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Original scientific paper

Improvement of Load Frequency Control with Dragonfly Algorithm in Single Shaft Combined Cycle Power Plant

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Abstract: Load Frequency Control (LFC) maintains power system frequency stability by minimizing deviations due to load changes. Gas turbine (GT)-based power plants are favoured for their fast response, easy installation, and efficiency. A simplified mathematical model is used for LFC of a Rowen model gas cycle power plant with a 265 MW single shaft Heavy Duty Gas Turbine (HDGT). Heuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization Algorithm (PSO) and Simulated Annealing Algorithm (SA) are used to perform the analysis with these known and widely used control methods. In addition, the same studies were also performed using the Dragonfly Algorithm (DA). These analyses offer a scientific foundation for the efficient application of LFC in gas cycle power plants. In the study, performance criteria which express the error in frequency changes were comparatively analyzed. According to the obtained results, it is observed that the proposed PID controller with the DA tuning provides better solutions in terms of overshoot and settling time of the system frequency compared to other commonly used algorithms. Thus, it is observed that the frequency oscillations are damped in a shorter period when the DA method is used, and the DA is proposed as an alternative and reliable solution method for frequency control in gas cycle power plants.

Keywords: dragonfly algorithm (DA); heavy-duty gas turbine (HDGT); heuristic algorithms; load-frequency control (LFC); performance criteria; PID controller

1 INTRODUCTION

Natural gas Combined Cycle Power Plants (CCPP) are increasingly favored for electricity generation due to their benefits, including high efficiency, low investment costs, quick installation, superior emission performance, and easy access to natural gas, making them a key player in both environmental and economic aspects of power generation [1-3]. A GT is a device designed to convert mechanical energy into electrical energy. GT performance varies depending on ambient conditions especially air temperature, pressure, dust and humidity [4, 5]. Research has shown that the thermal efficiency of GT has increased to over 40% thanks to advances in materials technology, new coating techniques, increased compressor pressure ratio and improved cooling methods [6, 7]. In CCPP, frequency must stay within specified limits during energy transfer to the grid. Load changes can cause frequency variations due to imbalances in mechanical and electrical power, resulting from fluctuations in the turbine shaft speed. LFC automatically adjusts mechanical power via a speed governor to minimize frequency deviations from the nominal value [8-10]. LFC studies are first performed using computer simulation programs. Hence, using a precise and reliable model that accurately reflects the system is crucial in LFC studies for analyzing the dynamics and estimating the parameters of GTs used in electric power generation [11-14]. Numerous simplified models are available for use in GT LFC studies. The Rowen model first appeared in 1983 in Rowen's paper on a GT that could be used for dynamic performance studies of a power system [15]. A simplified mathematical model is needed for controlling heavy-duty gas turbines [16]. Rowen's simplified model represents the steady-state thermodynamic characteristics of a GT, including basic time delays and control equations for temperature, governor, and acceleration. It models a HDGT in a simple cycle without heat recovery, aiming to maintain a constant speed within 95-107% of the nominal speed, operating at a reference ambient temperature of 15 °C and a pressure of 101.325 kPa [17]. It has also been observed that the Institute of Electrical and Electronics Engineers (IEEE) model is widely used in LFC studies [18-20].

In this study, the DA is used for LFC applications. The experiments are carried out on an example system based on the Rowen model to provide a reliable testbed. In a single-shaft combined gas cycle power plant, a PID controller is used to optimize LFC, ensuring the frequency remains at the reference level during load variations. In the first stage, GA, SA and PSO methods are applied, and then more reliable results are obtained by using the DA. These results suggest DA as an alternative solution method.

2 ROWEN MODEL OF GAS TURBINE

In the CCPP, the gas compressed in the compressor is heated by using a suitable fuel to increase the pressure and enthalpy value. The gas with increased pressure and enthalpy is used to obtain mechanical energy with the help of GT. Mechanical energy is converted into electrical energy by connecting the GT shaft to the electric generator. This is illustrated in Fig. 1 [21].

