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HYBRID GREY WOLF OPTIMIZATION-PATTERN SEARCH (hGWO-PS) OPTIMIZED 2DOF-PID CONTROLLERS FOR LOAD FREQUENCY CONTROL (LFC) IN INTERCONNECTED THERMAL POWER PLANTS

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Abstract

The combination of Grey Wolf Optimization and Pattern Search Technique (hGWO-PS) has been introduced to optimize the parameters of two Degree of Freedom Proportional-Integral-Derivative Controller (2DOF-PID) for controlling the load frequency in Automatic Generation Control (AGC) for interconnected power system. The interconnected two area power system of non-reheat thermal power plants consisting of 2DOF-PID controller in each area has been considered for design and analysis. Firstly, the proposed approach has been implemented in the aforementioned standard test system and thereafter, the robustness of the system consisting 2DOF-PID controller optimized by proposed technique has been estimated using the sensitivity analysis for the same. The robustness of the system consisting of 2DOF-PID controller optimized by proposed scheme is examined by varying the parameters of standard test system, loading conditions during operation, size and location of the disturbances. The performance of the 2DOF-PID controller optimized by proposed approach has also been compared with recently published approaches in the literature. The simulation results show that the proposed hGWO-PS optimized 2DOF-PID controller shows far better performance than recently published approaches in the literature in terms of dynamic response. The simulation results also show that system performances hardly change when the operating load condition and system parameters are changed by ±50% from their nominal values, i.e. the proposed controllers are quite robust for a wide range of the system parameters and operating load conditions from their nominal values.

Keywords:

Automatic Generation Control (AGC), Multi-Area Power System, Two Degree of Freedom-PID Controllers (2DOF-PID), Grey Wolf Optimization (GWO), Pattern Search (PS).

1. INTRODUCTION

Since the modern electric power system has been rapidly performing the task of generation, transmission and distribution of electric power, the size and complexity of the power system has grown along with increase in power and energy demand which leads various uncertainties in power system problems. So, intelligent system has become a necessary part to manage complex and large power system which combines knowledge, techniques and methodologies from various sources for the real-time control of power systems [1].

Automatic Generation Control (AGC) is an important control process of multi area interconnected power systems. It operates constantly to make a balance between the generation and load in power systems at a minimum cost, responsible for frequency control and power interchange, monitors the system frequency and tie-line flows in the power system, measures the net change in the generation required and changes the set position of the generators within the area so as to keep the time average of frequency deviations and tie-line power deviations at a low value [2-4].

Over the years Load Frequency Control (LFC) was the interesting topic of research and it has been a necessary part of Automatic Generation Control (AGC) in electric power system and it is used to maintain the system frequency at nominal or prescheduled value (Hz). The steady state operation of power system results in increase or decrease of load demand which yields the variation of speed and frequency accordingly. Therefore, the control of load frequency is necessary to make operation of the power system safe [2-4]. The various control strategies for LFC problems named as the classical and optimal control, robust and adaptive control, self-tuning control, VSC systems, digital and artificial intelligent/soft computing control techniques and the comparison, advantages and disadvantages of these approaches have been elaborated in [5]. A control strategy should be in such a way that it performs the following functions:

- maintains the frequency at constant value
- maintains desired tie-line power flow
- achieves zero steady state error and inadvertent interchange

Various controllers for the LFC problems have already been suggested in literatures. The literature review shows that the conventional proportional integral derivative (PID) controllers are most widely applicable frequency controller among all reported controllers due to its easy implementation and better system dynamic response but its performance degrades due to increase in the complexity by the disturbance such as load variation & boiler dynamics [7]. The concepts of optimal control theory (OCT) [8], Integral (I) [9], Proportional-Integral (PI) [10], Proportional-Integral-Derivative (PID) [11], Integral-Double Derivative (IDD) [12], Fractional Order PID (FO-PID) [13] and Proportional-Integral-Double Derivative (PIDD) [14] have also been implemented and compared. Also in [12], some conventional controllers like Integral (I), Proportional Integral (PI), Integral Derivative (ID), PID and Integral Double Derivative (IDD) have been implemented for controlling load frequency in an AGC system.

A number of researches on the soft computing based optimization methods have been carried out by the researchers. Recently, in order to tune or optimize the parameters of PID controllers for LFC, soft computing based optimization methods have been implemented in literature. The controller optimized by Bacterial Foraging Optimization Algorithm (BFOA) has been proposed in [15-16]. Also in [16], a gain scheduling PI controller with governor dead-band nonlinearity has been proposed for AGC of a two area thermal power system. An Imperialist Competitive Algorithm (ICA) to tune PID controller parameters in multi area power system [17], Differential Evolution (DE) algorithm to optimize the parameters of PI controller using a modified objective [10], DE algorithm to tune the parameters of classical controllers for a multi-area multi source power system (MAMS-PS) [18], Teaching Learning Based Optimization (TLBO) technique to design I/PID controllers for a multi-units multi-sources power system (MUMS-PS) [19], an intelligent controller based on emotional learning for LFC system of a two-area power system with generation rate constraint (GRC) [20], a Firefly Algorithm (FA) with on line wavelet filter for AGC of an interconnected unequal three area power system [21], Artificial Bee Colony (ABC) algorithm for AGC system in [22], Gravitational Search Algorithm (GSA) to optimize the parameters of PI/PIDF controller using conventional integral based objective functions for AGC system [23], have already been proposed.

Each heuristic algorithm has its own merits and demerits and there is no guarantee which algorithm is best suited for tuning the parameters of controllers while all optimization algorithms shows acceptable results [24]. Hence, proposing and implementing new high performance heuristic algorithms to real world problems has become a challenging task for researchers.

To improve the results, mixed/hybrid algorithms have been recently proposed in literature because it combines the advantage of two or more. A hybrid BFOA-PSO algorithm for AGC systems in [25] and hybrid PSO-PS algorithm for optimization of the fuzzy PI controller parameters in [26], have already been proposed.

The system performance depends upon the artificial techniques used, the structure of the controller and the selection of objective function. Two-Degree-of-Freedom (2DOF) controllers have an advantage over the classical One Degree of Freedom (1DOF) because they achieve high performance in tracking of set-point and regulation in the presence of disturbance inputs [27]. So, Two Degree Freedom of Proportional-Integral-Derivative (2DOF-PID) controller for AGC of interconnected power system has been considered in this paper.

A new meta-heuristic optimization technique named Grey Wolf Optimization (GWO) proposed in 2014 [28] is based on the social hierarchy and hunting behavior of grey wolves and it is used to search and hunt a prey (solution). The advantages of GWO algorithm over other well- established algorithms are as follows:

a) There is no need of specific input parameters for the implementation of the GWO algorithm.
b) It is simple and free from computational complication.
c) It can easily be programmed and understandable.

A balance of exploitation and exploration throughout the search procedure should be maintained to get excellent performance using any optimization technique. If GWO being a global search is applied alone, it will give the wide search space and may not give best solution. Therefore, local search methods such as Pattern Search (PS) is required to exploit the local but cannot perform extensive search [29]. Since both the algorithms have their own strengths, the hybridization of these algorithms may be achieved in order to get better results of optimization. So, in this paper, a hybrid GWO-PS technique abbreviated as *h*GWO-PS has been proposed to optimize the parameters of 2DOF-PID controller for controlling the load frequency in AGC of power system of thermal power plants.

The remaining part of this paper is organized as follows: In section 2, the single area and two area power system of thermal power plants, their transfer function model and their mathematical modeling have been described. The brief explanation of 2DOF-PID controller has been given in section 3. In section 4, The Integral of Time multiplied Absolute Error (ITAE) as objective function for the proposed work is defined and described. The overview of Grey Wolf Optimization and pattern Search have been elaborated in section 5 and section 6, respectively. In section 7, the hybrid Grey Wolf Optimization and Pattern Search Algorithm (*h*GWO-PS) with defined parameters have been explained. Section 8 shows the simulation results elaborating the full comparative study. Section 9 concludes the paper followed by the appendices and references at the end.

