OPTIMAL PID CONTROLLER BASED ON AN IMPROVED SPARROW SEARCH ALGORITHM FOR MULTI-AREA FREQUENCY CONTROL

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Abstract*: To boost power system reliability there must be a good scheme for the automatic generation control to maintain the generation-load balance. The development of this scheme started with the enhancement of the sparrow search algorithm, where the initial population and producer selection was targeted to improve the search quality. The enhancement made was used to optimize the gain parameters of the PID controller increasing the overall system performance. The proposed scheme was tested on the two-area power system in the MATLAB/Simulink environment and comparisons were made with recent publications. Integral time absolute error (ITAE) was used as the performance index. The proposed method shows improved performance with minimum settling time. This work presents the enhancement of the sparrow search algorithm for the automatic generation control of a two-area non-reheat thermal power system.*

1. INTRODUCTION

The goal of a proper electric power system is to supply power to consumers and retain its stability in the process as they have a generation-load balance, therefore sudden changes in generating system capacity or demand could cause a major imbalance[1]. With advancements made over the years, modern power systems now exist as an interconnection between areas and utilities with Tie-lines acting as the medium of power exchange[2] with one of the major identified areas of concern being frequency control [3].

It is imperative for the sustained supply of electricity to consumers to have a good frequency regulation scheme as the lack of any control method after an abrupt load change would cause a deviation in the frequency used in regulating the system. The major factors influencing the proper functioning of the regulating strategy in an AGC system are the controller placement and the level of controller optimization.

Conventionally, load frequency control is designed with an integral controller because it provides very low or zero steady-state deviation as the error signal in the feedback loop is evaluated, however, gives a poor dynamic response[4]. To attend to this setback the use of variable structure control[5], optimal control[6], and linear feedback[4] were proposed. However, the requirement of an in-depth system state became a problem as it was difficult to estimate completely. Consequently, intelligent controllers[3], classical controllers[7], and fuzzy logic controllers[8] have been used to improve on this setback. These techniques are, however, non-adaptive and, in some cases, would require training data offline or randomizing the values of certain parameters, inherently making them sub-optimal. With the various methods proposed, classical controllers such as PID are commonly used by industries. This controller is prone to a lot of errors as the gain parameters are either randomized or un-optimally selected. With the employment of metaheuristic algorithms due to their optimization problem-solving ability in recent times such as particle swarm optimization (PSO) algorithm [9] and teaching learning-based optimization (TLBO) algorithm[2] to optimize this controller, the results still fall short of optimal performance as the algorithms are not properly optimized for these function. The necessity therefore arises to use a better optimized and accurate method for the AGC regulating strategy. The contents of this paper address this challenge. This paper proposes the use of an enhanced sparrow search algorithm (SSA) to search the gain parameters of the PID controller.

2. THEORETICAL BACKGROUND

2.1. Sparrow Search Algorithm Optimization

The SSA as described by [10] is enhanced by targeting the initial population and producer selection to improve the search quality and speed. The key components of the algorithm are described below.

The sparrow search algorithm works on the basic foraging principle, with producers being the group in the population that searches for food and the scroungers being the group that follows the producers around to get food, while some members of the population perform anti-predation action, warning the others of dangerous predators causing the whole population to relocate.

The initial sparrow positions in the population are described as

$$x = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & \cdots & x_{1,d} \\ x_{2,1} & x_{2,2} & \dots & \dots & x_{2,d} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n,1} & x_{n,2} & \cdots & \cdots & x_{n,d} \end{bmatrix} \quad (1)$$

where number and dimension of sparrow are given as '*n*' and '*d*' respectively.

