Whale Optimization Based Automatic Generation Control for Two Area Interconnected Thermal Power System

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Abstract: This article presents automatic generation control (AGC) of an interconnected two area thermal system. A maiden attempt is made to apply a Proportional Integral (PI) controller in AGC using two objective functions. Controller gains are optimized using Whale optimization algorithm (WOA) and Opposition theory enabled whale optimization algorithm (OIWOA) techniques. The results of the proposed model is compared with GSA, PSO, and GA techniques. Results revealed that the OIWOA optimized PI controller shows effective and improved results over WOA, GSA, PSO, and GA techniques.

Keywords - AGC, ACE, LFC, AVR.

1. INTRODUCTION

With the rapid increase in the demand for electrical power, the interconnection of the power system is also increasing. An interconnected system consists of several areas of the power system and for its stable operation; constant frequency and constant tie-line power should be maintained. A sudden change in the load is the main reason for frequency and tie- line power variations. Hence, we required a controlled and monitoring system at the generating station for the stable operation of the interconnection system. Therefore, Automatic Generation Control (AGC) is required. The main function of the AGC is to maintain the system frequency and power flow between the control areas at specified values by adjusting the generated power of generators. AGC consists of two loops: automatic load frequency control and automatic voltage regulator. In each area, AGC supervises the system “area control error” (ACE). ACE is defined as a linear combination of net tie-line power and frequency deviations. It is taken as the controlled output of AGC [1]. Rapid change in the size and complexity of electric power systems, along with the increasing power demand, has also called for the requirement of optimal control techniques and intelligent systems. Therefore, we need efficient techniques to implement AGC for our system.

Several investigations had been carried out in the past for the optimal design of an AGC. Some of the methods like pole placement techniques [2], coefficient diagram method [3], neural networks and fuzzy logic’s [4], [5] have been applied for the AGC. However, these methods and techniques require much time, large calculations, and approximations and are not reliable. Hence, these methods are not suitable for optimal control. On the other hand, modern optimizations techniques like Genetic Algorithm (GA) [9], Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO) [7], [8], [10], Bacterial Foraging Optimization Algorithm (BFOA) [11], Differential Evolution (DE) [12], Moth flame Optimization (MFO) [13] , and Cuckoo Search (CS) [14], etc have been proved better for the design of controller and obtaining optimal parameters for AGC with respect to each other. However, due to the complexity and for different interconnections and systems, authors are looking forward to different and more optimize algorithms that can perform better over existing algorithms. In 2016, Mirjalili proposed a whale optimization algorithm (WOA) [15] that shows better exploration and exploitation abilities among many other algorithms over many applications and able to avoid local minima trap and therefore motivate us to implement this algorithm for the AGC. WOA is also successfully tested over different benchmark functions. This also motivated us to use a new variant of WOA for AGC. The newly developed variant of WOA used here is Opposition theory enabled whale optimization algorithm (OIWOA) [24]. This paper aims to implement the OIWOA and WOA for the optimization of control parameters for AGC of two areas interconnected power system.

The rest of the paper is structured as follows:

In Section-II, A brief description of the problem formulation and modeling of two areas interconnected system is presented. Section-II describes the whale optimization technique. Section-IV describes the new variant of whale optimization technique. Section-V shows the results and responses of OIWOA and WOA based AGC model. Section-VI describes the conclusion of this paper.

2. PROBLEM FORMULATION

Two areas interconnected thermal-thermal power system with a PI controller are taken for investigation, as shown in Fig. 1