2. BASIC CONCEPTS

In this section, the concept of single area, two area electric power systems of thermal plants, their transfer function models and their mathematical expressions have been discussed.

2.1 STRUCTURE OF SINGLE AREA POWER SYSTEM OF THERMAL PLANTS

A single area power system of thermal plants consisting of governor, turbine, load and generator has been shown in Fig. 1 in which each component of power system is represented by the transfer function model.

The mathematical modeling of single electric power system can be presented as follows [3]:

The transfer function of the turbine is defined as,

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_G(s)} = \frac{1}{1+sT_T}. \tag{1}$$

The transfer function of a governor is defined as,

$$G_G(s) = \frac{\Delta P_G(s)}{\Delta P_V(s)} = \frac{1}{1+sT_G}. \tag{2}$$

The speed governing system has two inputs ΔP_{ref} and Δf and governor has input ΔP_V and one output $\Delta P_G(s)$, so, ΔP_V is given by,

$$\Delta P_V(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta f(s). \tag{3}$$

The transfer function of generator and load is represented as,

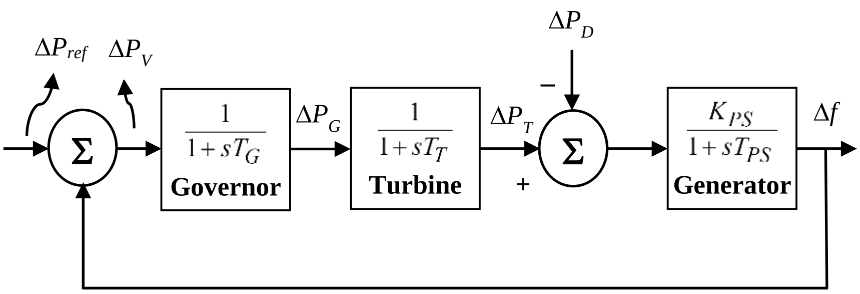

Fig.1. Transfer function model of single area power system of thermal plants

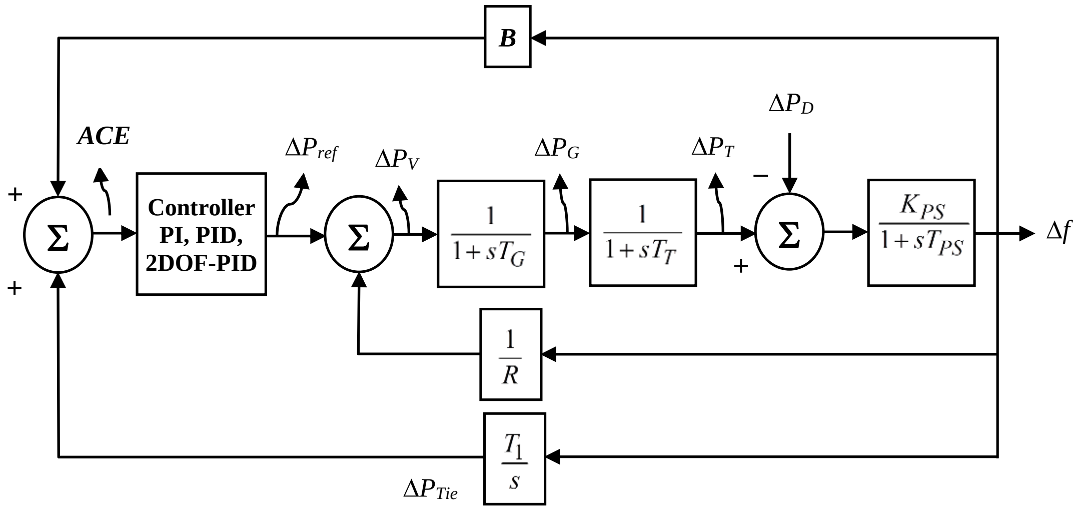

Fig.2. Transfer function model of AGC system of single area power system of thermal power plant

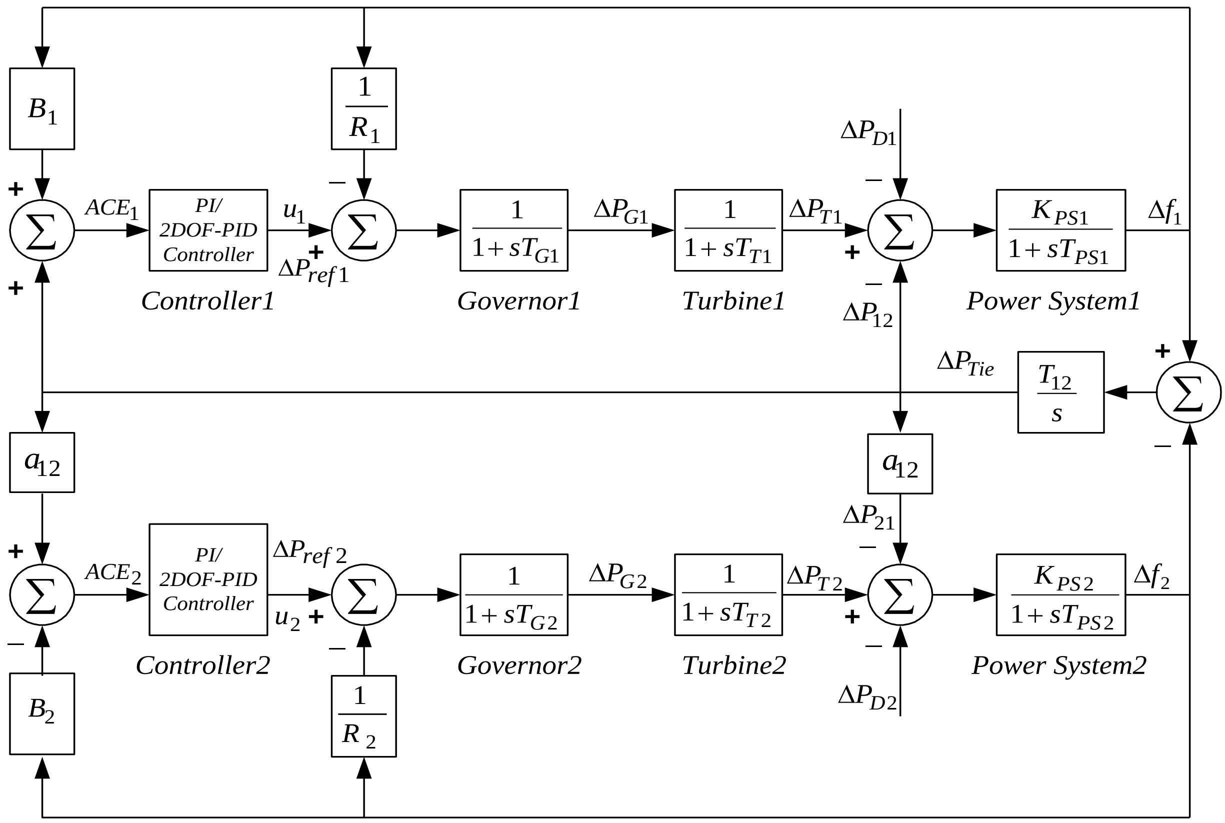

Fig.3. TF model of two area non-reheat thermal power plant

$$G_P(s) = \frac{K_{PS}}{1+sT_{PS}} \tag{4}$$

where, $K_{ps} = 1/D$ and $T_{PS} = 2H/fD$.