The fitness of the established sparrows is given as

$$Fx = \begin{bmatrix} F[(x_{1,1} & x_{1,2} & \cdots & \cdots & x_{1,d}]) \\ F[(x_{2,1} & x_{2,2} & \dots & \dots & x_{2,d}]) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ F[(x_{n,1} & x_{n,2} & \cdots & \cdots & x_{n,d}]) \end{bmatrix} \quad (2)$$

The Producer location update is given as

$$x_{i,j}^{t+1} = \begin{cases} x_{i,j}^{t}.\,exp\left(\frac{-i}{\alpha.iter_{max}}\right) & if \;\; R_2 < ST \\ x_{i,j}^{t} + Q.L \;\; if & R_2 \geq ST \end{cases} \quad (3)$$

where current iteration is indicated by *t*, *j* represents the dimension, *i* represents the current sparrow, the highest iteration is represented by $iter_{max}$, α is chosen as a random number between 0 and 1, ST ∈[0.5,1] is the safety threshold, the alarm value is represented by R2 ∈ [0,1], Q is a random number that follows a normal distribution, and *L* is a 1 × d matrix with all ones. A safe sparrow population is represented as $R_2 < ST$ while $R_2 \geq ST$ means the sparrows face danger.

The Scroungers location update is given as

$$x_{i,j}^{t+1} = \begin{cases} Q.\,exp\left(\frac{x_{worst}^{t} - x_{i,j}^{t}}{i^2}\right) & if \; i > \frac{n}{2} \\ x_{i,j}^{t+1} + \left|x_{i,j}^{t} - x_{p}^{t+1}\right|.\, A^{+}.L & otherwise \end{cases} \quad (4)$$

In the above equation the optimal position inhabited by the producer is given as Xp, the current global worst position is indicated as X_{worst} and A+ = $A^T(AA^T)^{-1}$ where *A* represents a matrix of 1 × d whose elements is randomly assigned 1 or −1.

The anti-predation action location update is given as

$$x_{i,j}^{t+1} = \begin{cases} x_{best}^{t} + \beta\,.\,|x_{i,j}^{t} - x_{best}^{t}| & if\, f_i > f_g \\ x_{i,j}^{t} + K.\left(\frac{\left|x_{i,j}^{t} - x_{worst}^{t}\right|}{(f_i - f_w) + \varepsilon}\right) & if\, f_i = f_g \end{cases} \quad (5)$$

The current global optimal location is denoted as x^t_{best}, the step size control parameter is given as β, with variance of 1 and mean of 0, K ∈ [−1, 1] is the sparrow flying movement indicator. The current sparrow fitness, the global best and worst sparrow values are given as, f_i, f_g and f_w respectively and ε is put in place to avoid prevent zero divison error. Sparrows at the edge and middle of the population are given as $f_i > f_g$ and $f_i = f_g$.

2.2. Automatic Generation Control

The interconnected power system is made up of several controlling areas with the generators acting as one unit. Contained in each area is the load drawn, the generator, the prime mover or turbine, and the governor. As the system load increases the turbine speed drops to allow the governor to adjust the input to the level of the new load. If the deviation to the turbine speed caused by the load increase, reduces, the system error signal reduces while the governor control mechanism gets closer to the constant speed maintenance threshold[11]. This, however, does not guarantee it gets to the exact point in the threshold required to maintain that constant speed as the turbine-governor control alone forces all generating units to respond irrespective of the location of load change. The addition of secondary control, however, guarantees the turbine speed returns to its initial set point. This entire scheme where a change in load would require an equivalent change in a generation to maintain the system frequency is known as Automatic Generation Control (AGC) also referred to as load frequency control[12]. The objectives of the LFC are fairly simple. The first is to maintain frequency uniformly, the second is to ensure the load is split among the generators, and lastly is to regulate tie-line flow. The use of the turbine-governor control is referred to as the primary control while the use of a supplementary control is known as the secondary control.

2.3. SSA-Based Pid Design

A load change by any area should be absorbed by that area. To achieve this the tie-line power and frequency deviation are added to the loop integrating the secondary controller into the system. This is also known as the tie-line bias control which is the basis for the conventional load frequency control. Therefore, by a linear combination, the net change observed by the system in the frequency and tie-line flows is weighted to an error unit known as the area control error ACE.

$$ACE_i = \Delta P_{tie_i} + B_i \Delta f_i \tag{6}$$

Where i in ACE_i denotes the area for the area control error unit. ΔP_{tie_i} denotes a change in tie line flow, B_i is the bias factor at each area i, and Δf_i is the frequency change.

