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doi:10.15199/48.2024.09.14

Design of PID controller with integral performance criteria using Salp swarm algorithm for interconnected thermal power systems

***Abstract**. This article is propose an application of Salp Swarm Algorithm (SSA) to design PID controller for Automatic Generation Control (AGC) of a two-area interconnected thermal power system with governor dead-band. The optimum controller gain is obtained by Integral Time-weighted Squared Error (ITSE) criterion. Furthermore, performance of the propose system is analysed from maximum overshoot and settling time of frequency deviation in each area, the line power deviation and the system error. The results of the simulation compared to PID controller tuned by Particle Swarm Optimization (PSO) show that SSA have a better performance.*

***Streszczenie.** W artykule zaproponowano zastosowanie algorytmu Salp Swarm (SSA) do zaprojektowania regulatora PID do automatycznego sterowania wytwarzaniem (AGC) dwuobszarowego połączonego systemu elektroenergetycznego ze strefą nieczułości regulatora. Optymalne wzmocnienie regulatora uzyskuje się na podstawie kryterium całkującego błędu kwadratowego ważonego w czasie (ITSE). Ponadto wydajność proponowanego systemu jest analizowana na podstawie maksymalnego przekroczenia i czasu ustalania odchylenia częstotliwości w każdym obszarze, odchylenia mocy linii i błędu systemu. Wyniki symulacji w porównaniu ze sterownikiem PID dostrojonym za pomocą optymalizacji roju cząstek (PSO) pokazują, że SSA mają lepszą wydajność. (**Projekt regulatora PID z kryteriami wydajności całkowej wykorzystującego algorytm roju Salp dla połączonych systemów energetycznych**)*

Keywords: load frequency control, optimization techniques, salp swarm algorithm.
Słowa kluczowe: kontrola częstotliwości obciążenia, techniki optymalizacji, algorytm roju salp.

Introduction

Power plants are vital facilities in generating electricity, which is an essential form of energy in today's world. A well-functioning power plant must be capable of producing enough electrical power to meet the ever-changing demands of electricity consumers. Additionally, it should be able to generate electricity with stability, maintaining the voltage and frequency within standardized limits, even when faced with various disturbances [1]. This ensures that consumers receive the best possible electrical energy without causing damage to their electrical appliances. Currently, automatic generation control has been employed to power systems to maintain the electrical voltage at a standard level (Automatic Voltage Regulator-AVR) and controlling the frequency within a standard range (Load Frequency Control-LFC). These automated systems help to resolve issues related to electrical voltage fluctuations and frequency deviations, ensuring a stable and reliable power supply.

In an automatic generation control, it is essential to have a suitable controller to regulate the system's operations to minimize errors as much as possible. To solve this problem, Optimization techniques [2] can be employed to find the optimal parameters for the controller that lead to the lowest possible error. The significant advancements in computer performance over the past years have greatly improved processing capabilities, allowing optimization algorithms to be developed and utilized more extensively in electrical systems. By taking advantage of these computing capabilities, optimization algorithms can efficiently analyze data and optimize control parameters to enhance the performance of electrical systems. This has led to the continuous development and application of various algorithms in power systems and other electrical applications. As a result, optimization algorithms and automatic generation control has become more prevalent and effective in the field of electrical engineering [3-11] .

The Salp Swarm Algorithm [12] is an algorithm that mimics the foraging behavior of salp colonies in the ocean, where they form chain-like structures and drift with the currents to find food. The distinctive feature of the Salp Swarm Algorithm lies in the continuous communication among the members of the swarm, allowing for rapid access to results and constant adaptation of key variables, which leads to an inherently w ide search space. This makes it suitable for finding solutions to complex and intricate problems.

In this article, the Salp Swarm Algorithm mentioned in the preceding paragraph is applied to solve the problem in the two-area interconnected thermal power system. The algorithm is implemented using a PID controller and its performance is compared with two-area interconnected thermal power system, but utilizing Particle Swarm Optimization (PSO) algorithm[13].