There are two inputs $\Delta P_T(s)$ and $\Delta P_D(s)$ to the generator load system with one output $\Delta f(s)$ given by,

$$\Delta f(s) = G_P(s)[\Delta P_T(s) - \Delta P_D(s)]. \tag{5}$$

2.2 STRUCTURE OF AGC FOR SINGLE AREA OF ELECTRIC POWER SYSTEM

The AGC in a single area electric power system is shown in Fig.2. From Fig.2, it is clear that the area control error *ACE* is defined as,

$$ACE = B\Delta f + \Delta P_{Tie}. \tag{6}$$

In Fig.2, the controller may be PI, PID, fuzzy controllers and Two Degree of Freedom PID controller etc. for AGC system.

2.3 TWO AREA INTERCONNECTED POWER SYSTEM OF THERMAL POWER PLANTS

A two area interconnected power system of thermal power plant has been widely used in the literature [10-11, 15, 25-26] for design and analysis of Load Frequency Control in Automatic Generation Control (AGC) and it is shown in Fig.3. This same system is also considered in the proposed work for the comparison of the results obtained by the proposed technique with the results obtained by most recently published techniques in literature. This two area interconnected power system of thermal power plants is obtained by two individual single area power system of thermal power plant connected in parallel fashion as shown in the Fig.3. The abbreviations of parameters and ratings of area and load are defined in Table.1.

Table.1. Abbreviations of parameters and rating of area and load

S. No.	Abbreviation	Parameters/Ratings
1	Rating of each area	2000 MW
2	Nominal Load	1000 MW
3	B_1, B_2	Frequency bias parameters
4	ACE_1, ACE_2	Area control errors
5	u_1, u_2	Control outputs from the controller
6	R_1,R_2	Governor speed regulation parameters in pu Hz
7	T_{G1}, T_{G2}	Speed governor time constants in sec
8	ΔP_{G1}, ΔP_{G2}	Change in governor valve positions (pu)
9	T_{T1}, T_{T2}	Turbine time constant in sec
10	ΔP_{T1}, ΔP_{T2}	Change in turbine output powers
11	ΔP_{D1}, ΔP_{D2}	Load demand changes
12	ΔP_{Tie}	Incremental change in tie-line power (pu)
13	K_{PS1}, K_{PS2}	Power system gains
14	T_{PS1}, T_{PS2}	Power system time constant in sec
15	T_{12}	Synchronizing coefficient in pu
16	Δf_1, Δf_2	System frequency deviations in Hz

From the Fig.3, the area control error for area-1 and area-2 are defined as,

$$ACE_1 = B_1\Delta f_1 + \Delta P_{Tie} \tag{7}$$

$$ACE_2 = B_2\Delta f_2 - \Delta P_{Tie} \tag{8}$$

where, *B* is frequency bias parameter.

3. IDEAL TWO DEGREE OF FREEDOM PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROLLER (2DOF-PID)

The regulatable variable within the process is measured by the degree of freedom of control system [32]. The degree of freedom is also determined by the number of closed-loop transfer functions which can be adjusted independently. So, it is clear that 2DOF controller consists of two closed loop transfer functions due to which it shows its superiority over single degree of freedom controller [30]. The 2DOF controller produces an output signal on the basis of the difference between a reference signal and measured system output. Controller determines a weighted difference signal for each of the proportional, integral and derivative actions according to the specified set point weights. The controller output is the sum of the outputs of proportional, integral and derivative actions on the respective difference signals, where each action is weighted according to the chosen gain parameters [27]. To limit noise or random error in terms of large controller output shifts produced by the derivative action in the measured process variable and to reduce the fluctuations in constant controller output, a derivative filter is used which improves the performance of 2DOF.

The structure of proposed ideal 2DOF-PID controller is shown in Fig.4 and Fig.5.

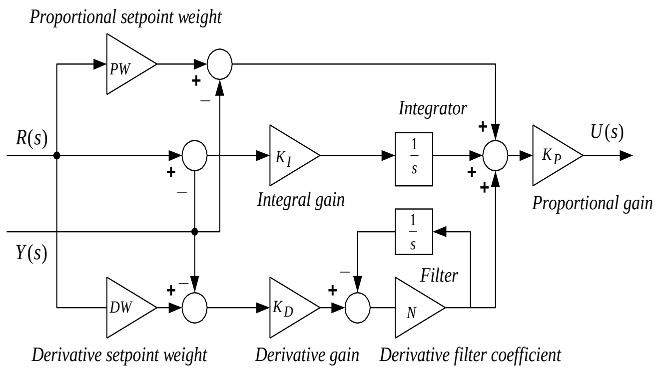

Fig.4. Two degree of freedom (2DOF- PID) control structure

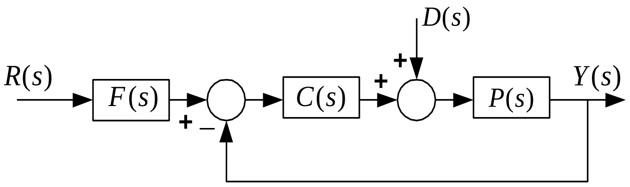

Fig.5. 2DOF control system

In Fig.4,

$R(s)$: Reference Signal
$Y(s)$: Feedback from Measured System Output
$U(s)$: Output Signal
K_P : Proportional Gain
K_I : Integral Gain
K_D : Derivative Gain
PW : Proportional Set Point Weight
DW : Derivative Set Point Weight
N : Derivative Filter Coefficient

For 2DOF-PID control system shown in Fig.5,

$C(s)$: *Signal Degree-of-Freedom Controller*
$D(s)$: *Load Disturbance*

$F(s)$ acts as a pre filter on the reference signal. For an ideal two-degree-of-freedom PID controller, $C(s)$ and $F(s)$ are given by,

$$F(s)=\frac{\left(PW+DWK_D\right)s^2+\left(PWN+K_I\right)s+K_I N}{\left(1+K_D N\right)s^2+\left(N+K_I\right)s+K_I N} \tag{9}$$

$$C(s)=K_P\,\frac{\left(1+K_D N\right)s^2+\left(N+K_I\right)s+K_I N}{s\left(s+N\right)} \tag{10}$$

4. OBJECTIVE FUNCTION

An Integral of time multiplied absolute error (ITAE) is used as an objective function in the present work to design the proposed controllers and it is defined by Eq.(11). Though other integral based objective factions may be used but the main reason of choosing ITAE as objective function for proposed controller design is that it gives less overshoot and settling time as compared to other criterion such as Integral Square Error (ISE) and Integral Absolute Error (IAE). The other integral squared criteria such as Integral of Time multiplied Squared Error (ITSE) and Integral of Squared Time multiplied Error (ISTE) have also not been used in proposed scheme because controller design based on these objective functions produces huge controller output when there is a sudden variation in reference, which is not desirable.

$$J=ITAE=\int_0^{t_{sim}}\omega_1\cdot\left(\left|\Delta f_1\right|+\left|\Delta f_2\right|+\left|\Delta P_{tie}\right|\right)\cdot t\cdot dt \tag{11}$$

where, Δf_1, Δf_2 represent system frequency deviations; ΔP_{tie} is incremental change in tie-line power and t_{sim} denotes time range of simulation.

The controller parameter bounds are the problem constraints. Therefore, the design problem can be formulated as the following optimization problem.

Subject to,

$$\begin{aligned} K_{P\min} &\le K_P \le K_{P\max}\\ K_{I\min} &\le K_I \le K_{I\max}\\ K_{D\min} &\le K_D \le K_{D\max} \end{aligned} \tag{12}$$

$$\begin{aligned} PW_{\min} &\le PW \le PW_{\max}\\ DW_{\min} &\le DW \le DW_{\max}\\ N_{\min} &\le N \le N_{\max} \end{aligned} \tag{13}$$

The parameters in Eq.(12) and Eq.(13) are tabulated in Table.2.

