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Robust Generation Control Strategy Based on Grey Wolf Optimizer

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This paper presents an application of Grey Wolf Optimizer (GWO) technique to estimate the parameters of the Proportional Integral Controller (PI) for Automatic Generation Control of two area power system. In this work two thermal units with non reheat turbines are considered. The detailed eigenvalue analysis is carried out for exhibiting the philosophy of damping requirement in the complex networks. The parameters namely proportional integral gain, speed regulation, frequency sensitivity coefficient are considered as the modifiable parameters. These parameters are estimated through optimization process with the aim to minimize the Area Control Error (ACE). The comparison between two objective functions namely Integral Square Error (ISE) and Integral Time Absolute Error (ITAE) is presented. Sensitivity analysis advocates the effectiveness of the proposed approach. To draw a fair comparison between the proposed method and the conventional methods (GSA, PSO and GA) convergence characteristics of the optimization techniques are compared and presented. It is observed that the proposed design satisfactorily handle different contingencies and operating conditions.

Keywords: Automatic generation control (AGC); Area Control Error (ACE); Integral square error (ISE); Proportional Integral (PI) Controller; Grey wolf optimizer (GWO).

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1. INTRODUCTION

Modern power system is a complex network. The complexity of the system is increasing with every passing day due to stressed conditions of the grid and ongoing addition of the utilities in generation, transmission and distribution side. The allocation of high distributed generating units present a potential threat to the power network. The philosophy of automatic generation control is to uphold a fair balance between the generation and demand. However, the dynamic operating conditions with multiple contingencies make the system vulnerable for oscillatory instability. With the growth of extensive power system and especially due to multiple interconnections of utilities the tie line of limited capacity causes heavy fluctuation in system frequency [1]. AGC has two objectives mainly:

1. To maintain the system frequency in nominal range i.e. 50 Hz or 60 Hz
2. To maintain tie line power flow in an acceptable range.

IEEE defines automatic generation control (AGC) as "the regulation of the power output of electric generators with in a prescribed area in response to changes in system frequency, tie-line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or the establish interchange with other areas within predetermined limits"[2].

A critical literature review presented in [3] on the AGC of power systems. In this paper various control aspects concerning the AGC problem have been studied. Authors also

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discussed the various AGC schemes, AGC strategies and AGC systems incorporating with BES/SMES, wind turbines, fact devices PV systems. Many researchers have come forward with the application of expert systems to obtained self tuning of the AGC regulators. The crticial issue is to obtain the modelling of an interconnected power system near any operating equilibrium [4-5]. S. Padhan *et.al.* [6] presented a coordinated scheme for fuzzy PID and TCSC device to improve the system damping performance. However, the response obtained under different perturbation exhibited the oscillatory characteristics. The computational burden and time elapsed during learning process is the problem associated with Neural Networks. In past many approaches based on genetic algorithm [7], bacterial foraging [8], differential evolution [9], particle swarm optimization [10], cuckoo search [11], gravitational search algorithm [12] have been applied by the researchers to design the AGC regulators. In[8] Nanda et.al. implementation of the bacterial foraging technique with integral controller was done and the resulting performance was better as compared to classical and GA. Recently Umesh kumar rout *et al.* [9] presented an application of Differential Evolution (DE) to estimate the integral controller parameters. In this work authors employed three objective functions to estimate the parameters of the governor loop. The formation of objective function is based on the frequency and tie line power change observed under the step load disturbance. However, it is empirical to judge that the value of frequency and tie line power deviations varies with the size of perturbations and the effect of this variation can affect the results of optimization process. To overcome this problem, this paper presents a detailed analysis of the indices ISE and ITAE under different size of disturbances.

This paper presents the application of Grey Wolf Optimizer (GWO) to estimate the parameters of primary governor loop for two equal area thermal interconnected units. GWO is a heuristic technique based on the behaviors of wolf packs proposed by Mirjalili et.al. in 2014 [13]. It is a population based algorithm and is mimicked by the leadership hierrarchy and the hunting behaviour of grey wolves [14]. The standard objective functions namely Integral Square Error (ISE) and Integral Time Absolute Error (ITAE) are employed to obtain the K_i (Integral controller gain), governor speed regulation parameter (R) and frequency sensitivity coefficient (D_i) parameters. There are 6 parameters for which optimization process is performed. Further the performance of the proposed GWO Controller is compared with GSA [18], PSO [19] and GA [20] based proportional integral controller. The robustness of proposed approach is verified through eigenvalue analysis of critical swing modes and damping calculations. Numerical simulations are exhibited for different type of perturbations, loading pattern and parametric variations to establish the efficacy of the proposed approach.

Following this introduction the next section of this paper presents the nomenclature. Section third gives the description of model used in simulation for the analysis. Section fourth describes grey wolf optimisation technique. Results and conclusion are given in section 5 and 6 respectively

2. NOMENCLATURE:

i Subscript referred to area i (1,2)

Δf_i Frequency deviation in area i (Hz)

ΔP_{Gi} Incremental generation of area i (p.u.)
ΔP_{Li} Incremental load change in area i (p.u.)
ACE_i Area control error of area i
B_i Frequency bias parameter of area i
R_i Speed regulation of the governor of area i (Hz/p.u.MW)
T_{gi} Time constant of governor of area i (s)
T_{ti} Time constant of turbine of area i (s)
K_{pi} Gain of generator and load of area i
T_{pi} Time constant of generator and load of area i (s)
ΔP_{tie} Incremental change in tie line (p.u.)
T_{12} Synchronizing coefficient
T Simulation time (s)
α Alpha wolf
β Beta wolf
δ Delta wolves
ω Omega wolves
t Current iteration
$\overrightarrow{X_P}$ Position vector of the prey
$\overrightarrow{X}$ Position vector grey wolf

3. SYSTEM MODELING

3.1. AGC Model

The two-area interconnected non reheat thermal power system is shown in the Fig. 1. The main components of the power system consist of speed governor, turbine, generator and load. The operating parameters of the interconnected power system must be assumed to be linear. The inputs of the power system are controller output u, change in load demand ΔP_L, and incremental tie line power ΔP_{tie} and the outputs are frequency deviation Δf and area control area, ACE. The ACE signal is the area control error, which controls the steady state errors of frequency deviation and tie-power deviation. Mathematically ACE can be defined as

$$ACE = B\Delta f + \Delta P_{tie} \quad (1)$$

Where B is the frequency bias parameter.

