller.

Parameters		FA optimized PID [34]	hFA-PS optimized PID [34]	BWOA optimized PID
Δf_1	OS	0.0002	0.0013	0.0133
	US	-0.1014	-0.1015	-0.1022
	ST	3.1	2.8	3.38
Δf_2	OS	0.0000	0.0000	0.0004
	US	-0.0727	-0.0728	-0.0733
	ST	4.9	4.5	3.67
ΔP_{tie}	OS	0.0000	0.0000	0.0000
	US	-0.0267	-0.0267	-0.0279
	ST	4.3	4.0	3.38

TABLE 5. Controller parameters and fitness function values.

Parameters	FA optimized PID [34]	hFA-PS optimized PID [34]	BWOA optimized PID
K_{p1}	0.3259	0.3834	0.4284
K_{i1}	0.5743	0.6127	0.7297
K_{d1}	0.4024	0.4021	0.2597
K_{p2}	0.3259	0.3834	0.0131
K_{i2}	0.5743	0.6127	-0.0487
K_{d2}	0.4024	0.4021	0.2396
Fitness Function Value	0.3240	0.2782	0.2272

optimized controller in comparison to hFA-PS optimized PID controller in the dynamic responses of frequency deviation of area-1, area-2, tie-line power deviation and fitness function respectively.
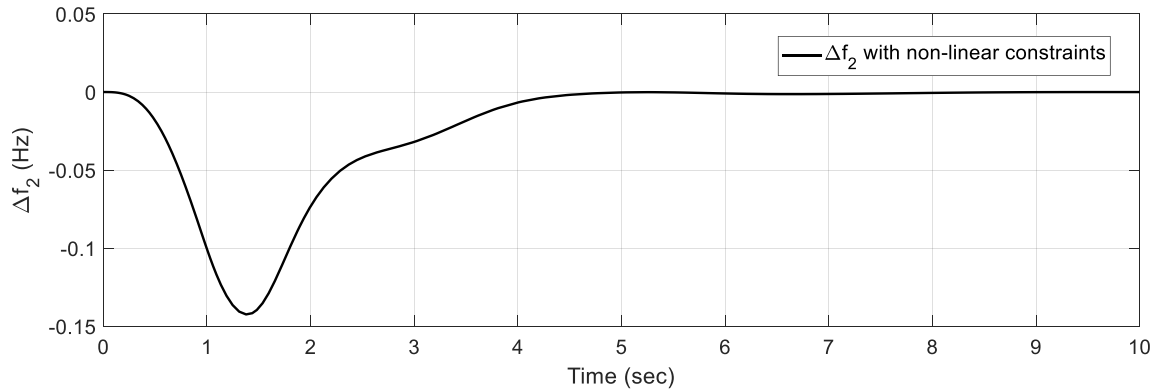
FIGURE 29. Region 2 Frequency deviation of two-area thermal system with non-linearities.
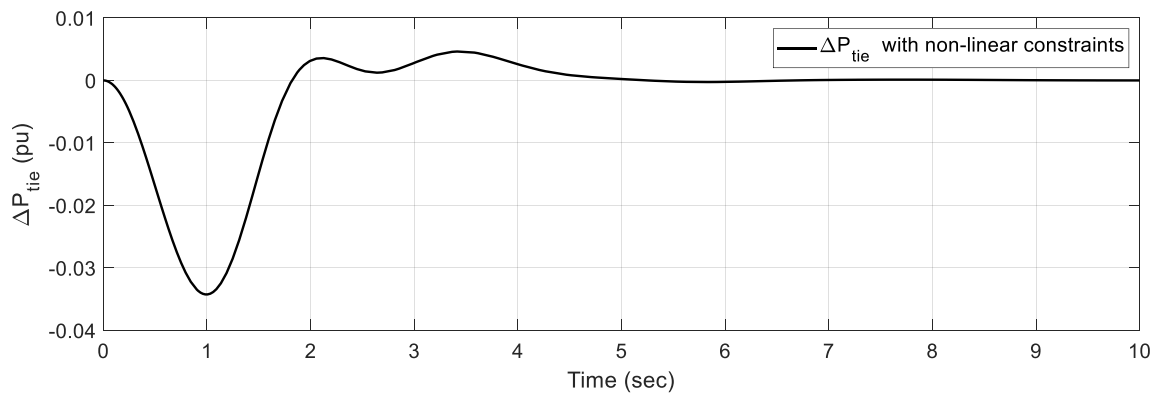