Table.2. List of Parameters and their Ranges

Parameters	**Description**	**Value**
$K_{P\min}$	Minimum value of proportional gain (controller parameter)	-2
$K_{P\max}$	Maximum value of proportional gain (controller parameter)	2
$K_{I\min}$	Minimum value of integral gain (controller parameter)	-2
$K_{I\max}$	Maximum value of integral gain (controller parameter)	2
$K_{D\min}$	Minimum value of derivative gain (controller parameter)	-2
$K_{D\max}$	Maximum value of derivative gain (controller parameter)	2
$PW_{\min}$	Minimum value of proportional set point weight	0
$DW_{\min}$	Minimum value of derivative set point weight	0
$PW_{\max}$	Maximum value of proportional set point weight	5
$DW_{\max}$	Maximum value of derivative set point weight	5
$N_{\min}$	Minimum value of derivative filter coefficient	10
$N_{\max}$	Maximum value of derivative filter coefficient	300

5. OVERVIEW OF GREY WOLF OPTIMIZATION

5.1 SOCIAL HIERARCHY

The Grey Wolf Optimization (GWO) algorithm is recently proposed bio inspired heuristic algorithm which was introduced in 2014 [28]. This algorithm is inspired by both the social hierarchy of wolves, as well as their hunting behavior. The search starts by a population of randomly generated wolves (solutions) in GWO. During hunting (optimization) process, these wolves estimate the prey's (optimum) location through an iterative procedure. Similar to the social hierarchy of grey wolves, there are four groups defined in GWO algorithm namely Alpha (α), Beta (β), Delta (δ), and Omega (ω) as shown in the Fig.6. During the designing stage, the social hierarchy of wolves is modeled. Alpha is the fittest solution followed by Beta and Delta as the second and third best solutions. The rest of the solutions are least important and considered as Omega. The functions of each group are given in the Fig.6.

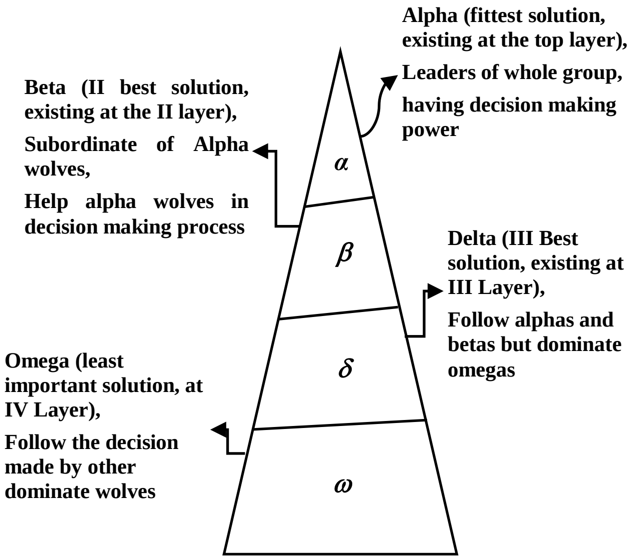

Fig.6. Social hierarchy of Grey Wolf Optimization and functions of each group

The hunting behavior is mainly divided into three steps:

a) Tracking, chasing and approaching the prey.
b) Encircling and harassing the prey until it stops moving.
c) Attacking the prey.

5.2 MATHEMATICAL REPRESENTATION OF GWO

GWO algorithm can be mathematically expressed as follows:

5.2.1 Encircling Prey:

The encircling behavior of grey wolves around the prey is expressed by the following equations as,

$$\vec{D} = \left|\vec{C}.\vec{X}_P(t) - \vec{X}(t)\right| \tag{14}$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}.\vec{D} \tag{15}$$

where, t represents the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_P$ denotes the position vector of the prey and $\vec{X}$ is the position vector of wolf. The coefficient vectors are calculated as,

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{16}$$

$$\vec{C} = 2.\vec{r}_2 \tag{17}$$

where, $\vec{r}_1$ and $\vec{r}_2$ are random vectors lie in the range 1 to 0 and vector $\vec{a}$ is linearly decreased during iterations from 2 to 0.

5.2.2 Hunting:

Though the hunting phase is guided by the best wolves, i.e. alpha wolves but beta and delta wolves also participate in hunting phase. The optimum position are obtained by saving three best positions corresponding to alpha, beta and delta wolves and remaining solutions including omega are competed. The updated wolf positions around the prey are determined by,

$$\begin{aligned}\vec{D}_\alpha &= \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right| \\ \vec{D}_\beta &= \left|\vec{C}_2.\vec{X}_\beta - \vec{X}\right| \\ \vec{D}_\delta &= \left|\vec{C}_3.\vec{X}_\delta - \vec{X}\right|\end{aligned} \tag{18}$$

$$\begin{aligned}\vec{X}_1 &= \vec{X}_\alpha - \vec{A}_1.\left(\vec{D}_\alpha\right) \\ \vec{X}_2 &= \vec{X}_\beta - \vec{A}_2.\left(\vec{D}_\beta\right) \\ \vec{X}_3 &= \vec{X}_\delta - \vec{A}_3.\left(\vec{D}_\delta\right)\end{aligned} \tag{19}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{20}$$

5.2.3 Attacking Prey:

This phase enables the algorithm to exploit the search process. The grey wolves end the hunt by attacking the prey when it stops moving. This process is mathematically expressed by decreasing $\vec{a}$ which also decreases the variations in $\vec{A}$. So initially, $\vec{A}$ is a random value in the interval [-a, a] and over the course of iterations a is decreased from 2 to 0. When $|A| < 1$, wolves move towards the prey for attacking.

5.2.4 Searching the Prey:

This phase enables the algorithm to explore the search process. Grey wolves search on the basis the position of the alpha, beta, and delta wolves. The wolves move away from each other to search for the prey and come together to attack the prey. When the values of $\vec{A}$ is outside the range from -1 to 1, the wolves diverge from the prey which incorporates the exploration capability in GWO algorithm. When $|A| > 1$, wolves move away from the prey to search for a better prey. The component $\vec{C}$ also assists in exploration process. This component which lies in the range from 0 to 2, assigns random weights for prey to define the distance. After each iteration, the GWO algorithm allows its search agents to update their position based on the location of α, β, δ and attack towards the prey.

Before starting the main objective of any meta-heuristic population based algorithm; two basic parameters are required to be initialized. The first and foremost parameter is the "maximum number of search agents" or "grey wolfs". The number of search agents may vary according to the application. In the proposed application, this value is taken as 20. The second important parameter is the "number of iterations". This also depends upon the type of application and varies in a broad range. The less the number of iterations, small will be the evaluation time. In the proposed work, this value is taken as 50. The pseudo codes for

GWO are given in Appendix B. The flow chart for GWO algorithm is shown in Fig.7 [28].