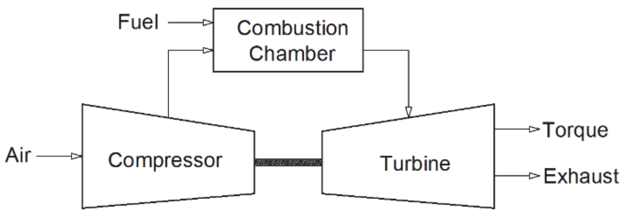

Figure 1 Gas turbine general schematic

In Eq. (1), *a*, *b*, and *c* represent the coefficients of the valve transfer function, while *T* denotes the time constant of the fuel system in Eq. (2).

$$\frac{V_p(s)}{W_d(s)} = \frac{a}{bs+c} \tag{1}$$

$$\frac{W_f(s)}{V_p(s)} = \frac{1}{Ts+1} \tag{2}$$

The gas turbine torque (F_2), as defined in Eq. (3), is expressed as a linear function of the turbine fuel flow lower limit (W_{fl}) and the rated turbine speed (N_{rated}) [22]. This torque functions to eliminate the speed error within the system.

When a step load disturbance with a magnitude of 1 p.u. is applied, the true torque is calculated as the difference between the gas turbine torque (F_2) and the torque (T). The torque characteristics of the gas turbine exhibit a linear relationship with both the fuel flow (W_f) and the turbine speed (N). The resulting true torque is then converted into the actual turbine speed through the rotor time constant (T_1) within the rotor dynamics block. This dynamic structure plays a crucial role in determining the system's performance and stability response.

$$F_2 = 1.3(W_f - W_{fl}) + 0.5(N_{\text{rated}} - N) \tag{3}$$

2.1 Speed Controller

The speed control transfer function model is shown in Fig. 2 [23]. The transfer function of the system is defined as a function that aims to maintain the turbine speed at the reference speed. Eq. (4) mathematically represents the relationship between speed deviation (e) and controller output (c) [23]. W, X, Y, and Z are the coefficients in the transfer function of the speed controller.

$$\frac{c(s)}{e(s)} = \frac{W(Xs+1)}{Ys+Z} \tag{4}$$

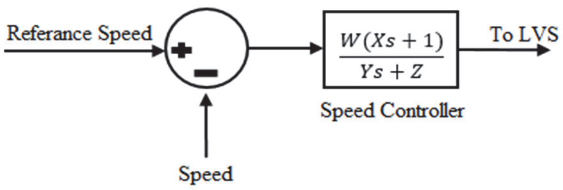

Figure 2 Transfer function model of the speed controller

2.2 Temperature Controller

LFC, when the pressure of the gas needs to be increased to balance the mechanical energy variations, the temperature of the gas is also increased. This relationship maintains the energy balance necessary to ensure efficient operation of the system. However, during this process, the exhaust temperature must not exceed the limit value in order not to damage the turbine blades. W_f and N are linear functions of the GT exhaust temperature, as expressed in Eq. (5). In Eq. (5), T_x is the exhaust temperature and T_R is the reference temperature. The transfer function model of the temperature controller is shown in Fig. 3.

$$F_1 = T_X = T_R - 700(1 - W_f) + 550(1 - N) \tag{5}$$

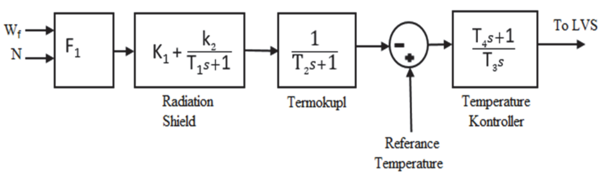

Figure 3 Transfer function model of the temperature controller

2.3 Acceleration Controller

The acceleration, calculated using the speed differentiator, is compared with the reference acceleration, and the resulting error is sent to the acceleration controller. The transfer function model of the acceleration controller is shown in Fig. 4 [23].

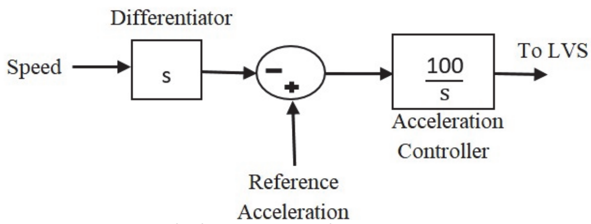

Figure 4 Transfer function model of the acceleration controller

2.4 Rowen's Simplified Model

The speed controller, temperature controller, and acceleration controller in the Rowen Model form the simplified heavy-duty HDGT model, which is shown in Fig. 5 [23]. In this model, the error value (e) represents the difference between the turbine speed and the desired reference speed value that must be maintained [23].