To model above components of power system the transfer functions (2) – (4) are used. The transfer function of a turbine is:

$$G_t(s) = \frac{1}{1 + sT_t} \quad (2)$$

Governor is represented by the transfer function:

$$G_g(s) = \frac{1}{1 + sT_g} \quad (3)$$

Generator and load is represented by:

$$G_l(s) = \frac{K_p}{1 + sT_p} \tag{4}$$

Where K_p = 1/D and T_p = 2H/ fD

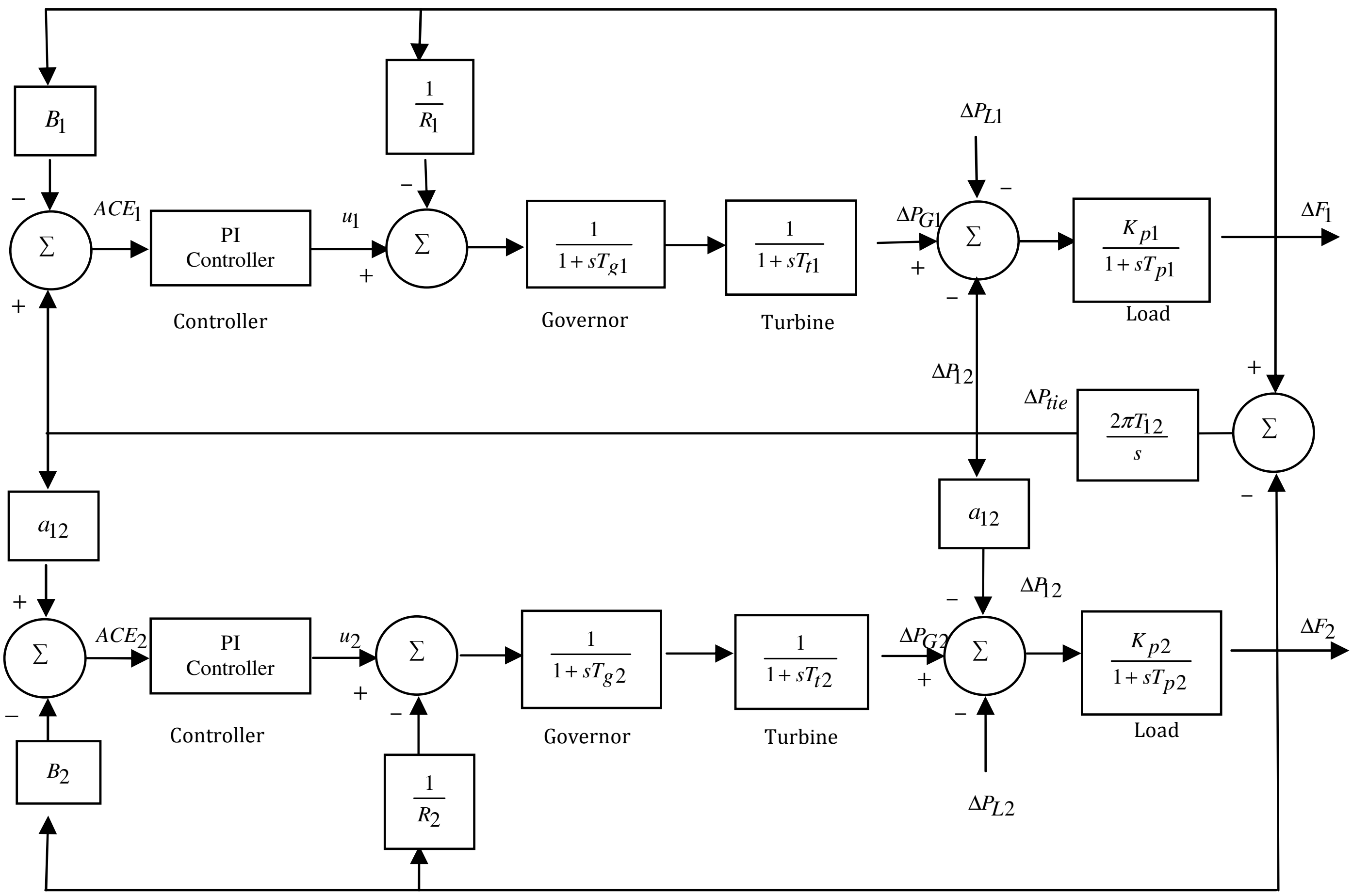

Figure 1 Transfer function model of two area non reheat thermal power system.

3.2. System investigated

Investigations have been carried out on two equal area power system connected by a weak tie line. System consists of two 1000 MVA thermal units. Here u_1, u_2 are the control output from the controller of both the area; B_1 and B_2 are the frequency bias parameter; ACE_1 and ACE_2 are the area control errors; R_1 and R_2 are the speed regulation of the governor; T_{g1} and T_{g2} are the governor time constants in seconds; T_{t1} and T_{t2} are the turbine time constant in seconds; ΔP_{L1} and ΔP_{L2} are the changes in load demand; K_{p1} and K_{p2} are the generator and load gain; T_{p1} and T_{p2} are the time constants of generator and load; ΔP_{tie} is the incremental change in tie line power; T_{12} is the synchronizing coefficient of area 1-2; Δf_1 and Δf_2 are the change in frequency deviation in Hz. The parameters for simulations are taken from [5]. The proposed method is implemented using MATLAB 2013 and run on a Pentium IV CPU, 2.69 GHz, and 1.84 GB RAM computer [21].