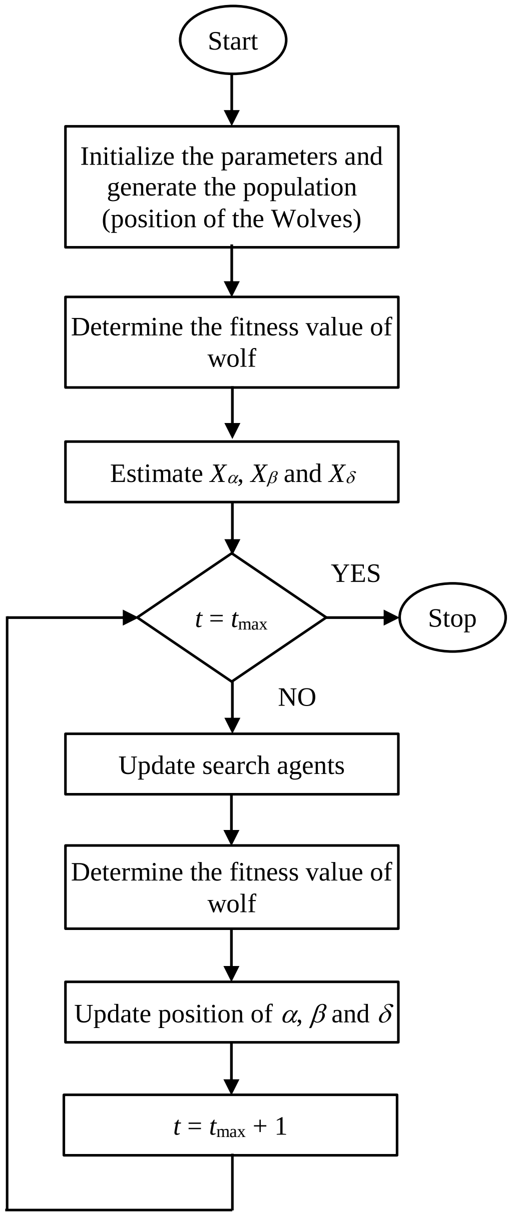

Fig.7. Flow chart of Grey Wolf Optimization

6. PATTERN SEARCH ALGORITHM

The complex problem which cannot be solved by conventional optimization techniques, are easily solved by pattern search algorithm which is effective and simple in nature. A flexible operator is used in PS algorithm to tune the local explore capability finely [26]. The PS method uses a series of polls x_k, $k \in N$. To get trial points $x_k^i = x_k + s_k^i$ at each poll, a number of trial steps s_k^i with $i = 1, 2, \ldots p$ are added to the polls x_k. The objective function value is calculated at these trial points through a sequence of exploratory steps and compared with its previous value $J(x_k)$. The trial step s_k^* corresponds to least value of $J(x_k + s_k^i) - J(x_k) < 0$ and it is then selected to produce the subsequent estimation of the patterns polls $x_{k+1} = x_k + s_k^*$. The trial steps s_k^i are produced by a step length parameter $\Delta_k \in R_+^n$. The Δ_k value is updated in subsequent polls as per x_{k+1} value. The improvement of Δk helps the algorithm to converge. These elements are explained in more details in [29].

7. HYBRID GREY WOLF OPTIMIZATION AND PATTERN SEARCH (*h*GWO-PS) ALGORITHM FOR PRESENT WORK

To improve the performance of the frequency controller in AGC of electric power system of non-reheat thermal plants, hybrid algorithms have been recently proposed in literature because it combines the advantage of two or more algorithms. In the present work, Grey wolf optimization and pattern search technique have been combined to make a hybrid technique, namely, hybrid grey wolf optimization pattern search algorithm (*h*GWO-PS) for two area power system of thermal plant. The flow chart of *h*GWO-PS is shown in Fig.8. To develop the transfer function model of proposed system, MATLAB/SIMULINK environment is used and the MATLAB program (.m file) for GWO is written. The controllers with similar characteristics are considered for each area as the two areas are assumed to be identical. A 10% step load change in area-1 is considered in order to simulate the proposed model. The objective function (ITAE) is calculated and used in the optimization algorithm. A series of runs are executed to select the algorithm parameters properly. Number of search agents and iterations are taken as 20 and 50, respectively. The optimization was repeated 10 times and the best final solution among the 10 runs is chosen as proposed controller parameters. In the next step, the proposed *h*GWO-PS algorithm is applied to optimize the controller parameters. In *h*GWO-PS algorithm, initially optimal GWO is applied for 40 iterations and then PS is applied for 10 iterations. The best set of values corresponding to the minimum objective function value provided by optimal GWO has been used as the beginning points of PS algorithm. The parameters used for the implementation of PS algorithm, are as follows:

Mesh size	: 1
Mesh Expansion Factor	: 2
Mesh Contraction Factor	: 0.5
Maximum number of function estimation	: 10
Maximum number of iterations	: 10

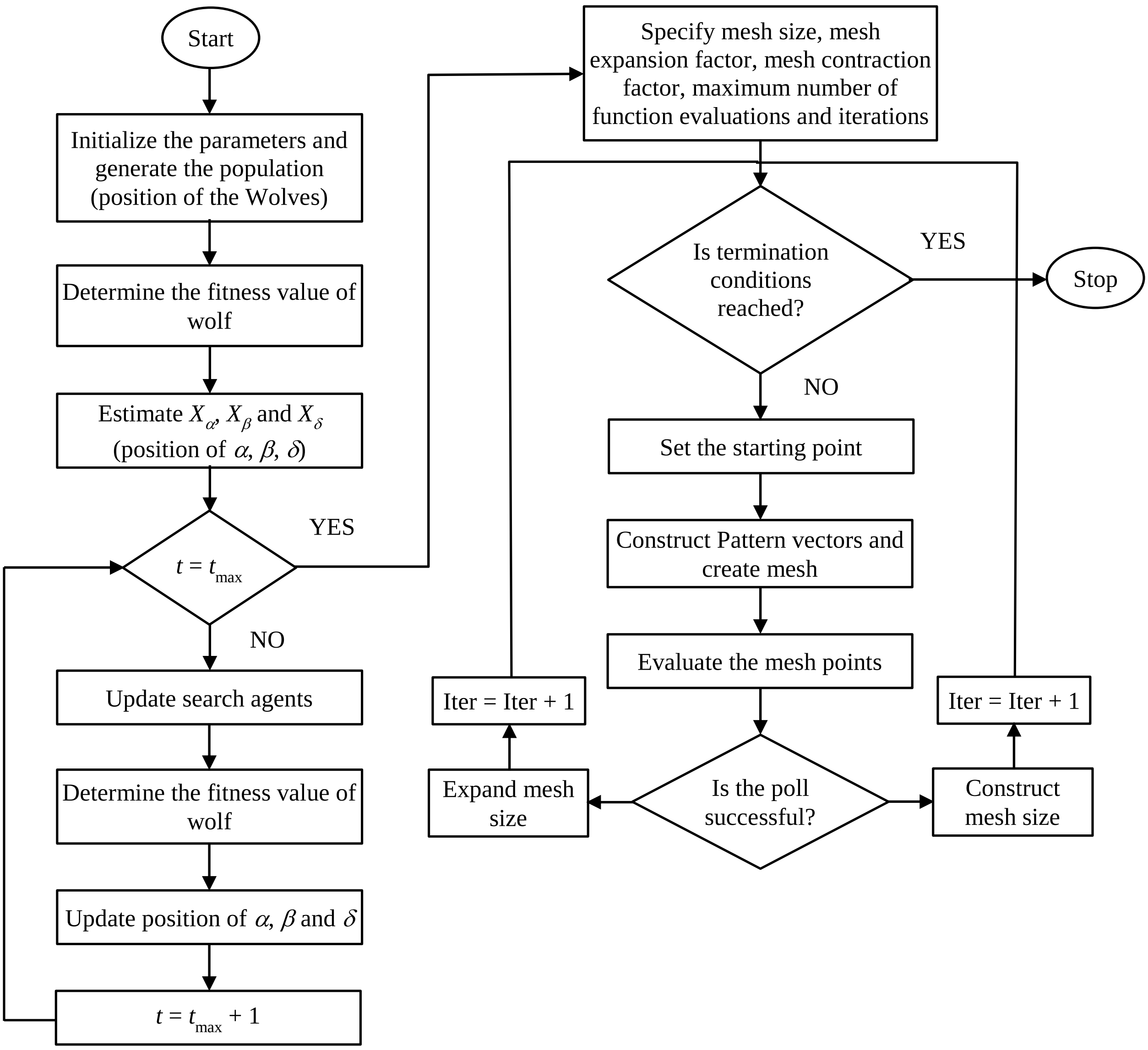

Fig.8. Flow chart of hybrid grey wolf optimization and pattern search technique

The optimized 2DOF-PID controller parameters have been given in Table.3. For comparison, the optimized PI controller parameters are also given in Table.3.