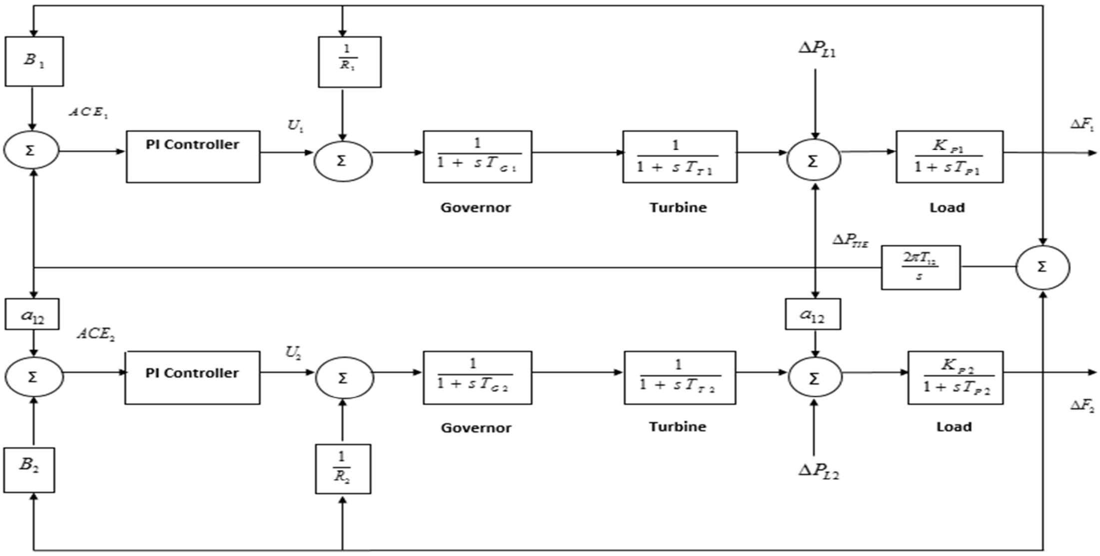

Figure 2: Two area power system

. In the considered system model, each area consists of speed governor, turbine and generator, and has three inputs and two outputs each.

The system is tested on the two equal thermal areas connected by a tie line. System parameters are used from [16]. This system is implemented using MATLAB 2017 and run on a Core i5 seventh gen. CPU, 2.50 GHz, and 8GB RAM computer.

The ACE is defined as:

$$ACE = B\Delta F + \Delta P_{tie} \tag{1}$$

B is frequency bias parameter, ΔF is the change in frequency and ΔP_{tie} is change in tie-line power.

The transfer functions to model each component of the each area are considered for better analysis [16].

ACE is the input of the PI controller for respective areas which are defined as:

$$ACE_1 = B_1\Delta F_1 + \Delta P_{tie} \tag{2}$$

$$ACE_2 = B_2\Delta F_2 + \Delta P_{tie} \tag{3}$$

The control inputs of the power system with PI controller are obtained as:

$$C_1 = K_{p1} \cdot ACE_1 + K_{I1}\int ACE_1$$

$$C_2 = K_{p2} \cdot ACE_2 + K_{I2}\int ACE_2 \tag{4}$$

For designing the PI controller, two objective functions are considered according to desired specifications and constraints. These are the ISE & ITAE and formulated as:

$$OF_1 = ITAE = \int_0^a \left(|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}|\right) \cdot t \cdot dt \tag{5}$$

$$OF_2 = ISE = \int_0^a \left(|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}|\right)^2 \cdot dt \tag{6}$$

where, OF_1 is ISE and OF_2 is ITAE.

The design problem can be formulated for the optimization as follows:

Minimize *OF*

Subject to:

$$K_{I\min} \le K_I \le K_{I\max}$$

$$K_{R\min} \le K_R \le K_{R\max}$$

$$K_{D\min} \le K_D \le K_{D\max}$$

where, 'I' is controller gain, 'R' is speed regulation and 'D' is frequency sensitivity coefficient.

In the following sections, we will discuss the proposed approaches for AGC model.

3. WHALE OPTIMIZATION ALGORITHM (WOA)

WOA is a nature-inspired meta-heuristic algorithm based on the unique hunting behavior of humpback whales. The search optimization process of the WOA includes three phases: Encircling prey, Bubble-net attacking method and Prey search. The detailed mathematical modeling of the above three phases are given in [15]. The mathematical equations are as follows:

$$\vec{W} = \left|\vec{Q} \cdot \vec{K}^{*}(x) - \vec{K}(x)\right| \quad (7)$$

$$\vec{K}(x+1) = \vec{K}^{*}(x) - \vec{P} \cdot \vec{W} \quad (8)$$

where, x is the current iteration, P and Q are the coefficient vectors. K* is the position vector of the best solution obtained, K is the position vector.

$$\vec{K}(x+1) = \overrightarrow{W'} - e^{yl} \cdot \cos(2\pi l) + \vec{K}^{*}(x) \quad (9)$$

$$\vec{K}(x+1) = \vec{K}_{rand} - \vec{P} \cdot \vec{W} \quad (10)$$

where, $\vec{K}_{\text{rand}}$ is a random position vector.