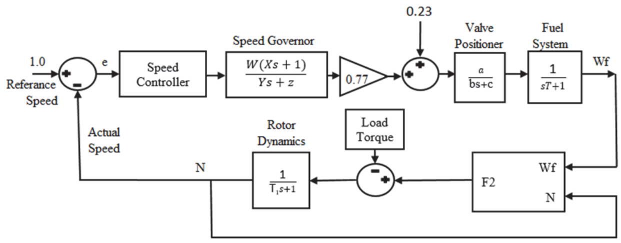

Figure 5 HDGT simplified rowen model

2.5 Performance Criteria Method

The most commonly used criteria are Integral of Squared Error (ISE), Integral of Absolute Error (IAE), Integral of Time-weighted Squared Error (ITSE) and Integral of Time-weighted Absolute Error(ITAE) [22], [24-26]. The performance index (J) tuning criteria used in our study are given in Eqs. from (6) to (9) respectively. In Eqs. from (6) to (9), the function e is the error function between the output and the desired reference in the control system, while t represents the evaluation time.

$$J_{\text{ISE}} = \int e^2 \text{d}t \tag{6}$$

$$J_{\text{IAE}} = \int |e| \text{d}t \tag{7}$$

$$J_{\text{ITSE}} = \int (e^2) t \text{d}t \tag{8}$$

$$J_{\text{ITAE}} = \int \left| e^2 \right| t \text{d}t \tag{9}$$

3 HEURISTIC ALGORITHMS

3.1 Genetic Algorithm

GA is a research algorithm that models evolutionary processes. This method mimics the principle of natural selection and utilizes genetic variation in the problem-solving process [27]. GA is an effective optimization method that finds optimal solutions to complex problems and operates based on Darwinian principles [28, 29]. This algorithm evolves a randomly generated initial population using crossover and mutation operators, evaluates it through the fitness function, and aims to create a population that achieves better solutions over time [23].

3.2 Simulated Annealing Algorithm

The finite-time implementation of SA is achieved by creating homogeneous Markov chains of finite length (M) for a finite sequence of decreasing temperature values (T). In each iteration, the current solution (X_i) is replaced by a new solution (X_{i+1}), randomly chosen from the neighborhood. This new solution is accepted if it improves the objective function (E), or with a certain probability (e) based on the difference between the objective function values (ΔE) and the annealing temperature (T). This probability varies with decreasing annealing temperature based on the annealing program [30, 31].

3.3 Particle Swarm Optimization Algorithm

PSO is an optimization algorithm based on population, introduced by Kennedy and Eberhart in 1995, and inspired by the social behavior of animals in groups [32]. According to the comparisons made in the literature, PSO and its dual version BPSO stand out as the most popular approaches among swarm-based methods [33]. In one study, for example, the coefficients of a reduced model for HDGT plants were optimized with the PSO algorithm, demonstrating the effectiveness of the algorithm in practical applications [34]. In PSO, the sigmoid function values are computed based on the velocity of each particle, and the positions of the particles are updated using these values [35]. The velocity update is performed via a specific formula in PSO and is defined by Eq. (10).

$$v_{ij}^{(t+1)} = wv_{ij}^{(t)} + c_1 r_1 \left(pbest_{ij}^{(t)} - x_{ij}^{(t)} \right) + c_2 r_2 \left(gbest^{(t)} - x_{ij}^{(t)} \right) \tag{10}$$

In Eq. (10), c_1 and c_2, which are the basic parameters of the PSO algorithm, represent the convergence rates of the particle to its own best position and the global best position respectively. In this study, the values of c_1 and c_2 are set in the range [0.2, 1]. Moreover, the coefficients r_1 and r_2 are binary randomly generated values with a normal distribution in the interval [0, 1]. These random coefficients are updated at each iteration, adding randomness to the movement of the swarm and increasing the diversity of the optimization process [35-37, 38].