Table.3. Tuned controller parameters

Technique: Controller	**Controller parameters**
GWO: PI	K_P = -0.3058, K_I = 0.4656
hGWO-PS	K_P = -0.3121, K_I = 0.4584
GWO: 2DOF-PID	K_P =1.9996, K_I = 1.4433, K_D = 1.4956, PW = 9.5076, DW = 0.2101, N = 432.1273
hGWO-PS: 2DOF-PID	K_P = 1.9996, K_I = 1.4433, K_D = 1.3706, PW = 9.5076, DW = 0.0851, N = 433.1273

8. SIMULATION RESULTS

The simulation has been carried out for 2DOF-PID controller optimized by proposed technique (*h*GWO-PS) and the results have also been compared with that of the PI controller optimized by PSO Fuzzy [26] and hybrid PSO-Fuzzy [26] on the basis of ITAE value and system dynamic response. The sensitivity analysis of the controller optimized by proposed technique has also been given to evaluate its robustness. The simulation results show that the 2DOF-PID controller optimized by *h*GWO-PS technique is far better than the controller optimized by recently published approaches in the literature [26].

8.1 COMPARISON OF ITAE VALUE

At t = 0 second, a 10% step load increase in area-1 is considered and the ITAE value for both PI and 2DOF-PID controllers optimized by GWO and *h*GWO-PS algorithm are shown in Table.4. The effectiveness of proposed method for optimizing controller parameters can be seen when it is compared with some recently published modern heuristic optimization methods such as PSO optimized Fuzzy PI [26] and hybrid PSO-PS [26] optimized fuzzy PI controllers for the same interconnected power system.

The Table.4 shows that using same type of PI controller, same objective function (ITAE) and same type of system, significant minimum ITAE value is obtained with proposed *h*GWO-PS optimized 2DOF-PID controller (ITAE = 0.112) as compared to other existing optimization methods. Therefore, from Table.4, it can be concluded that 2DOF-PID controller optimized by proposed *h*GWO-PS outperforms 2DOF-PID controller optimized by GWO and fuzzy PI controller optimized by PSO [26] and fuzzy PI controller optimized by Hybrid PSO-PS [26].

8.2 COMPARISON OF SYSTEM DYNAMIC RESPONSE

The study of the time domain simulations have been elaborated for step load change at different locations.

Case 1: At time t = 0 second, a step increase in demand of 10% is applied in the area-1

The dynamic responses of 2DOF-PID controller optimized by proposed *h*GWO-PS algorithm are shown in Fig.9 to Fig.11. The assessment of dynamic response of power plant (considered in the present work) consisting of proposed *h*GWO-PS optimized controllers has been done by comparing it with the dynamic response of same power plant consisting of PI controller optimized by recently published approaches namely, PSO fuzzy PI [27] and *h*PSO-PS fuzzy PI [26]. These comparisons are shown in Fig.12 to Fig.14. The comparative study shows that the significant improvement in the dynamic response (Fig.12 to Fig.14) is observed with proposed *h*GWO-PS optimized 2DOF-PID controller as compared to other approaches reported in the literature. For a better illustration of proposed approach over some recently published approaches, the performance index in terms of ITAE values and settling times in frequency and tie-line power deviations for the above disturbance is also summarized in Table.5, which shows that best system performance in terms of minimum ITAE values and settling times are obtained with proposed 2DOF-PID controller optimized by *h*GWO-PS as compared to other recent approaches.

Table.4. ITAE values with different controllers and optimization techniques

Controller	Tuning method/ Optimization technique	ITAE Value
PI	Hybrid Grey Wolf Optimization - Pattern Search	1.1761
PI	Grey Wolf Optimization (GWO)	1.1766
2DOF-PID	Hybrid Grey Wolf Optimization - Pattern Search	0.112
2DOF-PID	Grey Wolf Optimization (GWO)	0.1349
Fuzzy PI	Particle Swarm Optimization (PSO) [26]	0.4470
Fuzzy PI	Hybrid PSO-PS [26]	0.1438