The flowchart of the WOA is given in Fig. 2. The WOA starts with random solutions within the search space and terminates by $\vec{K}^{*}$.

Although the original WOA has already proven itself an efficient optimization algorithm in many problems. However, according to NFL theorem [17], WOA also need more optimized mathematical modeled in a new problem such as the better performance of AGC for interconnection power systems.

Now, In the next section we will briefly discuss OIWOA.

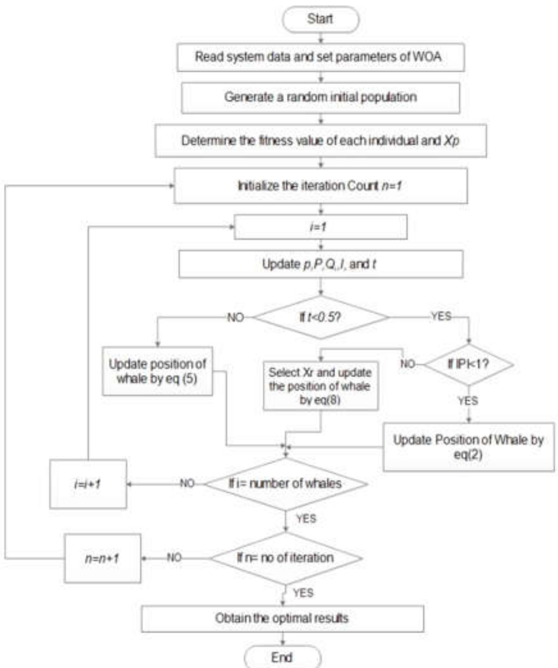

Figure 2: Flowchart of WOA

4. OPPOSITION THEORY ENABLED WHALE OPTIMIZATION ALGORITHM (OIWOA)

The WOA is exhibits higher accuracy than many meta-heuristic techniques but to further improve convergence rates and other capabilities for many complex issues; it needs some improvements. Therefore, a newly developed algorithm i.e., OIWOA [24] is considered in the proposed test model to improve controller parameters.

OIWOA is successfully tested over benchmark functions and gives improved results over WOA. This algorithm improves the performance of WOA by finding the best solution according to OBL [18], [19], [20]. In addition, using sinusoidal function [21] and crossover operator, OIWOA has better search capabilities and convergence rate than original WOA. The crossover operator is familiar with [22], [23]. The crossover operator used here is “crate”, which is constant value.

The significant changes in the modeling of OIWOA with respect to WOA are in the following equations:

$$\vec{W} = \left|crate \cdot \vec{Q} \cdot \vec{K}^{*}(x) - \vec{K}(x)\right| \quad (11)$$

$$\vec{K}(x+1) = crate \cdot \vec{K}^{*}(x) - \vec{P} \cdot \vec{W} \quad (12)$$

$$\vec{K}(x+1) = \overrightarrow{W'} - e^{yl} \cdot \cos(2\pi l) + crate \cdot \vec{K}^{*}(x) \quad (13)$$

$$\vec{W} = \left|crate \cdot \vec{Q} . \vec{K}_{rand} - \vec{K}\right| \quad (14)$$

$$\vec{K}(x+1) = crate \cdot \vec{K}_{rand} - \vec{P} \cdot \vec{W} \quad (15)$$

Now, In the next section we will discuss and present the simulation results of AGC of two area thermal interconnected power system using both WOA and OIWOA.

5. RESULTS AND DISCUSSIONS

This section provides the simulation results and analysis of WOA and OIWOA based AGC controller realization on a two-area thermal interconnected power system. WOA and OIWOA based AGC controller is compared with GSA, PSO, and GA using two objective functions. The analysis is carried out using a sensitivity test and with different load variations. The optimized parameters of the PI controller with the OIWOA, WOA, GSA, PSO, and GA algorithms on two objective functions are shown in Table I.

Table II depicts the sensitivity analysis of the system, after the application of OIWOA and WOA on AGC. Eigen value analysis plays an important role in system stability. From table II, it can be concluded that a considerable amount of damping is improved in each case when the controller parameters are obtained with OF1.

The overall damping of the system is effective with the OIWOA controller using OF1 (0.1907).