3.4 Dragonfly Algorithm

The DA developed in recent years has been effectively applied to LFC problems in gas cycle power plants as a heuristic optimization technique. Inspired by the unique intelligence and big eyes in the hunting behavior of dragonflies around the world, this algorithm has gained an important place in the field of optimization [38]. While dragonflies can make localized changes by moving back and forth in small groups in static swarms during foraging, they have the ability to travel long distances in large groups in dynamic swarms during migration [39]. According to Reynolds, swarm behavior is governed by three fundamental principles: separation, alignment, and cohesion. These principles control how individuals interact with others in their vicinity, helping the swarm meet its needs for survival, navigation toward food, and protection from external dangers. In the DA location update process, five main factors drive these interactions, as illustrated in Fig. 6 [38, 40-42]. Fig.6 shows the five main factors that explain the relationships between individuals in a swarm. DA describes three fundamental principles of swarm behavior and interactions in the position update process under the heading [43].

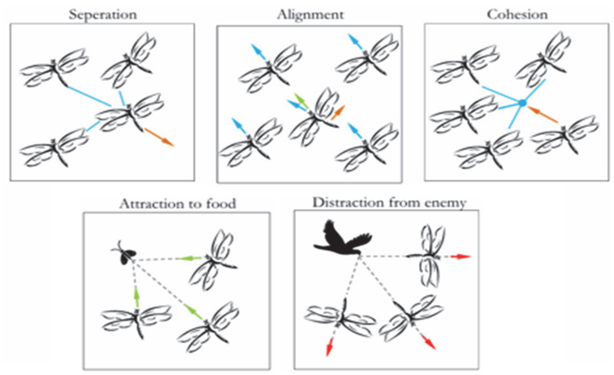

Figure 6 Primitive corrective patterns in swarms [38, 39, 41, 42]

The mathematical models formulated for each of these five behaviors are presented below [38, 40, 41]. The separation is determined using the following mathematical formula:

$$S_i = -\sum_{j=1}^{N} X - X_j \tag{11}$$

In Eq. (11), X denotes the position of the current individual, and X_j, j represents the position of the neighboring individual, where N is the total number of neighboring individuals. The alignment is calculated using the following mathematical expression:

$$A_i = \frac{\sum_{j=1}^{N} V_j}{N} \tag{12}$$

The term V_j in Eq. (12) denotes the velocity of the j. neighboring individual. Harmony is calculated with the following mathematical expression:

$$C_i = \frac{\sum_{j=1}^{N} X_j}{N} - X \tag{13}$$

The attraction towards the food source is calculated by the equation in Eq. (13):

$$F_i = X^{+} - X \tag{14}$$

In Eq. (14), the term X^{+} refers to the position of the food source. The outward behavior is calculated in Eq. (15), where X^{-} represents the position of the threatening enemy.

$$E_i = X^{-} + X \tag{15}$$

Step vector ΔX and position vector X were employed to update the positions of artificial dragonflies and simulate their movements.

$$\Delta X_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta X_t \tag{16}$$

Eq. (16) expresses the weight values of the factors *s, a, c, f, e*. Also, the value *w* represents the inertia weight at cycle *t*. After the step vector is calculated, the position vector is calculated in Eq. (17).

$$X_{t+1} = X_t + \Delta X_{t+1} \tag{17}$$

To enhance the stochastic behavior and exploration abilities of artificial dragonflies, the random walk (Le'vy flight) method was applied. In this scenario, the positions of the dragonflies were updated using the following mathematical equation.

$$X_{t+1} = X_t + Le'vy(d) * X_t \tag{18}$$

In Eq. (18), *t* denotes the current cycle, and *d* represents the size of the position vector. The pseudo-code steps of the DA algorithm are outlined below [38, 41].

4 RESULTS & DISCUSSION

4.1 Gas Turbine Modeling and Comparison of Results

In this study, LFC of a Rowen model gas cycle power plant with a 265 MW single shaft HDGT is investigated using different control methods, various performance indices and heuristic optimization techniques. A PID controller is employed for the LFC of the gas turbine. The parameters of these controllers are optimized using heuristic optimization techniques like SA, GA, PSO, and DA. The outcomes are compared with similar studies from literature. Performance metrics such as ISE, ITSE, ITAE, and IAE are used to assess the effectiveness of the control methods.

Fig. 7 illustrates the Simulink model for PID optimization in GT LFC.