Two criteria ISE and ITAE are used for the analysis of the AGC regulator.

$$J_1 = ITAE = \int_0^T (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|) \cdot t dt \quad (5)$$

$$J_2 = ISE = \int_0^T (|\Delta f_1|^2 + |\Delta f_2|^2 + |\Delta P_{tie}|^2) dt \quad (6)$$

The problematic constraints are the parameters of AGC regulator which contains proportional integral gains, speed regulations and the frequency sensitivity coefficients as they are bounded with the limits. Hence the design problem can be formulated as

Minimize J
Subjected to

$$K_{P_{\min}} \le K_P \le K_{P_{\max}}, \qquad K_{I_{\min}} \le K_I \le K_{I_{\max}} \quad (7)$$

$$R_{\min} \le R \le R_{\max} \quad (8)$$

$$D_{\min} \le D \le D_{\max} \quad (9)$$

J is the objective function (J_1 and J_2).

4. GREY WOLF OPTIMIZER

A recent population based swarm intelligence technique, called grey wolf optimizer inspired by the nature of grey wolf is discussed here. This technique was proposed by Mirjalili et.al. [13] in 2014. In GWO the leadership hierarchy and the hunting behavior of grey wolf is mimicked. GWO overcomes the possibility of local optimal solutions and has greater exploration and share information about the search space. Grey wolves are basically categorized into four groups namely alpha, beta, delta and omega for the simulation of leadership hierarchy. The three important steps of hunting, searching for prey, encircling the prey, and attacking towards prey are employed to carry out the optimization.

Alphas are the leaders of the pack. Alpha are decision makers regarding hunting, sleeping place and time to wake up etc and that decision will be followed by the pack. Hence, alpha wolf is also known as dominant wolf. Alpha is not essentially the strongest member in the pack but good in organization and discipline of the pack.

Beta comes in the second level on the hierarchy of grey wolves. Betas help alpha wolves in decision making and the activities of the pack. Betas are the best candidate to get the position of alpha in case of alpha wolves passes away or becomes very old. The beta supports alpha's command throughout the pack.

Omega wolves have the lowest ranking in the pack. They always have to surrender to all other dominant wolves. Omega is not a main member but everyone faces the fighting and problems in case of losing omega.

If a wolf is not coming in the above specified levels then he/she is delta wolves. Delta wolves have to submit alpha and beta but they dominate omega. Scouts, elders, hunters, sentinel and care takers belong to this group. According to Muro et.al. [14] below are the main stages of grey wolf hunting.

- Tracking, chasing and approaching the prey
- Pursuing, encircling and harassing the prey
- Attack towards the prey

In the mathematical modeling of social hierarchy of wolf, alpha (α) is considered as the fittest solution, beta (β) and delta (δ) are the second and the third best fittest solutions respectively in designing of GWO. The rest of the candidates solutions are considered as omega (ω). The hunting is guided by α, β and δ. The ω wolves follow α, β and δ wolves.

a. Encircling the prey

For the modeling of encircling the prey following equations are proposed.

$$\vec{D} = \left| \vec{C}.\vec{X}_P(t) - \vec{X}(t) \right| \quad (10)$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}.\vec{D} \quad (11)$$

Where t represents current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X_P}$ is the position vector of the prey and $\vec{X}$ is the position vector of grey wolf.

The vectors $\vec{A}$ and $\vec{C}$ can be calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r_1} - \vec{a} \quad (12)$$

$$\vec{C} = 2.\vec{r_2} \quad (13)$$

The components of $\vec{a}$ are decreased linearly from 2 to 0 over the course of iterations and r_1, r_2 are random vectors in [0,1].

a. Hunting for the prey

During hunting, the first three best solutions (α,β,δ) obtained are saved and coerce the other search agents (including the omega) to update their positions according to the best search agent. The following are the proposed formula.

$$\vec{D_\alpha} = \left| \vec{C_1}.\vec{X_\alpha} - \vec{X} \right|, \qquad \vec{D_\beta} = \left| \vec{C_2}.\vec{X_\beta} - \vec{X} \right|, \qquad \vec{D_\delta} = \left| \vec{C_3}.\vec{X_\delta} - \vec{X} \right| \quad (14)$$

$$\vec{X_1} = \vec{X_\alpha} - \vec{A_1}.(\vec{D_\alpha}), \qquad \vec{X_2} = \vec{X_\beta} - \vec{A_2}.(\vec{D_\beta}), \qquad \vec{X_3} = \vec{X_\delta} - \vec{A_3}.(\vec{D_\delta}) \quad (15)$$

$$\vec{X}(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (16)$$

Fig. 2 shows the updating position of search agent according to the alpha, beta and delta. It can be observed that alpha, beta and delta estimate the position of the prey and other wolves update their position stochastically around the prey and final position is randomly within the circle.

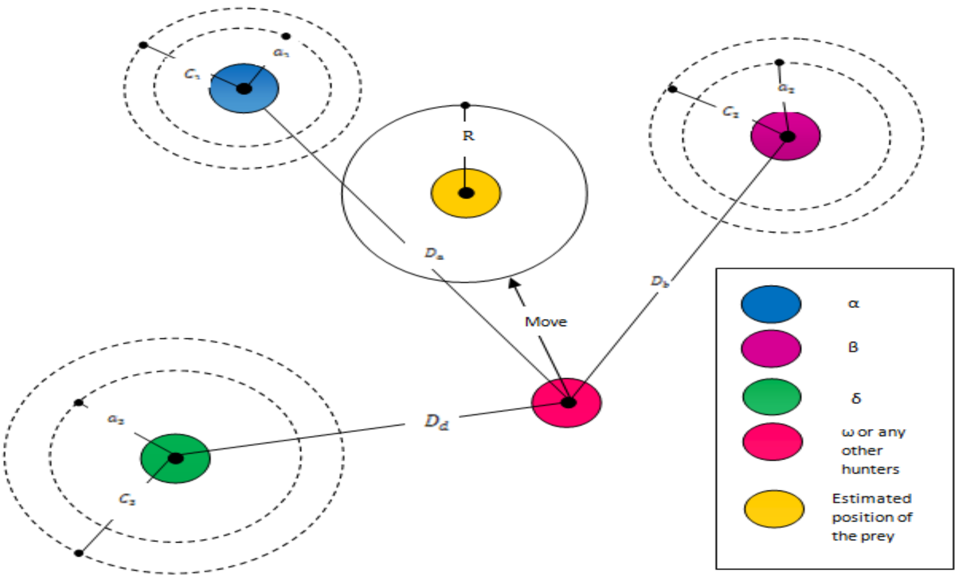

Figure 2 Position updation in GWO

a. Attacking towards the prey.