In the sensitivity analysis, both real and imaginary parts have their real importance. The real part shows the damping behavior, which represents the damp oscillations, which means the more significant the magnitude, the higher the rate of failure. Imaginary parts show the frequency of oscillations.

Table 1: Optimized Controller Parameters

	OIWOA		WOA		GSA [26]		PSO [8]		GA [25]	
	OF_1	OF_2	OF_1	OF_2	OF_1	OF_2	OF_1	OF_2	OF_1	OF_2
K_{I1}	0.3147	0.3884	0.346	0.3997	0.3817	0.4171	0.3131	0.4498	0.3031	0.6525
K_{I2}	0.19748	0.2002	0.2035	0.2017	0.2153	0.2028	0.1091	0.2158	0.3063	0.796
R_1	0.03758	0.04079	0.0385	0.0417	0.0401	0.0435	0.0581	0.0201	0.0794	0.0503
R_2	0.061949	0.04548	0.0679	0.049	0.0657	0.0635	0.0531	0.03	0.0737	0.0609
D_1	0.434	0.4449	0.4247	0.45445	0.5889	0.4778	0.4756	0.591	0.7591	0.7216
D_2	0.77978	0.84444	0.8747	0.85787	0.8946	0.8744	0.6097	0.8226	0.895	0.8984

Table 2: Eigen values and Min. Damping Ratio

WOA				OIWOA			
System Modes		Minimum Damping ratio		System Modes		Minimum Damping ratio	
OF_1	OF_2	OF_1	OF_2	OF_1	OF_2	OF_1	OF_2
-5.9777	-6.4847			-5.47497	-5.5487		
-4.576448	-4.315			-4.4179	-4.1879		
-0.4627±1.7879i	-0.2816±1.9547i	0.1907	0.04487	-0.4129±1.4454i	-0.2798±1.4387i	0.1849	0.03548
-0.2959±1.4487i	-0.0648±1.7177i			-0.11287±1.5474i	-0.05794±1.4878i		
-0.1878	-0.09157			-0.1971	-0.0184		
-0.2157	-0.4787			-0.2048	-0.4128		
-0.2754	-0.5871			-0.2179	-0.5489		

For better analysis and understanding, OIWOA based controller is tested with different loading conditions using four different cases as shown in table III.

Case i: Load in area-1 is changed by +10%.
Case ii: Load in area-2 is changed by +20%.
Case iii: Load in area-1 is changed by +25%.
Case iv: Load in area 1 is changed by -25%.

All the above cases are given in Table III with OIWOA and WOA for the Eigen values obtained. Results show that all modes are located in the left half of the s-plane with the OIWOA and thus, ensure the system's stability.

The frequency plots are given from Fig. 3 to 8.

This section concludes the successful implementation of PI controller tuned by OIWOA and WOA on comparing with the GA, PSO, and GSA for AGC of two areas interconnected thermal power system. In the next section, the conclusion of this work is mentioned.