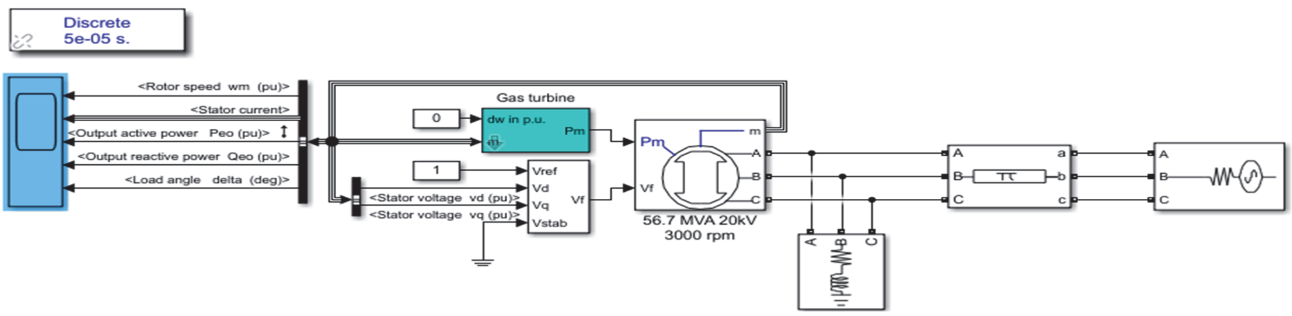

Figure 7 Simulink model of PID optimization in gas turbine load-frequency control

4.2 Determination of Gas Turbine PID Control Parameters and ISE Performance Index

Tab. 1 shows the PID parameters obtained by various methods and their time responses and ISE performance indices. Especially the performance of the DA method seems to be more advantageous compared to the other methods.

As a result, the DA method provides the best performance in GT control compared to other methods. It provides a fast response with low Rise Time and Peak Time values, while offering stable and precise control with the lowest Settling Time and Overshoot values.

In addition, the low ISE performance index increases the sensitivity and accuracy of the system. Therefore, the DA method stands out as the most suitable method for optimization of GT PID parameters.

Table 1 Gas turbine PID parameters, time responses, overshoot values and ISE performance criteria table

Methods	PID Parameters			Time Responses			Overshoot / %	ISE Performance Index
	Kp	*Ki*	*Kd*	Rise Time t_r / ms	Peak Time t_p / s	Settling Time t_s / s		
Ref. [25]	5.36	0.154	0.9200	132.981	0.350	70	34.459	0.1372
SA	4.5063	0.9346	0.9351	140.535	0.350	25	25.949	0.1306
GA	3.629	0.5520	0.924	151.678	0.350	34	17.069	0.1271
PSO	3.1602	0.2250	0.9879	151.259	0.350	45	13.068	0.1242
DA	**2.4231**	**0.2298**	**1.1947**	**140.811**	**0.322**	**4**	**9.341**	**0.1206**

When the PID optimization and ISE performance graph of the GT LFC given in Fig. 8 is examined, it is seen that the DA method exhibits the best performance. DA gives the best result with low overshoot, fast settling time and low ISE performance index. Therefore, choosing the DA method in GT control systems will be the most effective approach to optimize the performance of the system. Apart from the DA method, the PSO method performs best compared to GA, GA, Ref. [25], SA methods, PSO performs the best performance. PSO stands out with the lowest overshoot value and the lowest ISE performance index. Although SA is faster in terms of settling time, PSO is found to be the most suitable method in terms of accuracy and precision when the overall performance is evaluated.

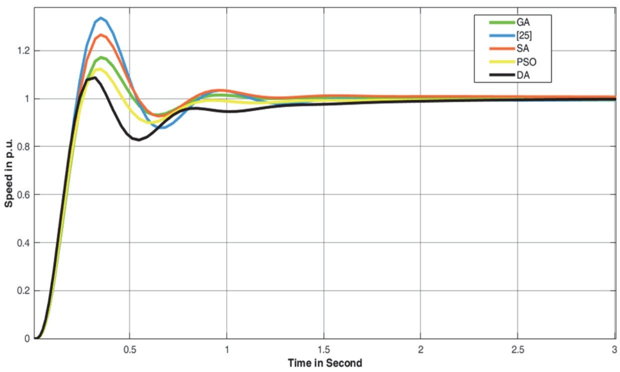

Figure 8 Performance graph of PID optimization and ISE in gas turbine

As a result, according to Fig. 8, in terms of PID optimization and ISE performance in GT LFC, the DA method is the most superior method with fast response, low overshoot, fast stability and low error rate. The DA method, represented by the black line in the graph, performs better than the other methods. Therefore, the use of the DA method in GT control systems can significantly improve the system performance.