When the prey stops moving, grey wolf finishes their hunt by attacking on it. Mathematically, as approaching towards the prey, the value of $\vec{a}$ decreases. Hence the fluctuation range of $\vec{A}$ is also decreased by $\vec{a}.\vec{A}$ is a random value in the interval [-a, a] where a is decreased from 2 to 0 over the course of iterations. When random values of $\vec{A}$ are in [-1, 1] the next position of a search agent can be in any position between its current position and the position of the prey. If $|A|<1$, grey wolves converge towards the prey and attacks on it.

b. Searching for the prey.

The searching of grey wolves depends on the position of the alpha, beta and delta. For searching, they diverge from each other. Mathematically $\vec{A}$ varies with random values greater than 1 or less than -1 to oblige the search agent to diverge from the prey. This brings out exploration and allows GWO algorithm to search globally. If $|A|>1$, grey wolves diverges from the prey to find the fitter prey.

5. SIMULATION RESULTS

To illustrate the effectiveness of the proposed optimization approach various frequency plots of Area 1 and 2 is exhibited in this section. The Simulink implementation of two area interconnected network has been implemented in Matlab. The modeling of the system and simulation studies are performed over Intel ® core ™, i7, 2.9 GHz 4.00 GB RAM processor unit. Objective functions used for realization of the controller parameters are given in section 2. System is subjected to nominal load and step perturbation 0.1875 p.u. or (187.5 Mw) is given to Area 1 0.1275 p.u. (127.5 Mw) load disturbance is given to area 2.The system swing modes and critical eigenvalues under this operating condition are shown in the table 1.

Table I System eigenvalues and damping ratio

GWO		**GSA [18]**		**PSO [19]**		**GA [20]**	
J1	**J2**	**J1**	**J2**	**J1**	**J2**	**J1**	**J2**
-5.8597	-5.9843	-5.8468	-5.976	-5.846		-5.6586	-5.808
-4.2274	-4.3812	-4.313	-4.4257	-4.4443	-4.8155	-4.2083	-4.2168
-0.4638±1.7329i	-0.2900±1.9211i	-0.399±1.7029i	**0.2511±1.9124i**	**-0.4010 ± 1.7004i**	-0.0030 ±2.6953i	-0.4925±1.3799i	-0.2024 ± 1.6817i
-0.2848±1.4917i	-0.0582±1.7136i	-0.260±1.6066i	-0.192±1.7420i	**-0.2406 ± 1.7718i**	-0.0220 ±2.1889i	-0.2491 ± 1.4729i	**0.0361 ± 1.5786i**
-0.121	-0.0879	-0.3395	-0.5169	**-0.0983 ± 0.0157i**	-0.4666	-0.1353	-0.1058
-0.2008	-0.4496	-0.1102	-0.0884	-0.3521	-0.0494	-0.3294	-0.7991
-0.2217	-0.5606	-0.2061	-0.2416		-0.2144	-0.3712	-0.9209
Damping 0.1875	0.0339	0.1601	0.1098	0.1345	**0.0011**	0.1668	0.0229

Following conclusions can be drawn from the table I.

1. Table shows the eigenvalues obtained after outfitting controller through different objective functions and algorithms.
2. The value of minimum damping is highest (0.1875) when the parameters of the controller is optimized and estimated through GWO approach. The criteria ITAE is suitable for the realization of the objective function.

3. It is empirical to observe that the some of eigenvalues possess positive real part. Eigenvalues with positive real part is the indication of the oscillatory behaviour of the system. Surprisingly with the realization of the controller parameters through GSA and GA swing modes posses positive real part. These positive real parts are highlighted.
4. While designing the controller with the PSO algorithms the no. of swing modes increases up to 3. The value of minimum damping is very low when the optimization process is realized with ISE setting with PSO.
5. Value of minimum damping is 0.0229 in case of GA, 0.0011 in case of PSO, 0.1908 in case of GSA and 0.0339 in case of GWO with setting J2. Hence, it can be concluded that the criteria J1 gives better results. This analysis is exhibited through numerical simulation results.

The comparisons of all the algorithms are examined by the four cases.

Case A: Load change in area-1 by 10%. The dynamic responses of Δf_1, Δf_2 and ΔP_{tie} are given in Fig 3(a) - (c) for all the algorithms.
Case B: Load change in area-2 by 20%. Fig 4(a)-(c) shows the dynamic responses of the system.
Case C: Load is increased in area 1 by 25%. In Fig 5(a)-(b) the system dynamic responses are shown.
Case D: Load is decreased in area 1 by 25% and its responses are given in Fig 6(a)-(c).