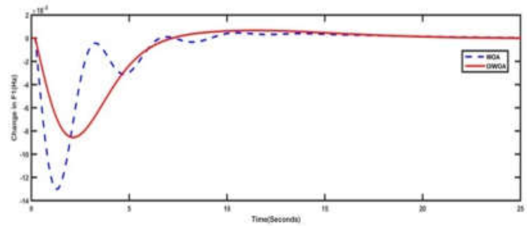

Figure 3: Frequency deviation of area-1 by +10% load change in area-1

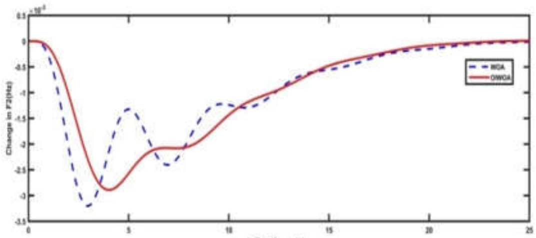

Figure 4: Frequency deviation of area-2 by +10% load change in area-1

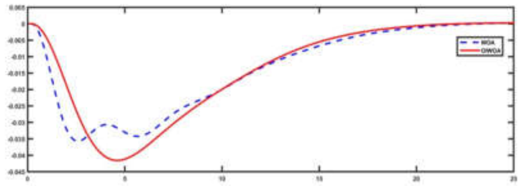

Figure 5: Change in tie-line power +10% in area-1

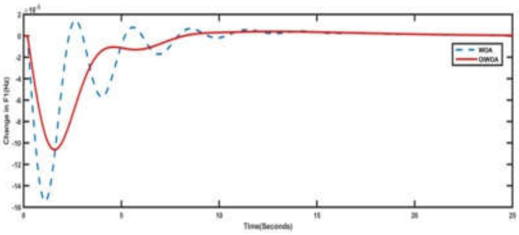

Figure 6: Frequency deviation of area-1 by -25% load change in area-2

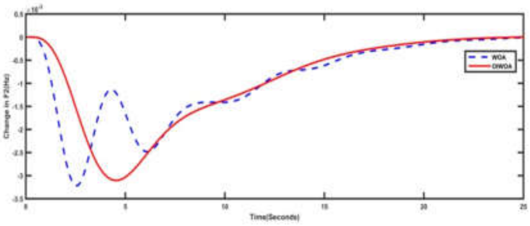

Figure 7: Frequency deviation of area-2 by -25% load change in area-2

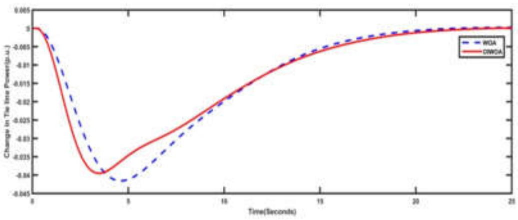

Figure 8: Change in tie-line power -25% in area-2

6. CONCLUSION

In this paper, an attempt has been made to apply the PI controller for AGC of two areas interconnected power systems. OIWOA is used for the first time in this field, and the gains of the PI controller are optimally tuned using ITAE objective functions. It is observed that recently modified WOA, i.e., OIWOA provides a better dynamic response in the design and outperforms the other algorithms with minimum settling time and oscillations. It is also concluded that the OIWOA can find the optimum value of the objective function.

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Table 3: System modes for different load variation

	OIWOA		WOA	
	OF_1	**OF_2**	**OF_1**	**OF_2**
Case-i	-5.9478	-5.8479	-5.7548	-5.5547
	-4.2647	-4.5748	-4.1449	-4.48489
	-0.5129±1.4879i	-0.5174±1.4712i	-0.5017±1.5547i	-0.4978±1.1794i
	-0.2947±1.4147i	-0.2996±1.1794i	-0.2794±1.1297i	-0.2917±1.3598i
	-0.1977	-0.1487	-0.1179	-0.14999
	-0.2479	-0.2418	-0.2177	-0.2148
	-0.2481	-0.25179	-0.2129	-0.2055
Case-ii	-5.8947	-6.7948	-5.6791	-5.5794
	-4.4791	-4.7498	-4.4978	-4.5479
	-0.5177±1.9874i	-0.5479±1.4174i	-0.41479±1.1787i	-0.4178±1.4987i
	-0.3548±1.4791i	-0.1279±1.7894i	-0.2147±1.1236i	-0.2124±1.419i
	-0.1517	-0.1074	-0.1347	-0.07459
	-0.2415	-0.4597	-0.2259	-0.5179
	-0.2581	-0.5147	-0.2747	-0.5547
Case-iii	-5.9748	-5.8459	-5.8412	-5.7984
	-4.6477	-4.8248	-4.4494	-4.8447
	-0.5214±1.94788i	-0.3847±1.7849i	-0.5147±1.1478i	-0.41778±1.7947i
	-0.2963±1.4149i	-0.0549±1.1794i	-0.24794±1.1977i	-0.0817±1.147i
	-0.1348	-0.0987	-0.1184	-0.0974
	-0.2587	-0.4848	-0.2147	-0.4614
	-0.2649	-0.5697	-0.2329	-0.2979
Case-iv	-6.4789	-6.4979	-6.0548	-6.2019
	-4.6479	-4.37748	-4.4499	-4.184
	-0.3729±2.548i	-0.1974±2.2479i	-0.3546±2.1315i	-0.1907±2.1847i
	-0.2897±1.4847i	-0.06796±1.1794i	-0.2594±1.1497i	-0.0817±1.3598i
	-0.1469	-0.0947	-0.1479	-0.0749
	-0.2017	-0.4479	-0.1719	-0.487
	-0.2249	-0.5717	-0.2141	-0.5517