4.3 Determination of Gas Turbine PID Control Parameters and ITSE Performance Index

According to the data in Tab. 2, the DA method has significant advantages over other methods in tuning the PID controller for the GT.

Although the SA method has the lowest rise time, its overshoot and ITSE performance lags the DA method. GA may have the lowest damping time but its overshoot and ITSE performance is lower than that of the DA method. This evaluation shows that the DA method has the potential to significantly improve the overall system performance when turning into the PID controller for GT.

Table 2 Gas turbine PID parameters, time responses, overshoot values and ITSE performance criteria table

Methods	PID Parameters			Time Responses			Overshoot / %	ITSE Performance Index
	Kp	*Ki*	*Kd*	Rise Time t_r / ms	Peak Time t_p / s	Settling Time t_s / s		
Ref. [25]	4.14	0.1300	0.7800	155.726	0.377	30	22.840	0.01378
SA	3.8881	0.9391	1.2391	126.777	0.321	11	21.341	0.01129
GA	3.601	0.413	0.832	161.378	0.377	4	15.698	0.01123
PSO	3.2159	0.6859	1.1206	140.366	0.320	10	14.368	0.01092
DA	**2.9016**	**0.2867**	**1.1068**	**144.317**	**0.320**	**2**	**11.798**	**0.01028**

The PID optimization and ITSE performance graph analysis of the GT LFC in Fig. 9 shows that the DA method outperforms the other methods. The DA method, with its low overshoot, allows the system to stabilize faster without exceeding the desired speed level. It also has the fastest settling time, enabling the system to reach the desired speed level faster and stably. The DA method is found to operate more stably and reliably with less oscillations compared to other methods. Comparing the other methods, GA shows reasonable performance, while SA and PSO methods lag DA in terms of overshoot and settling time. In addition, the reference method performs poorly compared to the others and is characterized by high overshoot and long settling time. It is clear from Fig. 9 that the choice of DA for optimizing the PID controller in GT LFC increases efficiency, reduces costs and ensures system reliability, which is a significant advantage in energy management.

4.4 Determination of Gas Turbine PID Control Parameters and ITAE Performance Index

The PID parameters, time responses, overshoot values and ITAE performance criterion presented in Tab. 3 were obtained by various optimization methods. According to our analysis, the method of Ref. [25] has the highest overshoot and settling time and the performance criterion is relatively high. The SA method performs better than DA but lags in terms of overshoot and settling time.

The GA method performs moderately well, while the PSO method performs well in general, but the overshoot and settling time are higher than DA. The use of DA in PID controller optimization for GT LFC improves efficiency, reduces costs and ensures system reliability in power systems. Therefore, the choice of DA helps to significantly improve system performance and provide critical advantages in energy management.

Table 3 Gas turbine PID parameters, time responses, overshoot values and ITAE performance criteria table

Methods	PID Parameters			Time Responses			Overshoot / %	ITAE Performance Index
	Kp	*Ki*	*Kd*	Rise Time t_r / ms	Peak Time t_p / s	Settling Time t_s / s		
Ref. [25]	5.48	0.3360	0.8000	139.176	0.3664	20	36.301	0.1073
SA	4.2219	1.7004	1.3830	115.674	0.290	12	27.564	0.2003
GA	3.7563	0.5582	0.9109	149.984	0.3664	15	18.452	0.0928
PSO	3.6273	0.4204	0.9327	149.602	0.3664	7	17.059	0.05945
DA	**3.3094**	**0.3669**	**0.9024**	**157.869**	**0.3664**	**3**	**13.068**	**0.05351**

The superior performance of the DA method is evident in Fig. 9, which compares different methods for optimizing the performance of the PID controller in GT LFC. The graph shows the variation of the time-varying speed per unit (p.u.) and compares the performance of various optimization algorithms. SA lags DA with higher overshoots and longer settling time. PSO performs well but lags DA in terms of overshoot and settling time. The reference method in [25] performs poorly compared to the others with high overshoot and longer settling time.