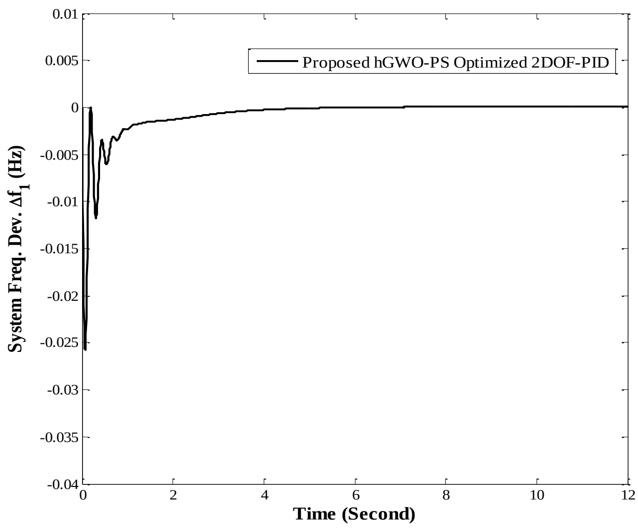

Fig.9. Change in frequency of area-1 for 10% step load increase in area-1

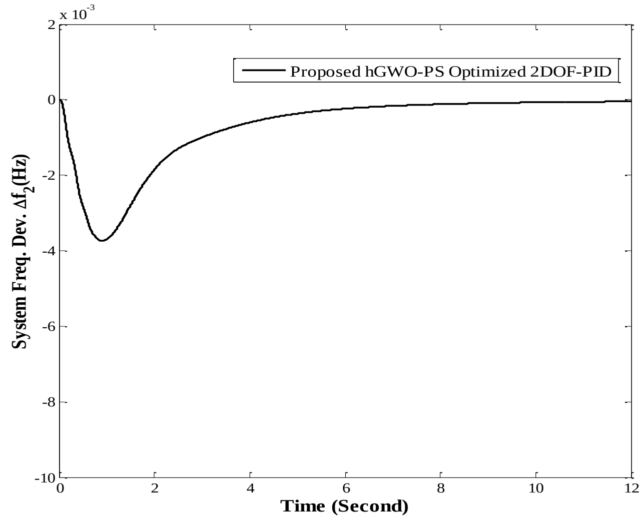

Fig.10. Change in frequency of area-2 for 10% step load increase in area-1

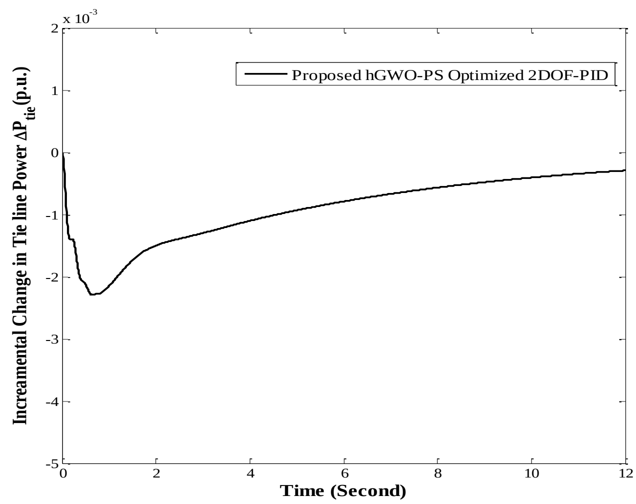

Fig.11. Change in tie line power for 10% step load increase in area-1

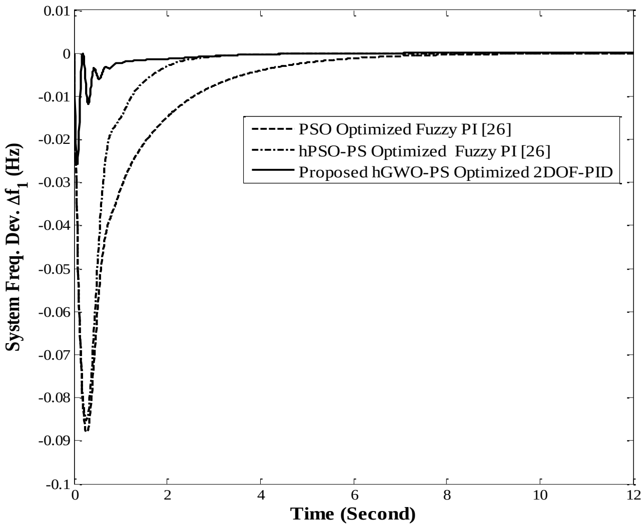

Fig.12. Change in frequency of area-1 for 10% step load increase in area-1

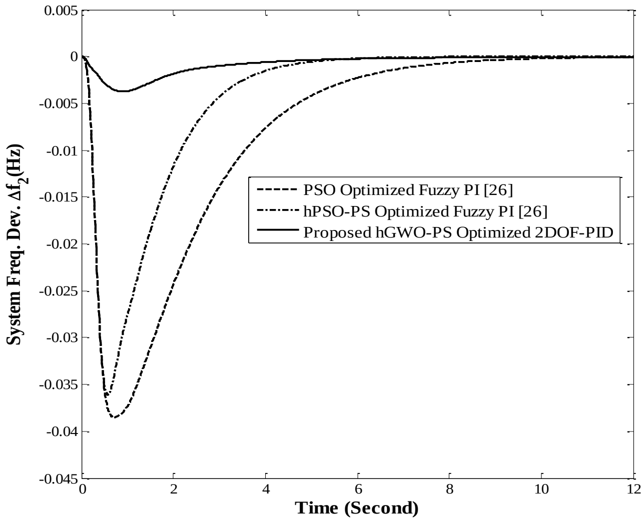

Fig.13. Change in frequency of area-2 for 10% step load increase in area-1

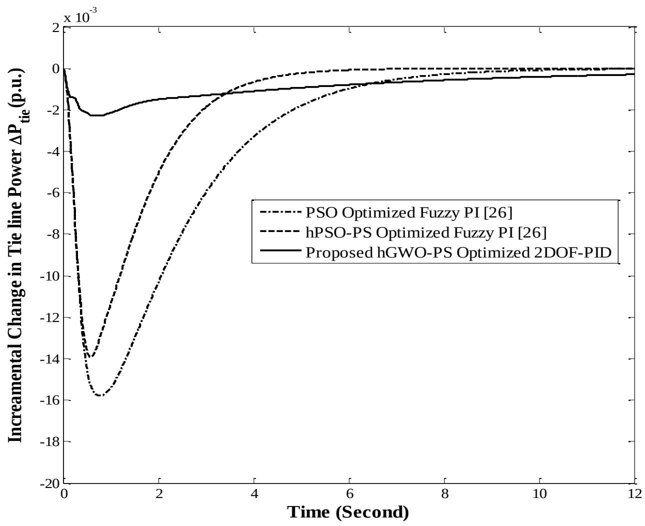

Fig.14. Change in tie line power for 10% step load increase in area-1

Table.5. Performance comparison with recent AGC approaches

Performance/Technique: Control Structure	ITAE value	Settling times (2% band) T_s (Sec)		
		Δf_1	Δf_2	ΔP_{tie}
PSO: Fuzzy PI [26]	0.4470	5.13	6.22	4.83
hPSO-PS: Fuzzy PI [26]	0.1438	2.26	3.74	2.94
Proposed hGWO-PS: 2DOF-PID	0.112	1.45	2.5	1.56

Case 2: The system dynamic response for a simultaneous step increase in load of 10% in area-1 and 20% in area-2 at t = 0 second.

The dynamic responses for the above disturbances are shown in Fig.15 to Fig.17 and the comparison with other techniques in literature, are shown in Fig.18 to Fig.20. The simulation results shown in Fig.18 to Fig.20 show that the controller optimized by the proposed method performs satisfactorily when the location and size of the disturbance changes and results also demonstrate the fact that in all the cases, an improved dynamic performance is observed with proposed *h*GWO-PS optimized 2DOF-PID controller as compared to other recently published approaches.

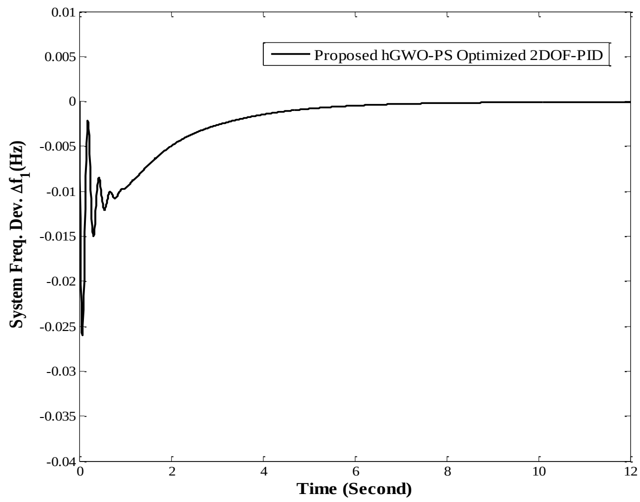

Fig.15. Change in frequency of area-1 for 10% step load increase in area-1 and 20% step load

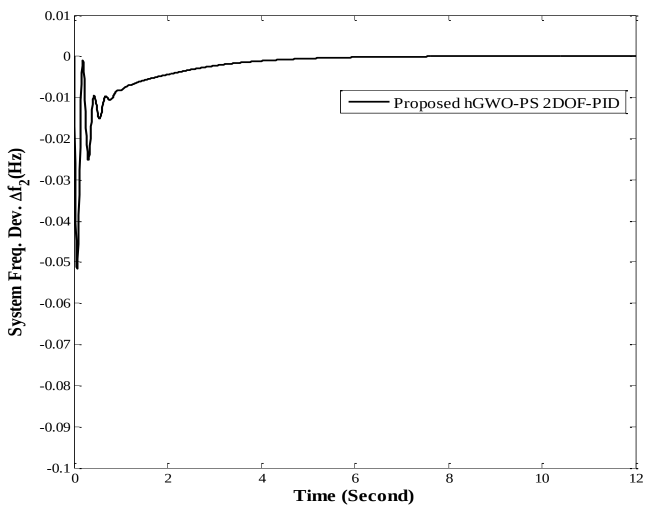

Fig.16 Change in frequency of area-2 for 10% step load increase in area-1 and 20% step load increase in area-2

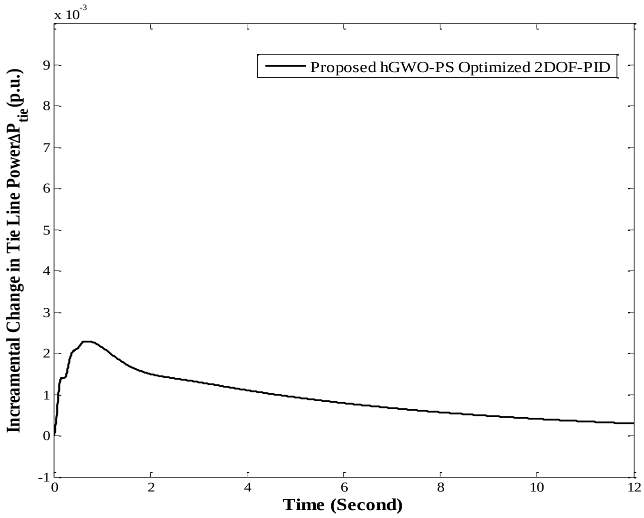

Fig.17 Change in tie line power for 10% step load increase in area-1 and 20% step load increase in area-2