Interconnected Thermal Power System

In this article, the performance of the Salp Swarm Algorithm in finding suitable parameters for the PID controller is tested for the two-area interconnected thermal power system. The simulation involves each power plant having a production capacity of 2000 MW and supplying energy to a load of 1000 MW [14]. To enhance the system's realism, a governor dead band has been introduced, making the system nonlinear to study the transient response of frequency in both power plants, including the tie line power, when subjected to a Step Load Perturbation (SLP) disturbance of 0.01 p.u. in the thermal power plant of area 1, as shown in Figure 1. Whist, Table 1 depicts the parameters for two-area interconnected thermal power system.

The PID Controller

As shown in Figure 1, PID controller [15] is a control mechanism that aims to adjust the system's output to be close to the desired value. Figure 2 shows the configuration of PID controller. This controller operates using three main components: P (proportional), I (integral), and D (derivative). These components work together to fine-tune and regulate the system's output, making it align with the desired value. The PID controller is widely used in various systems where precise control and achieving desired values are essential. In this study, the boundaries of the PID parameters are defined in Table 2.

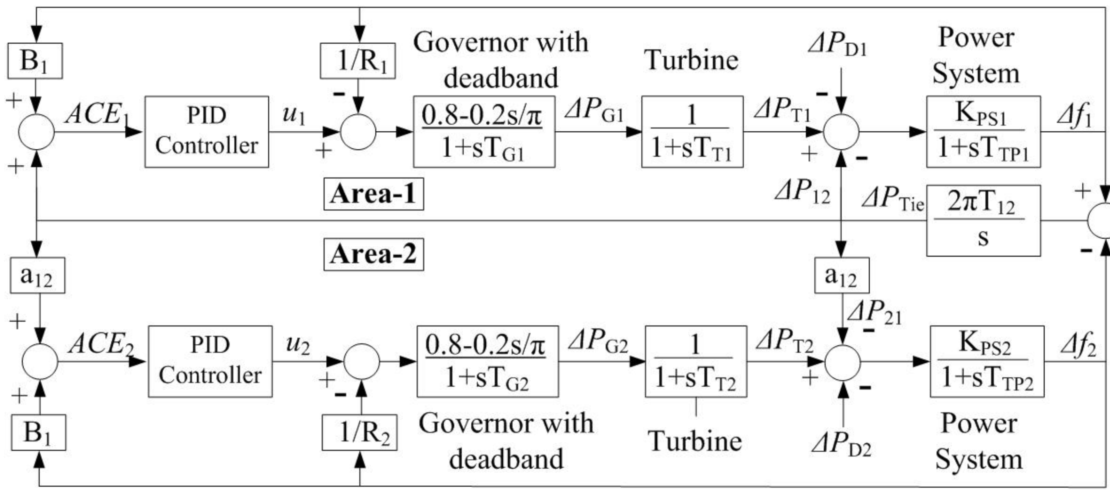

Fig. 1 Two-area Interconnected Thermal Power Systems

Table 1. parameters for two-area interconnected thermal power system

Parameters		Values
a_{12}	Coefficient between the two-control area	-1
B_1, B_2	Frequency bias constant	0.425 p.u.MW/Hz
R_1, R_2	Regulation constant	2.4 Hz/p.u.
T_{T1}, T_{T2}	Time constants of the governor	0.2 s
T_{G1}, T_{G2}	Time constants of the governor	0.3 s
K_{PS1}, K_{PS2}	Gain of power system	120 Hz/p.u. MW
T_{PS1}, T_{PS2}	Time constants of the governor	20 s
T_{12}	Synchronization time between the two-control area	0.0707 p.u.

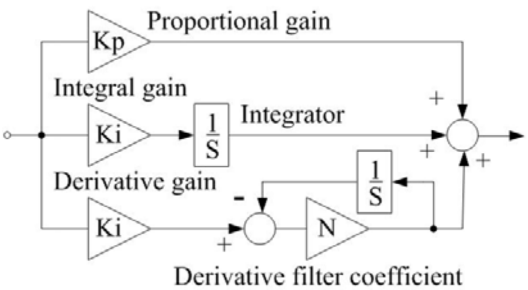

Fig. 2 PID Controller

Table 2. The boundaries of the PID parameters

Parameters	K_P	K_i	K_d	N
Minimum	0	0	0	0.01
Maximum	10	10	10	100

The Objective Function

In this study, the most chosen PID controller, consisting of parameters, was selected. proportional gain (Kp), integral gain (Ki), differential gain (Kd) and filter coefficient (N) evaluation of responses from the objective function (Objective function) by Integral Time-weighted Squared Error (ITSE) method. This allows for a comprehensive assessment of the stability of the control system, as it examines the error over time using time-weighted contributions to capture the actual error occurrence accurately. The ITSE criterion has been used as objective function to find optimum controller gain. Consequently, ITSE is given by

$$\text{ITSE} = \int_0^{t_{sim}} \left[\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2\right] \cdot t \cdot dt \qquad (1)$$