The controller function is based on a feedback control principle. The three major parameters for this controller are the proportional gain value, the integral gain value, and the derivative gain value[13]. These three parameters have varying reactions when actively operating. The response to recent or current errors is decided by the proportional function, the response to the sum of recent errors is controlled by the integral function and the response to the rate of error change is determined by the derivative function[8]. When in operation in a feedback control system the cumulative sum of these three parameters is used to make adequate adjustments to the system. To tune the PID controller optimally it needs to be integrated into the system. The integration of the ACE to the PID controller is given as

$$U_i(t) = K_p ACE_i + K_i \int ACE_i dt + K_d \frac{d(ACE_i)}{dt} \tag{7}$$

where K_p, K_i, and K_d represent the proportional, integral and derivative gain parameters of the PID controller. $U_i(t)$ is the controlled input to the PID controller.

2.4. Objective Function

The best PID controller gains for a system depend on the desired performance, as measured by a performance index. The most common performance index is the integral criterion, which measures the total accumulated error over time. Examples of integral criterion-based performance indices include integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time multiples of square error (ITSE)[14]. With IAE there is a degree of difficulty in computing the error's absolute value analytically and as such systems with this criterion give a slow response. Though impractical for real-time analytical works, it is often employed in a system digital simulation. ISE produces less overshot but has a large settling time as it focuses on larger errors. The ITSE though having an extra time error function and prioritizing errors with longer duration tends to give large outputs when the reference has a sudden change in its value. The ITAE also has an extra time error function and giving priority to long-duration errors reduces the system overshoot and increases the system settling time, with works from [14],[15], and [16] showing significant system improvement while using the ITAE. The ITAE for a two-area power system is represented as objective function J

$$J = \int_{t=0}^{t_{final}} t(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|)dt \tag{8}$$

From the equation above Δf_1 and Δf_2 indicate the deviation in system frequency for area 1 and 2 while ΔP_{tie} is change in tie line power and t_{final} is the duration of simulation.

$$\Delta f_i = \frac{U_i(t)}{B(K_i \int dt + K_p + K_d \frac{d}{dt})} - \frac{\Delta P_{tie}}{B} \tag{9}$$

Equation 9 represents the gain parameters of the PID controller as object to frequency change in any area:

$$\Delta P_{tie} = \frac{U_i(t)}{K_i \int dt + K_p + K_d \frac{d}{dt}} - \ B\Delta f_i \tag{10}$$

Equation 10 represents the gain parameters of the PID controller as object to change thr line power.

The LFC is solved as an optimization problem with constraints and the controller parameter being the boundaries of the constraints. In this case the PID controller. The objective function J is minimized using the equation below.

$$\begin{Bmatrix} K_{p,min} \ \le \ k_p \ \le \ k_{p,max} \\ K_{i,min} \ \le \ k_i \ \le \ k_{i,max} \\ K_{d,min} \ \le \ k_d \ \le \ k_{d,max} \end{Bmatrix} \tag{11}$$

The gain parameters are chosen randomly from 0 to 1, making 0 the lower bound and 1 the upper bound.

3. THE ENHANCED SPARROW SEARCH ALGORITHM

3.1. Opposition Based-Initialization

The initialization of the sparrow population greatly affects its search ability. Therefore, the opposition-based initialization is applied. The idea is that the random initialization of a search agent could make it far from the ideal position. Taking the opposite of the search agent in a defined search space makes brings it closer to the ideal position[17]. If a search space has boundaries “a” and “b” and the agent generated is x, the opposite of this agent would be given as:

$$X_{opp} = (a + b) - x \tag{12}$$

3.2. Improved Producer Selection

The sparrow population selects individuals with good fitness values as the producers. This may reduce the efficiency as the population almost entirely depends on this group for survival. The fitness of every sparrow generated is assessed and the average fitness is calculated. Individuals with fitness values above average are selected as producers. Thus, giving the function of the producers to highly fit members. The average fitness is given as:

$$F_{average} = \frac{f1+f2+\cdots fn}{N} \quad (13)$$

This improvement is called the Adaptive opposition SSA (AOSSA).