FIGURE 30. Tie-line power variation of two-area thermal system with non-linearities.

Further, the analysis has been extended with inclusion of non-linear constraints namely governor deadband of 0.036Hz, GRC of ±0.05 and time delay of 100ms present in the real-time system [34], [35]. The dynamic responses of the two-area thermal interconnected system with no change in controller gains as reported in Table 4 are shown in Fig. 28 to Fig. 30. It is evident that the BWOA optimized controller effectively handles the non-linear constraints establishing the superiority of proposed optimization technique for fine tuning the controller gains.

VI. CONCLUSION

The objective of the present study to regulate frequency of photovoltaic integrated power system is achieved through tuned proportional integral and proportional integral derivative controller optimized using the distinct feature of cannibalism of the black widow optimization algorithm. BWOA optimized PID controller is also used to regulate frequency of two-area thermal power system. A comparative analysis of the proposed controlled technique with some known algorithms, namely GA, FA, hFA-PS, WOA and MWOA algorithm optimized controllers, establishes the superiority of the proposed black widow optimization algorithm optimized controller in terms of objective function value, faster convergence, undershoot, overshoot and settling

time of responses. The integral time absolute error fitness function shows improvement by 88.37%, 81.02%, 65.79% and 9.64% with respect to the values obtained using GA, FA, WOA and MWO algorithm respectively for photovoltaic-thermal interconnected power system. The proposed BWOA tuned PID improves settling time of dynamic responses of frequency in area 1, frequency in area 2 and tie-line power by 54.09%, 54.90% and 71.51% respectively as compared to MWOA tuned PID controller. Moreover, changes in load demand and system characteristics over a range from +50% to -50% proves the proposed bio-inspired optimized controller's robustness and sensitivity. The variation of sharing factor of photovoltaic system from 0.1 to 0.4 in order to study the impact of variable solar radiance and temperature evidently shows that the oscillations in the dynamic responses gets settles down by the proposed BWOA tuned PID controller. Further, the efficacy of the proposed control scheme has also been proven by implementing the technique on widely used two-area interconnected power system comprising of non-reheat thermal power system with non-linear constraints namely time delay, generation rate constraint and governor deadband.

In the future, the work will be extended to multi-area interconnected power system comprising of multiple sources of generation including renewable energy sources such as

solar, wind etc. in each area. The work will focus on design of hybridized meta-heuristic algorithm based PID controller to diminish the transient oscillations in power system arising as a result of perturbation or intermittent nature of renewable energy source in the system. Further, the system stability will be analyzed incorporating battery energy storage systems or generators with fast ramp up time which will provide electrical power in case of non-availability of renewable energy sources.

APPENDIX

Parameter	Description	Value
A	PV panel gain parameter 1	18
E	PV panel gain parameter 2	900
C_T	PV panel time constant 1	100
D_T	PV panel time constant 2	50
T_g	Governor time constant	0.08 sec
T_t	Turbine time constant	0.3 sec
K_r	Reheat turbine gain	0.33 p.u. MW
T_r	Reheat turbine time constant	10 sec
K_{ps}	Power System Gain of Thermal area	120 Hz/p.u. MW
T_{ps}	Power System Time Constant	20 sec
R	Regulation Droop	0.4 Hz/p.u. MW
B	Frequency Bias constant	0.8 p.u.
T_{ptie}	Tie-line power coefficient	0.545

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