Where Δf and ΔP_{tie} are the frequency deviation and the tie-line power deviation of power systems, respectively.

The objective function and parameter ranges of the PID controller, as demonstrated above, have been applied to the Salp Swarm Algorithm. In this application, the position of the food source represents the values of the PID controller parameters, and the fitness value corresponds to the overall error of the system.

The Salp Swarm Algorithm

The Salp Swarm Algorithm (SSA) is an algorithm that mimics the behavior of salps, which are marine organisms living in the ocean. It was developed by Mirjalili in 2017 [12] and has gained significant popularity due to its ease of use and high efficiency. In nature, salps form chains to search for food. To simulate their behavior, the algorithm divides the population of salps into two groups: leaders and followers. The leader salp is the first salp in the chain, while the rest are followers. Each follower salp moves towards the salp directly in front of it, simulating their movement towards food sources. The Salp Swarm Algorithm has proven to be an effective optimization technique and has found widespread use due to its simplicity and impressive performance.

The simulation process of SSA begins by randomly generating a population of salps within the predefined boundaries. Then, each salp's fitness is evaluated based on the objective function, with the salp having the lowest value or closest proximity to the food source designated as the leader. The remaining salps become followers. Next, the value of c1 is updated according to Equation (3), with the leader salp moving towards the food source using Equation (2). The follower salps, on the other hand, move towards the salp in front of them using Equation (5). This process iterates continuously until the termination condition is met, or when the best food source is discovered.

(2) $$x_j^1 = \begin{cases} F_j + c_1((ub_j - lb_j)c_2 + lb_j) & c_3 \geq 0 \\ F_j - c_1((ub_j - lb_j)c_2 + lb_j) & c_3 < 0 \end{cases}$$

(3) $$c_1 = 2e^{-(\frac{4l}{L})^2}$$

(4) $$c_2 = rand() \quad and \quad c_3 = rand()$$

(5) $$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1})$$

Simulation Results

The two-area interconnected thermal power system was simulated using MATLAB SIMULINK. The goal was to compare the system's performance when subjected to a Step Load Perturbation (SLP) of 0.01 p.u. in the thermal power plant in area-1. The comparison aimed to evaluate the frequency response between the PID controller tuned with SSA and PSO from 30 runtimes as shown in Table 3.

Table **3**. The optimization controller parameters.of PID parameters

Optimization technique /Controller parameters	Particle Swarm Optimization (PSO)	Salp Swarm Algorithm (SSA)
K_p	0.8219	0.7521
K_i	2.3338	2.6641
K_d	1.5432	1.0282
N	99.8458	100.000

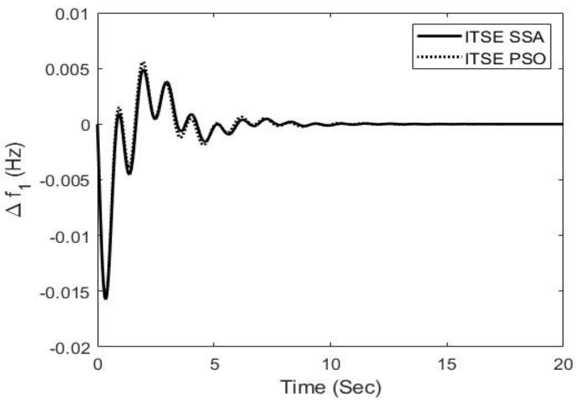

Fig. 3 Frequency deviation of area-1 with ITSE objective function.