4. IMPLEMENTATION OF ADAPTIVE-OPPOSITION BASED SSA (AOSSA) IN PID CONTROLLER

1 step Parameter initialization. Population size, Max number of iterations, objective or fitness function, boundary limits, and dimension

2 step The PID controller parameters are randomly generated as the search agents. These are the P, I, and D gain constant of the controller

3 step Evaluate the opposite of the generated search agents

4 step The fitness function of the generated search agents is evaluated using J

5 step The average of the fitness function is taken

6 step Generate alarm value randomly

7 step Position update for the producer

8 step Position Update for the scroungers

9 step Anti-Predation position update for the population

10 step Calculate fitness value from the updated locations

11 step If the new location is better than the old update it

12 step Analogously the controller gain parameters are modified

13 step If the stopping criterion is reached the best parameter variable are given as outputs else the process is repeated from step 7

4. TESTING

A two-area interconnected system with non-reheat thermal power plants is used as the test system. A case study involving a step load change is applied to both areas as shown.

The controller to be used for this work replaces the original secondary controller with a slight change. The controller placement is imperative to the overall effectiveness of the scheme. Therefore, to improve the tie-line control the secondary controller replaces the original control strategy placed on the tie-line. The parameters of the system are given in *figure 1* [11].

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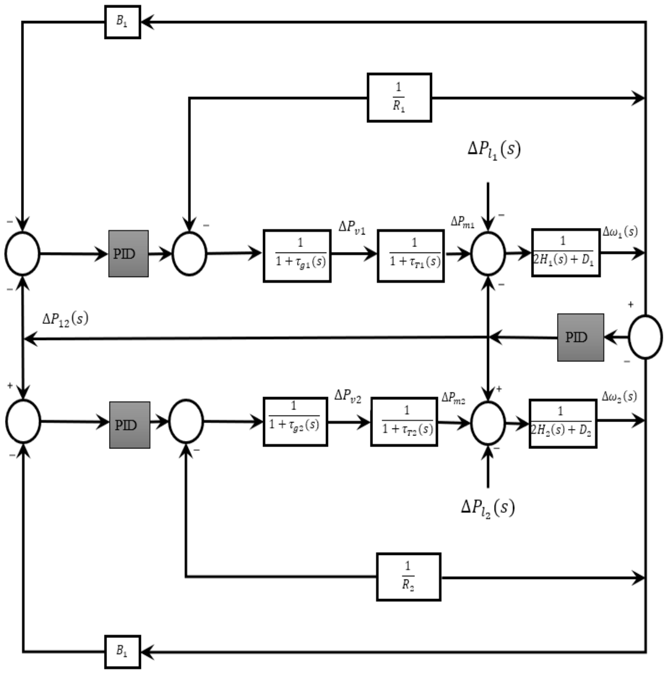

Fig.1 Two-area AGC diagram with PID controller

Table 1. Transposing principle

AREA	1	2
Speed Regulation (R)	0.05	0.0625
Frequency-Sensitive Load Coefficient (D)	0.6	0.9
Inertia Constant (H)	5	4
Base Power	1000MVA	
Governor Time Constant (Tg)	0.2	0.3
Turbine Time Constant (Tt)	0.5	0.6
Step Load	0.1875	0.140

The proposed model was simulated in MATLAB 2021 in a computer designed with, Intel(R) Core (TM) i7-8750H CPU @ 2.20GHz 2.21 GHz, 8.00 GB (7.89 GB usable) RAM, 64-bit operating system, x64-based processor, and Windows 11 Pro.

To test the effectiveness of the proposed scheme it is tested on 3 different AGC two-area systems.

The first test (test 1) is carried out on a modified non-reheat thermal power system [11] comparing PID tuned with the classical method, PID tuned with original SSA and PID tuned with AOSSA.