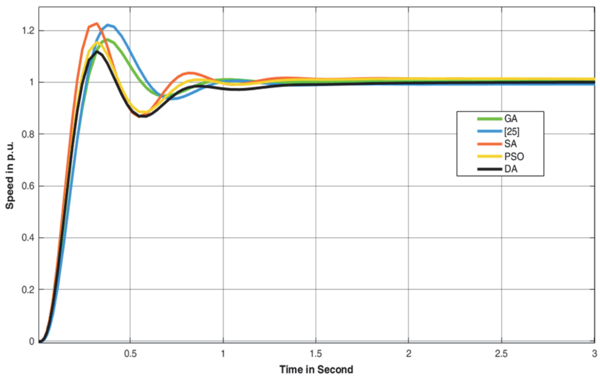

Figure 9 Performance graph of PID optimization and ITSE in gas turbine load-frequency control

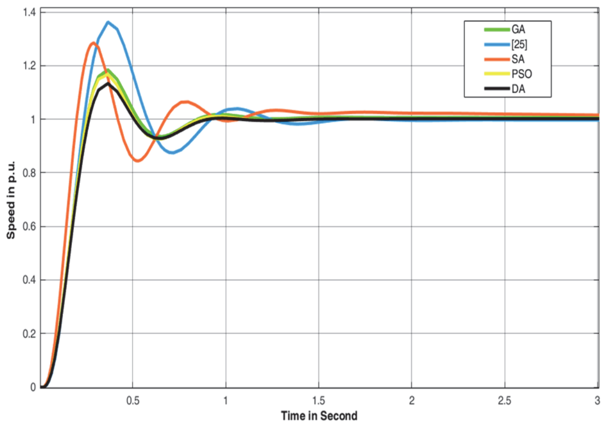

Figure 10 Performance graph of PID optimization and ITAE in gas turbine load-frequency control

In Fig. 10, the obvious advantages of the DA method are as follows:

Low overshoot: DA offers the lowest overshoot compared to other methods, which allows the system to stabilize faster without exceeding the desired speed level.

Fast Settlement Time: DA has the fastest settling time, which allows the system to stabilize and reach the desired speed level faster.

Less Oscillation: DA oscillates less than other methods, which makes the system more stable and reliable.

As a result, the superior performance of DA plays an important role in optimizing the PID controller in GT LFC. With low overshoot, fast settling time and lower ITAE performance criterion, DA increases efficiency, reduces costs and ensures system reliability in power systems. Therefore, the use of DA in the optimization of the PID controller in GT LFC significantly improves system performance and provides a critical advantage in energy management.

4.5 Determination of Gas Turbine PID Control Parameters and IAE Performance Index

A comparison of different methods for optimizing the performance of the PID controller in GT LFC is given in Tab. 4.

As a result, the DA method exhibits superior performance in optimizing the PID controller in GT LFC. With low overshoot, fast settling time and low IAE performance criterion, DA increases efficiency, reduces costs and ensures system reliability in power systems. Therefore, the use of DA in optimizing the PID controller in GT LFC significantly improves system performance and provides a critical advantage in energy management.

Table 4 Gas turbine PID parameters, time responses, overshoot values and IAE performance criteria table

Methods	PID Parameters			Time Responses			Overshoot / %	IAE Performance Index
	Kp	*Ki*	*Kd*	Rise Time t_r / ms	Peak Time t_p / s	Settling Time t_s / s		
SA	3.6674	0.8502	1.0682	140.980	0.346	20	17.059	0.2379
GA	3.1712	0.4188	0.9519	156.112	0.346	24	11.798	0.208
PSO	2.9823	0.2785	0.9384	159.138	0.313	3.5	10.556	0.2027
DA	**2.904**	**0.2821**	**0.8904**	**168.160**	0.346	**3**	**8.152**	**0.2022**

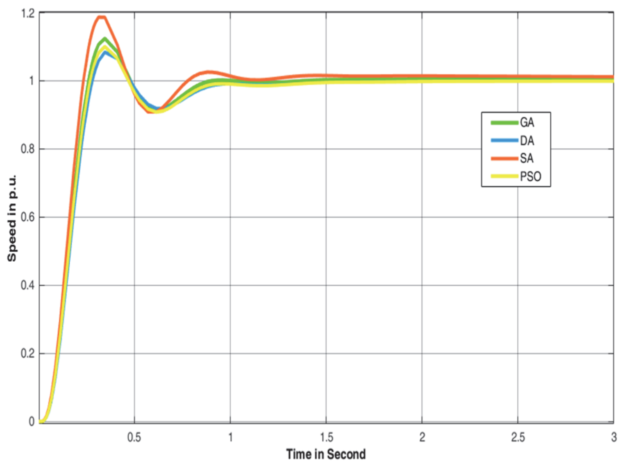

Figure 11 Performance graph of PID optimization and IAE in gas turbine load-frequency control