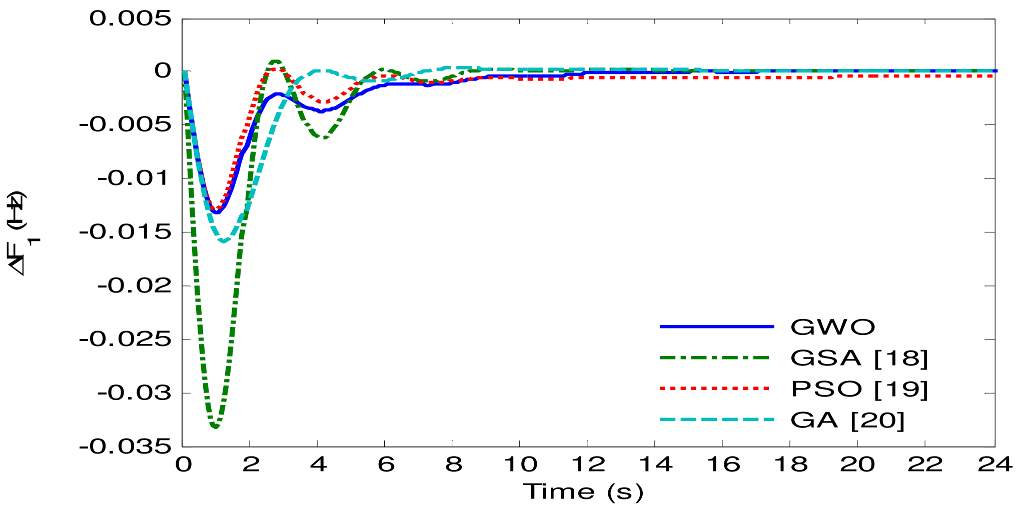

Figure 3(a). Change in frequency of area 1 by 10% load change in area-1

Fig. 3(a) shows the deviation of frequency in Area 1 under case A. Fig. 3(b) and 3(c) show the frequency deviation in Area 2 and tie line power exchange. It is observed from Fig. 3(a)-3(c) that GWO based controller exhibits the better dynamic performance as compared with the others. Percentage overshoot and settling time is much less in these cases. It is worth mention here that the low oscillatory response is good for equipment health.
Fig. 4(a) -4(c) show the responses of the frequency deviations in Area1 &2 with tie line exchanges. It is empirical to judge that due to low values of damping, system is yet under damped. The oscillatory response of the frequency deviation in Area 2 advocates this fact.
The GA based controller is unable to mitigate the frequency oscillations due to change in the load. On the other hand GWO based controller shows a better dynamic response and yields a satisfactory performance over a wide range of loading conditions.