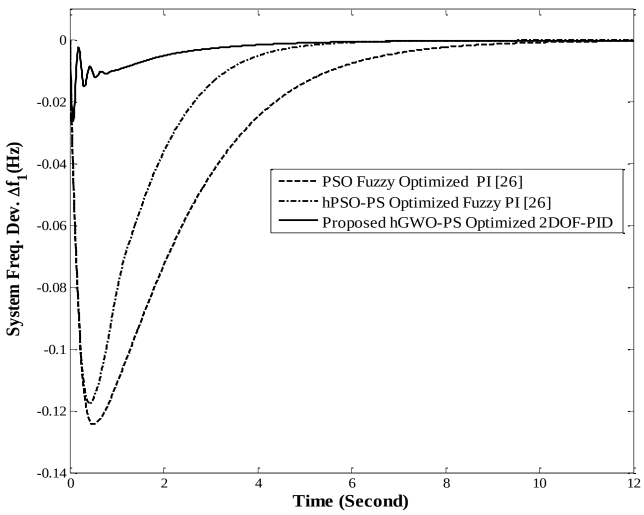

Fig.18. Change in frequency of area-1 for 10% step load increase in area-1 and 20% step load increase in area-2

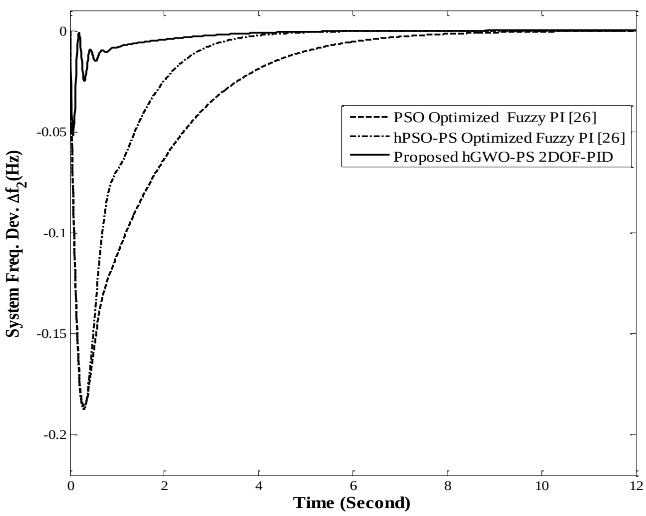

Fig.19. Change in frequency of area-2 for 10% step load increase in area-1 and 20% step load increase in area-2

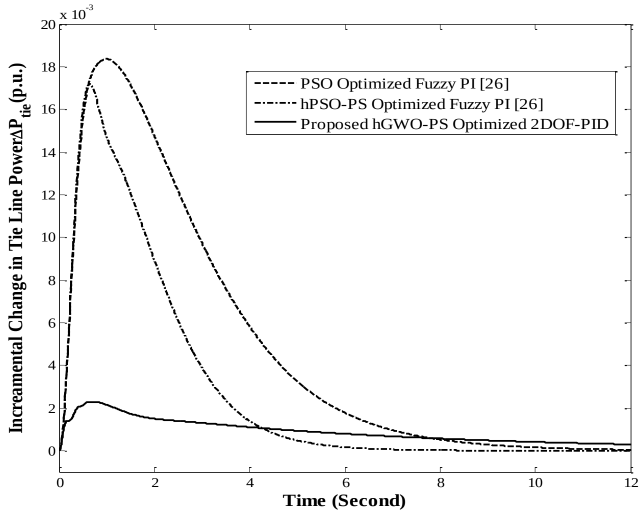

Fig.20. Change in tie line power for 10% step load increase in area-1 and 20% step load increase in area-2

Table.6. Sensitivity analysis for two area two unit system

Parameter variation	% Change	Performance index with Proposed *h*GWO-PS optimized 2DOF-PID			
		Settling time T_s(Sec)			ITAE value
		Δf_1	Δf_2	ΔP_{tie}	
Nominal Loading condition	0	1.45	2.5	1.56	0.112
	+50	1.45	2.51	1.56	0.112
	+25	1.45	2.51	1.56	0.112
	-25	1.45	2.51	1.56	0.112
	-50	1.48	2.53	1.58	0.112
T_g	+50	1.77	2.53	1.59	0.1109
	+25	1.58	2.5	1.56	0.1114
	-25	1.48	2.54	1.58	0.1126
	-50	1.51	2.57	1.61	0.1132
T_t	+50	1.08	2.33	1.53	0.1075
	+25	1.3	2.42	1.55	0.1097
	-25	1.62	2.62	1.6	0.1142
	-50	1.8	2.74	1.65	0.1165
T_{12}	+50	1.4	2.27	1.46	0.1025
	+25	1.42	2.39	1.54	0.1062
	-25	1.62	2.65	1.54	0.1216
	-50	1.86	2.71	1.54	0.1403

8.3 STUDY OF ROBUSTNESS OF THE SYSTEM

In order to study the robustness of the system for the wide changes in the operating conditions and system parameters, the sensitivity analysis has also been examined in the proposed work by assuming a 10% step increase in load demand in area-1 at t = 0 second. Taking one at a time, the operating load condition and time constants of speed governor, turbine and tie-line power are changed from their nominal values in the range of +50% to -50% in steps of 25%. The ITAE values and settling times under above varied system conditions are given in Table.6. It is clear from Table.6 that the system performances hardly change when the operating load condition and system parameters are changed by ±50% from their nominal values. So, it can be concluded that, the proposed *h*GWO-PS control strategy provides a robust and stable control as compared to approach in [26] and the controller parameters obtained at the nominal loading conditions with nominal parameters, need not to be reset for wide changes in the system loading or system parameters.

9. CONCLUSIONS

A new hybrid Grey Wolf Optimization and Pattern Search (*h*GWO-PS) approach has been proposed to optimize the parameters of parallel Two Degree of Freedom of Proportional-Integral-Derivative (2DOF-PID) controller for controlling the load frequency (LFC) in Automatic Generation Control (AGC) of two area interconnected power system of non-reheat thermal power plants. MATLAB/SIMULINK environment is used to simulate the results. The simulation results obtained by proposed technique (*h*GWO-PS) have also been compared with the results obtained by PSO optimized fuzzy PI controller and hybrid PSO-PS optimized fuzzy PI controller. The simulation results demonstrate that using the same PI controller, same objective function and same test system, the proposed *h*GWO-PS optimized controller and performance analysis of aforementioned system using this optimized controller show the superiority over the other existing techniques available in the literature, since minimum value of ITAE is obtained for proposed technique as compared to other reported techniques. The dynamic response of the aforementioned standard test system has been studied for step load change at different locations and the simulation results show that the proposed 2DOF-PID controller optimized by *h*GWO-PS achieves better dynamic performance when compared with recently reported approaches. Moreover, the robustness of the system consisting of *h*GWO-PS optimized 2DOF-PID controller using sensitivity analysis is also estimated by varying the system parameters and operating load conditions from their nominal values. Further, it can also be concluded that the proposed *h*GWO-PS optimized 2DOF-PID controller provides the quite robust thermal power system for a wide range of the system parameters and operating load conditions from their nominal values.

APPENDIX A

Nominal parameters of the two area thermal power system are shown in Table.7 [15, 18, 26, 27, 31].

Table.7. Nominal parameters of the two area thermal power system

Nominal parameters	**Value**
P_R	2000MW (rating)
P_L	1000MW (nominal loading)
F	60Hz
B_1, B_2	0.425 pu MW/Hz
$R_1 = R_2$	2.4Hz/pu Hz/pu
$T_{G1} = T_{G2}$	0.08sec
$T_{T1} = T_{T2}$	0.3sec
$K_{PS1} = K_{PS2}$	120Hz/pu MW
T_{12}	0.545 pu

APPENDIX B

The pseudo code of GWO algorithm is given below,

Initialize the algorithm parameters and generate the initial populations (positions of the wolves or agents)
Determine the fitness of each agent
Estimate X_α, X_β and X_δ, the position of α, β and δ wolves (the three best search agents)
while(t<Max number of iterations)
  for each search agent
    Update the position of current search agents
  end for
  Update search agents
  Calculate the fitness of all search agents
  Update the position of α, β and δ wolves
  Increase the iteration count
end while
Display the best wolves X_α

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