The second test (Test 2) is carried out on a standard non-reheat thermal power system [18] with a step load of 0.014 and 0.028 in areas 1 and 2 respectively, comparing an adaptive PI-GA control technique to the PID tuned with AOSSA

The third test (Test 3) is carried out on a standard thermal power system [9] with a step load of 0.2 and 0.1 in areas 1 and 2 respectively, comparing a PID tuned with Particle swarm optimization to the PID tuned with AOSSA

All system loading conditions are modified at t=0. The system results are then analyzed for the Area control error for areas 1 and 2, the frequency response for areas 1 and 2, and the Tie-line response and are compared on basis of Peak overshoot, Peak undershoots, and Settling time.

NB: Tests 2 and 3 use a table for comparing values as the complete data points are unavailable.

6. RESULTS AND ANALYSIS

6.1. *Opposition Based-Initialization Results for the optimized load frequency control scheme*

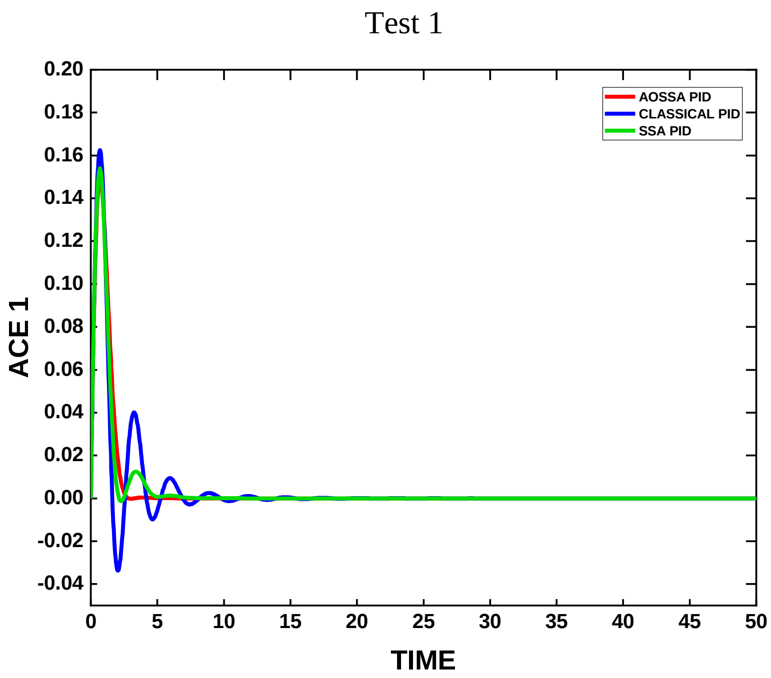

Fig. 1. ACE 1(test 1)

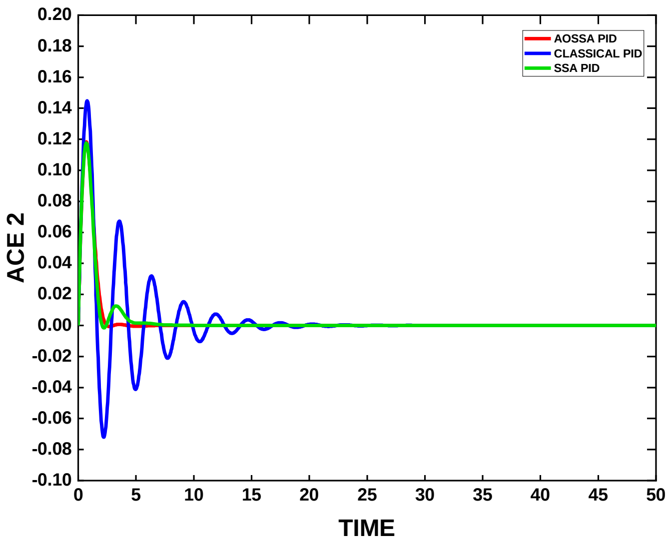

Fig. 2. ACE 2(test 1)