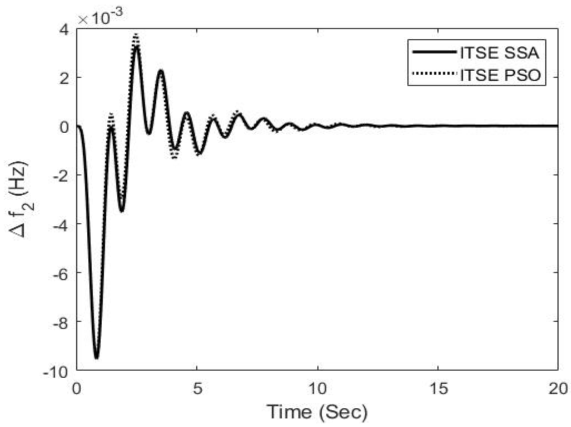

Fig. 4 Frequency deviation of area-2 with ITSE objective function.

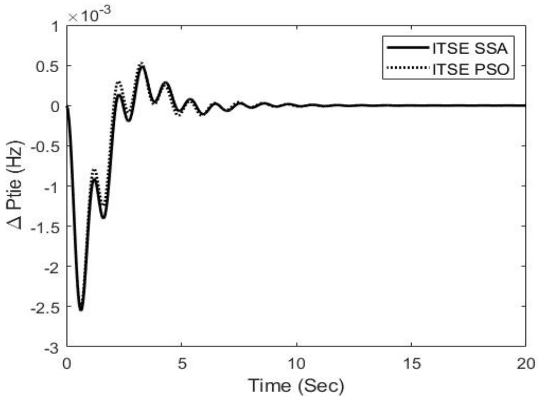

Fig. 5 Tie line power deviation with ITSE objective function.

The results of the study showed how each tuning method, using either the Salp Swarm Algorithm or the Particle Swarm Optimization Algorithm, affected the frequency response of the power system. The deviations in the frequency response were measured to determine the stability and robustness of the system in the presence of the SLP disturbance. The frequency response of the two-area interconnected thermal power system was evaluated under the influence of a Step Load Perturbation (SLP) of 0.01 p.u. at time t=0s in area 1. The frequency deviations Δf_1 and Δf_2, as well as the tie line power deviation ΔP_{tie}, were analyzed and compared for each tuning method as shown in figures 3 to figure 5.

The evaluation of algorithm performance can be measured by comparing the maximum overshot, settling time, and integral of absolute error of the system. These performance metrics are presented in Table 4 to Table 6 for analysis and comparison.

Table 1 Comparison of overshot between SSA and PSO.

Optimization technique	Peak of overshoot		
	Δf_1	Δf_2	ΔP_{tie}
PSO	0.0056	0.0038	0.0005
SSA	0.0049	0.0033	0.0005

Table *5* Comparison of settling time between SSA and PSO.

Optimization technique	Settling time		
	Δf_1	Δf_2	ΔP_{tie}
PSO	9.0127	8.4713	4.5223
SSA	8.4076	8.0255	4.6178

Table 6 Comparison of overall error between SSA and PSO.

Optimization technique	Overall error
PSO	0.0001519958
SSA	0.0001511709

Table 4 compares the frequency response performance using the maximum overshot of both algorithms. The maximum overshot values in area-1 and area-2 show that the system tuned with the Salp algorithm has lower maximum overshot compared to the system tuned with the Particle Swarm algorithm. Table 5 compares the frequency response performance using the settling time at 2% of both algorithms. The settling time at 2% of the Salp algorithm in area-1 is lower than that of the Particle Swarm algorithm. However, the settling time at 2% of the Salp algorithm in area-2 and tie line power is higher than that of the Particle Swarm algorithm. Table 6 compares the transient response performance using the integrated error of both algorithms. It is observed that the integrated error of the system with the Salp algorithm is slightly lower than that of the Particle Swarm algorithm.

Conclusions

The performance of the two-area interconnected thermal power system can be observed that the system's efficiency, when tuned using the Salp Swarm Algorithm. This algorithm was better than the system tuned using the Particle Swarm algorithm, albeit slightly. However, the Salp Swarm Algorithm offers greater ease of use and adaptability due to its fewer parameter adjustments required to suit specific problems. This makes it more feasible for application in more complex problem scenarios compared to the Particle Swarm Algorithm.

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