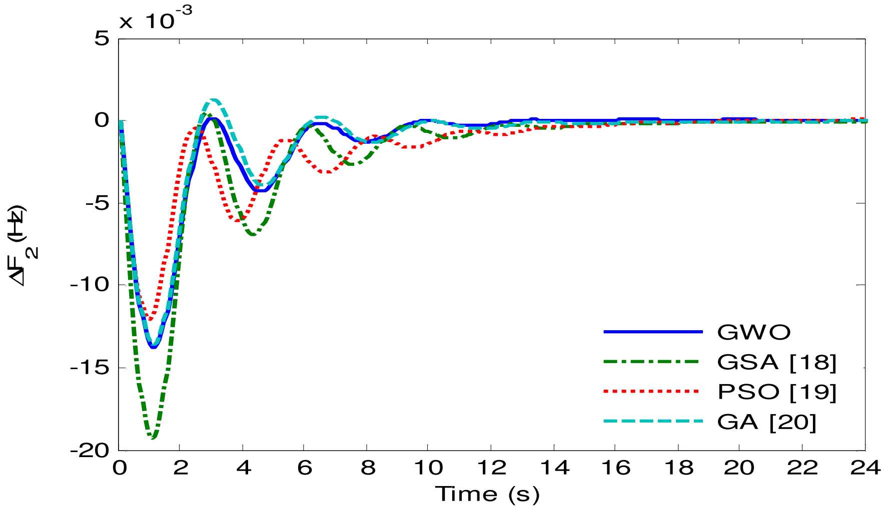

Figure 3(b). Change in frequency of area 2 by 10% load change in area-1

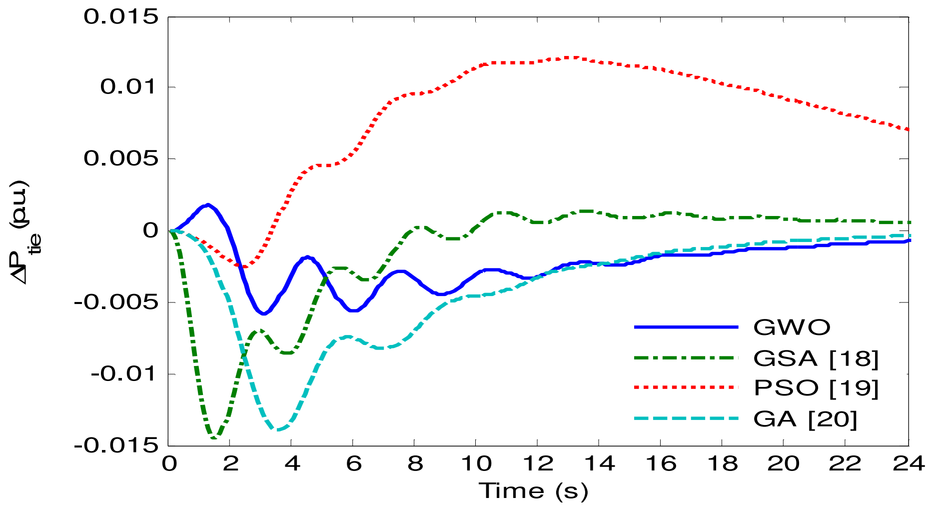

Figure 3(c). Change in tie line power by +10% load change in area-1

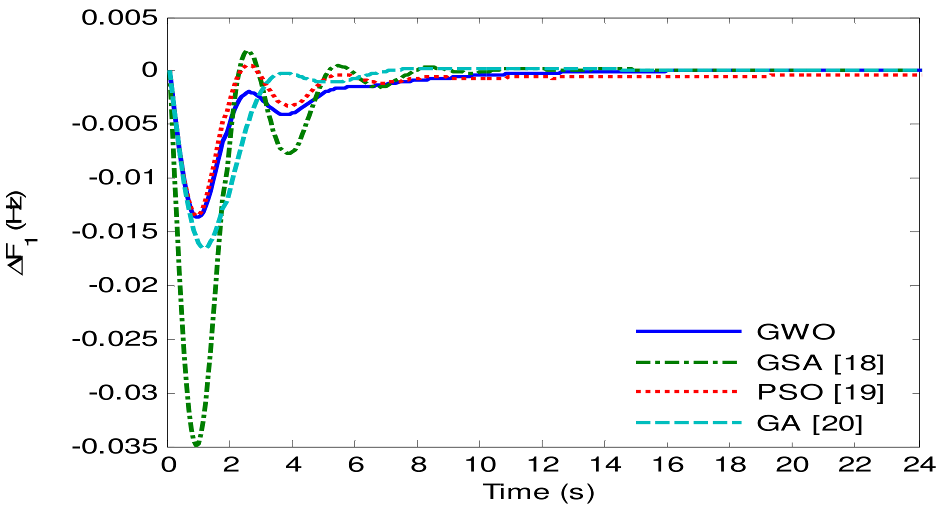

Figure 4(a). Change in frequency of area 1 by +20% load change in area-2

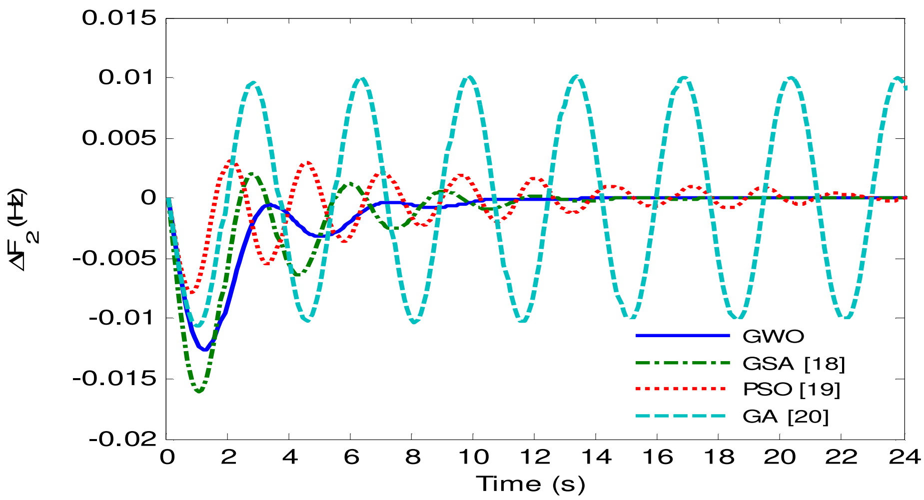

Figure 4(b). Change in frequency of area 2 by +20% load change in area-2

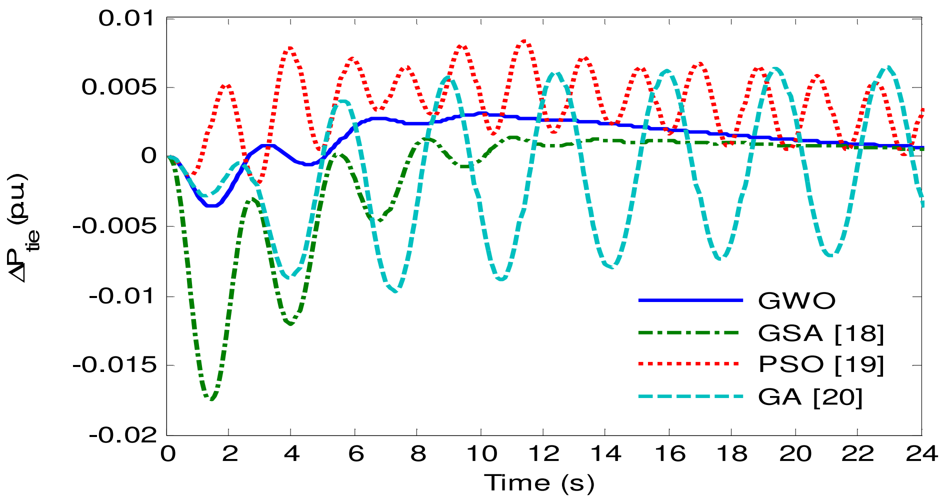

Figure 4(c). Change in tie line power by +20% load change in area-2

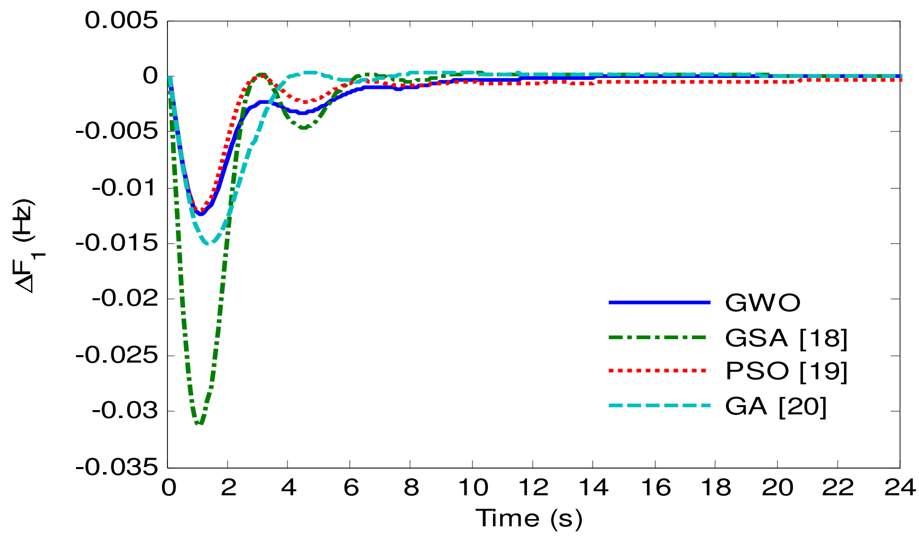

Figure 5(a). Change in frequency of area 1 with 25% increase in load in area-1

Fig. 5(a)-5(b) and 6(a)-6(c) show the frequency deviations of Area1 &2 along with tie line power exchanges. GWO tuned controller yields a better dynamic performance. An oscillatory response is obtained by the GA, GSA and PSO tuned controllers.