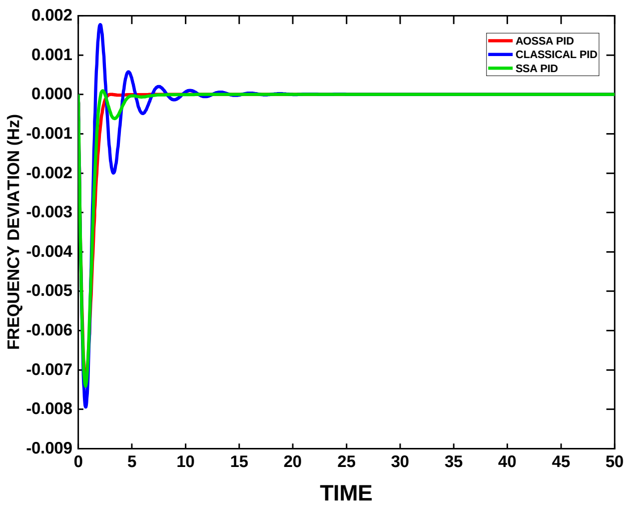

Fig. 3. Frequecy response Area 1(test 1)

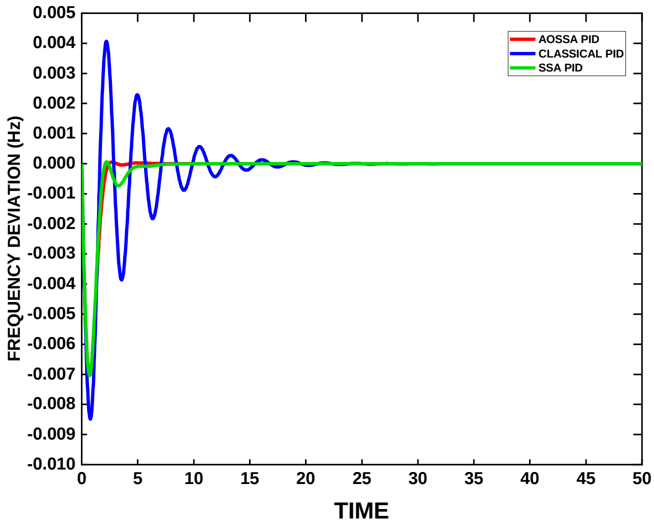

Fig. 4. ACE 1 Frequency Response Area 2(test 1)

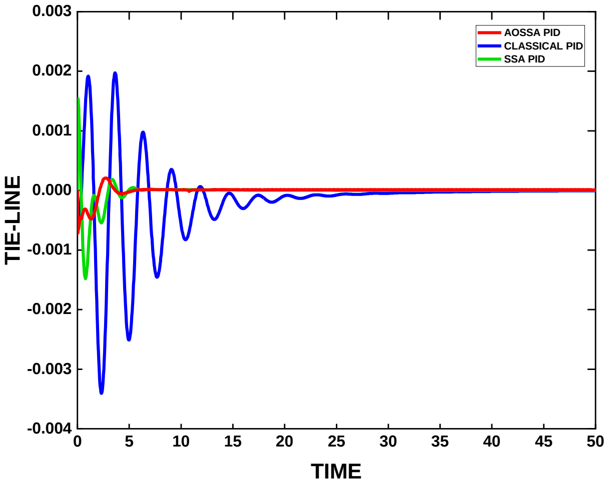

Fig. 5. Tie-line response (test 1)