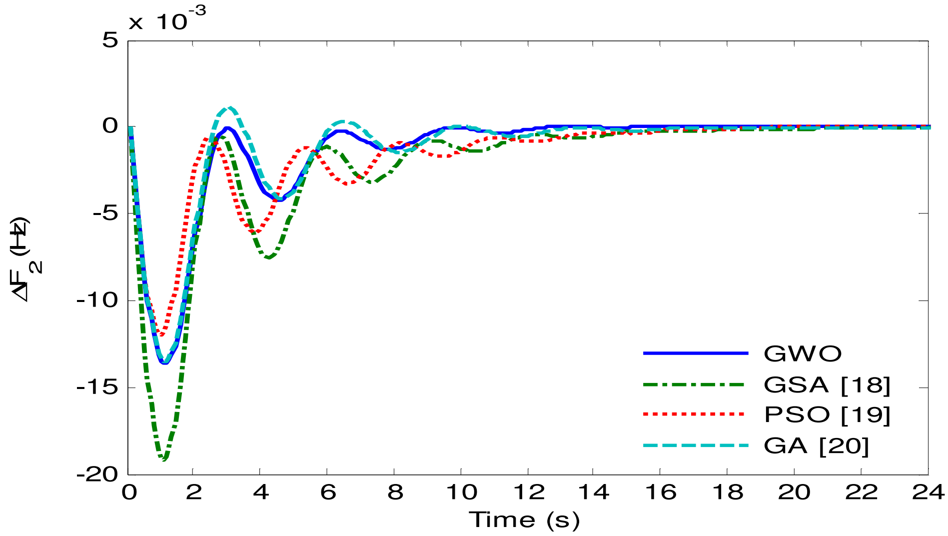

Figure 5(b). Change in frequency of area 2 on +25% load change in area-1

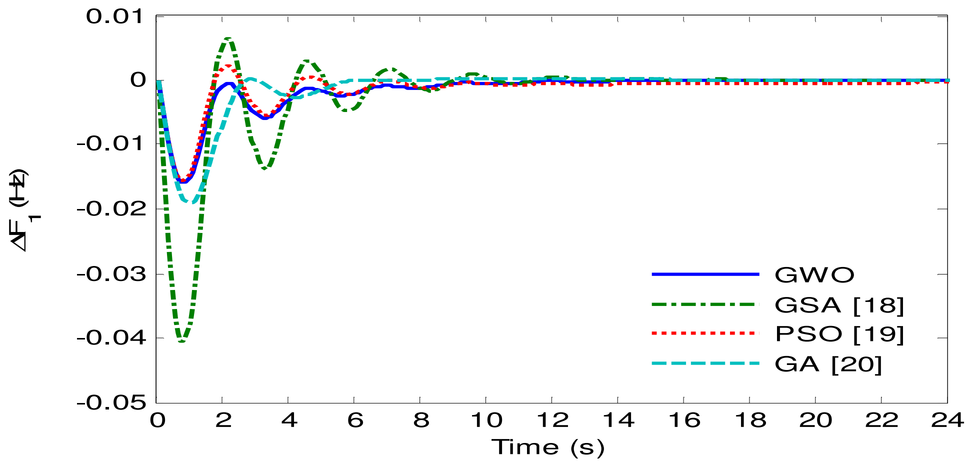

Figure 6(a) Change in frequency of area 1 on -25% load change in area-1

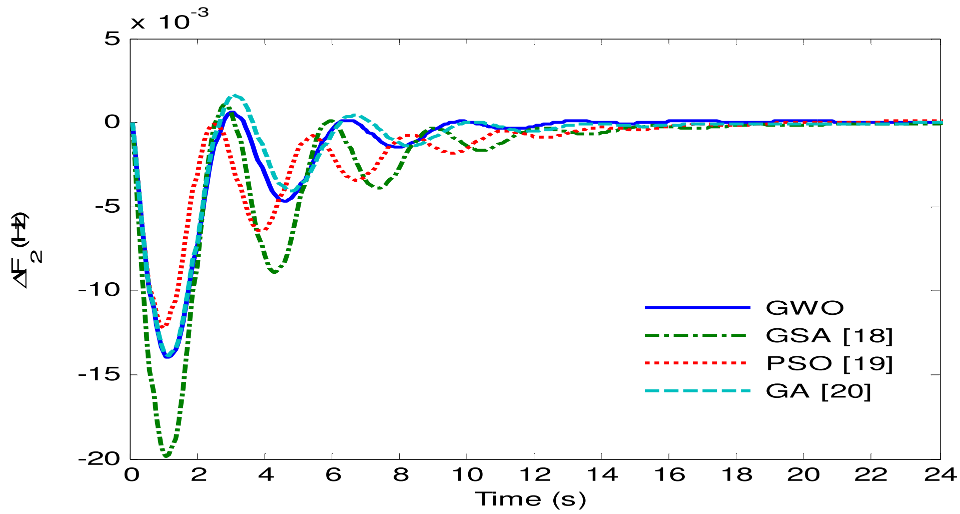

Figure 6(b) Change in frequency of area 2 on -25% load change in area-1

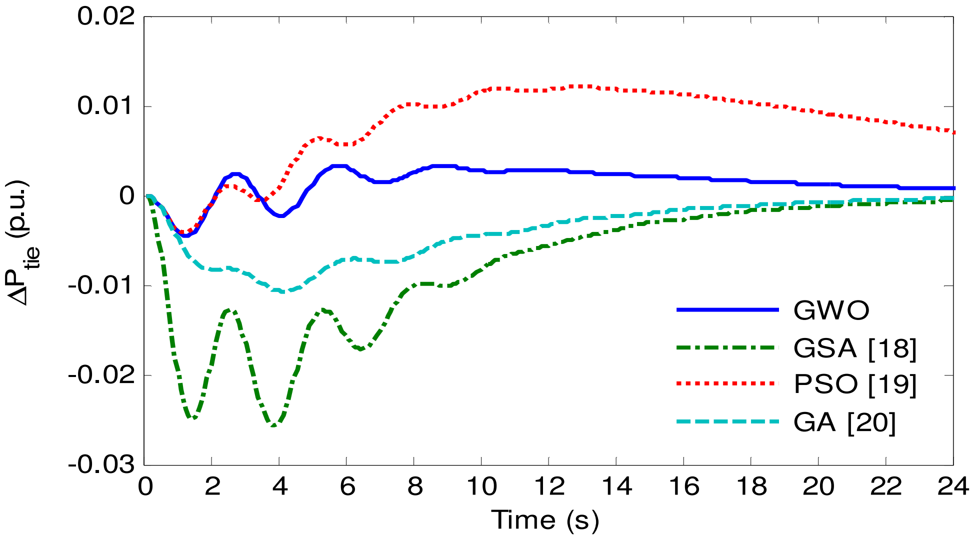

Figure 6(c) Change in tie line power by -25% load change in area-1

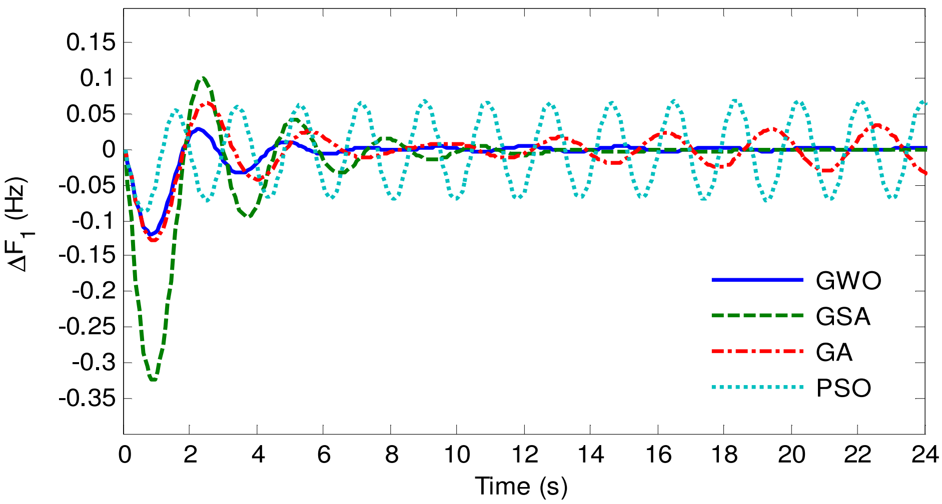

Figure 7 Change in frequency of area 1 by 25% load through J2.

Fig. 7 shows the realization of the controller optimization process through J2. It possess high oscillations.

Meaningful comparison of the dynamic responses of frequency deviations in areas and tie line power flows clearly reveals that in all the above cases GWO outperforms the other algorithms with minimum settling time and oscillations. However, it is observed that when the load is increased in area 2 by 20%, algorithms PSO [19] and GA [20] shows oscillatory response and makes the system extremely unstable.

The eigenvalues obtained from all the algorithms (J1 and J2) at base load is provided in table 1. It clearly shows that all the modes come from the GWO technique lie in the left half of the s-plane and thus sustain the stability of the system. The negative real part obtained through this realization contains larger numeric value. However, in case of GA a few modes lie in the right half of s-plane and make the system unstable. This phenomenon can be observed in fig. 4(b) and 4(c).

6. CONCLUSION

This paper presents application of swarm intelligence based algorithm GWO to find optimal parameters of the AGC –PI Regulator. In this study two are interconnected network with thermal units with a weak tie line is considered for the implementation of the proposed controller. The proposed controller is tested under different load variations and step disturbances. Following are the major findings of the work:

A. Comparison of the application of two objective functions for controller parameter estimation namely ISE and ITAE in optimization process is exhibited through eigenvalue analysis. Results reveal that ITAE is a better choice to optimize the regulator parameters. The nonlinear simulation results validate the efficacy of proposed controller.
B. Nonlinear simulation is performed to test the effectiveness of proposed approach and to compare the results of proposed approach with the recently published approaches. It is observed that the damping obtained from GWO regulator is more positive and possess higher numeric values as compared with the other algorithms.
C. Convergence characteristics of the algorithms are exhibited to show the flow of optimization process. It is empirical to judge that GA has a major problem of premature convergence and the time taken by the optimization process is much more in comparison with PSO, GSA and GWO. A value of ISE for GA under nominal load is 0.0206, PSO is 0.0449, GSA is 0.0042 and GWO is .0044. Similarly the value of ITAE for GA is 11.03, PSO is 6.60, GSA is 2.43 and GWO is 2.54. However, GSA takes more time to converge as compared with GWO.

D. Better damping performance is exhibited by GWO under different contingencies, load changes and step disturbances in both areas. PI controller setting obtained through GWO with J1 setting exhibits the better dynamic performance and overall low settling time.

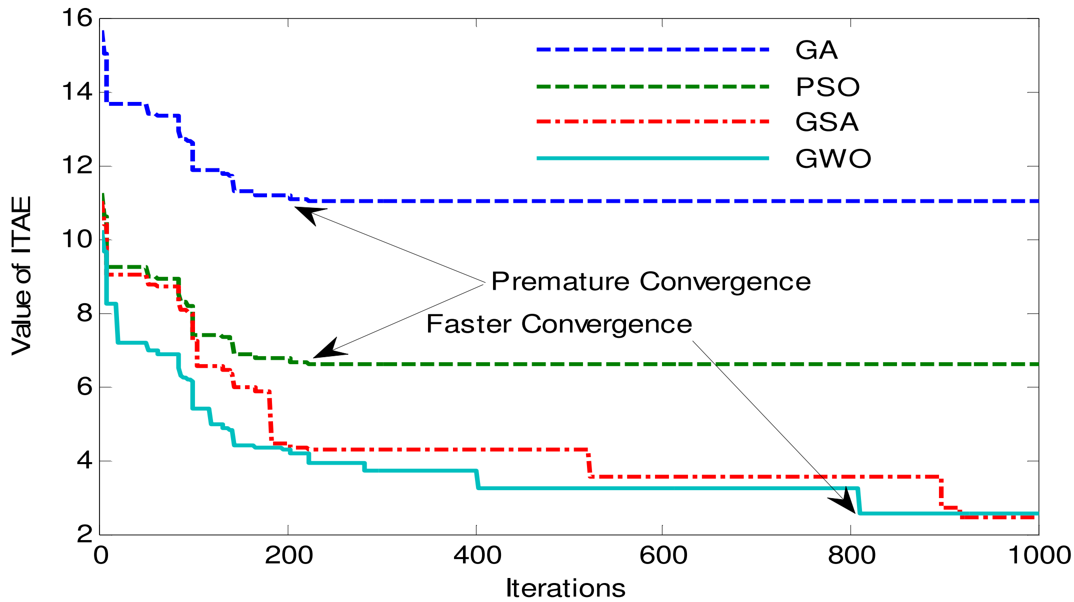

Figure 8 Convergence Characteristics of Proposed GWO Regulators

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