Table 1. test 2 and 3 results

Evaluations	*PI-GA*	*AOSSA*		*PSO*	*AOSSA*
	Test 2			*Test 3*	
ACE 1					
OVERSHOOT	*0.0022*	***0***		*0.15*	***0.1473***
UNDERSHOOT	***0.001***	*0.016*		*0.00008*	***0***
SETTLING TIME	*7*	***5.5***		*7.5*	***2.9***
ACE 2					
OVERSHOOT	*0.0009*	***0***		*0.1035*	***0.1177***
UNDERSHOOT	***0.0032***	*0.0115*		*0.0002*	***0***
SETTLING TIME	*7.2*	***6.5***		*11*	***2.618***
TIE-LINE					
OVERSHOOT	*0.0018*	***0.001***		*0.0015*	***0.000224***
UNDERSHOOT	***0.0002***	*0.0058*		*0.003*	***0.0007***
SETTLING TIME	*8*	***6.4***		*20*	***5.8***
Δf_1					
OVERSHOOT	*0.0025*	***0.0015***		*0.0001*	***0***
UNDERSHOOT	***0.0028***	*0.037*		*0.0072*	***0.007***
SETTLING TIME	*10*	***4.1***		*16*	***2.597***
Δf_2					
OVERSHOOT	*0.0041*	***0***		*0.000003*	***0***
UNDERSHOOT	***0.0048***	*0.027*		*0.00615*	***0.007***
SETTLING TIME	*10*	***7***		*20*	***2.85***

6.2. Test analysis

The results presented *figure 2* which represents area control error measurement for area 1, shows that the PID controller tuned with the AOSSA has a 9% improvement in peak overshoot, 100% improvement in peak undershoot, 83.4% improvement in settling time in comparison to the PID controller tuned with the classical method and 4.3% improvement in peak overshoot, 100% improvement in peak undershoot and 45.3% improvement in settling time in comparison with the PID controller tuned with the original sparrow search algorithm. *Figure 3* which represents the area control error measurement for area 2 shows the PID controller tuned with AOSSA having a 17%, 100% and 97% improvement in peak overshoot, peak undershoot and settling time respectively in comparison to the PID controller tuned with the classical method and a 0%, 0% and 6.5% improvement in peak overshoot, peak undershoot and settling time respectively in comparison to the PID controller tuned with the original SSA.

Figure 4 representing the frequency response in area 1 shows a 100%, 9% and 97% improvement the proposed method has over the PID controller tuned with the classical method in peak overshoot, peak undershoot and settling time respectively and a 100%, 2.3% and 64% improvement the proposed method has over the PID controller tuned with the original SSA in peak overshoot, peak undershoot and settling time respectively. Figure 5 representing the frequency response in area 2 shows a 100%, 16.7% and 87.7% improvement the proposed method has over the PID controller tuned with the classical method in peak overshoot, peak undershoot and settling time respectively and a 0%, 0.7% and 33.7% improvement the proposed method has over the PID controller tuned with the original SSA in peak overshoot, peak undershoot and settling time respectively.

The tie-line power flow represented by *figure 6* shows a 98.5%, 95% and 3% improvement the proposed method has over the PID controller tuned with the classical method in peak overshoot, peak undershoot and settling time respectively and a 0%, 0.7% and 33.7% improvement the proposed method has over the PID controller tuned with the original SSA in peak overshoot, peak undershoot and settling time respectively. Table 2 depicts the performance of the of the proposed method in comparison with methods in literature. Table 2 shows in bold the method with the better performance in each measured category. Test 2 shows the PID tuned with AOSSA having a better performance in peak overshoot and settling time in comparison PI-GA in all evaluations provided. Test 3 shows the PID controller tuned with AOSSA having a better performance in peak overshoot, peak undershoot and settling time in comparison to the PID controller tuned with PSO.

The results show the proposed control scheme having the best performance in peak overshoots, peak undershoots, and settling time when compared to the PID tuned with the classical method and PID tuned with the original sparrow search algorithm.

7. CONCLUSION

Firstly, a modification was made to the sparrow search algorithm to improve the adaptability and search quality. This improvement is called the Adaptive opposition-based sparrow search algorithm. (AOSSA). The improvement targeted the initial sparrow population and the producer selection. The enhancement made was used to search the gain parameters of the PID controller, then 3 tests were performed. The control scheme proposed performed better than the other control schemes, having a better settling time and a good dynamic performance. Overall, the enhancement made in this paper achieved the load frequency control objective with sufficient improvements.

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