According to Fig. 11, although the GA method offers a reasonable overshoot and settling time, it is not as effective as the DA. The GA method has higher overshoot and settling time. The SA method has the highest overshoot and the longest settling time, which causes the system to take more time to stabilize and oscillate more. Although the PSO method performs well, it lags DA in terms of overshoot and settling time.

4.6 Gas Turbine Load-Frequency Control Performance Evaluation

Fig. 12 compares four different performance indices (ISE, ITSE, ITAE and IAE) for the evaluation of GT LFC performances. In each graph, the performance criteria of the different methods are shown. Each index value is determined to determine which method performs the best.

The DA method achieves the best performance across all evaluated indices, with the lowest values recorded for ISE (0.1206), ITSE (0.01028), ITAE (0.05351), and IAE (0.2022). As shown in Fig. 12, the DA method consistently outperforms other methods, demonstrating its superior effectiveness and efficiency.

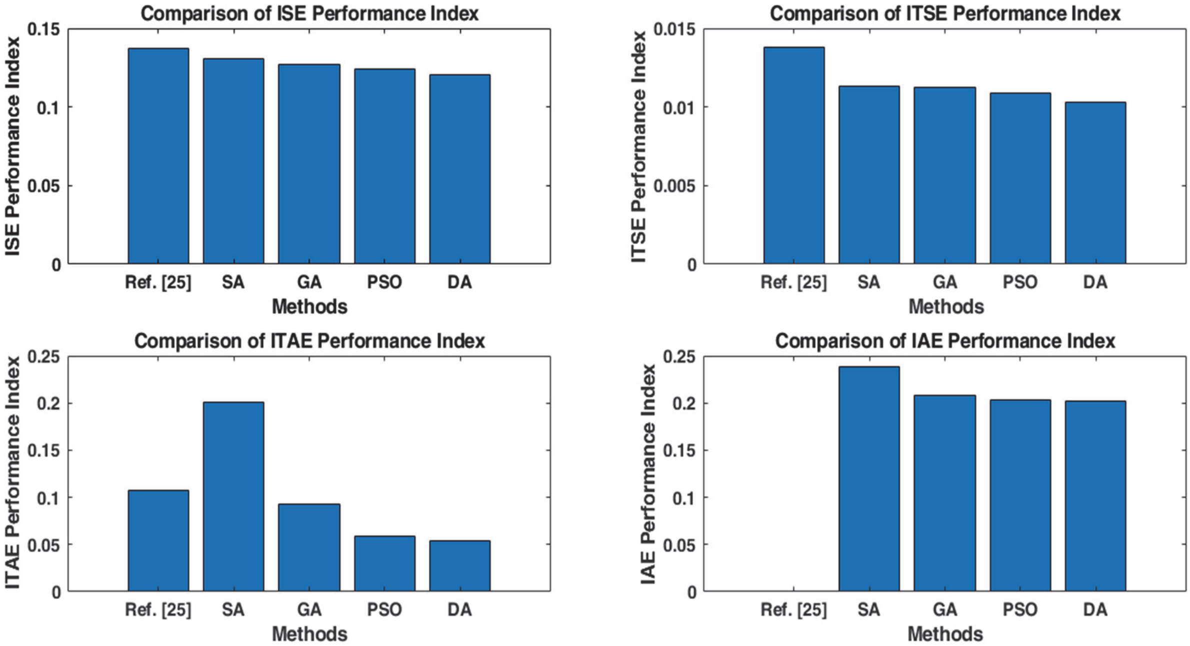

Figure 12 Evaluation of gas turbine load-frequency control performances a) ISE performance index; b) ITSE performance index; c) ITAE performance index; d) IAE performance index

The DA method shows a clear superiority compared to the other methods. As can be seen from the graph DA method:

Low Overshoot: It has the lowest overshoot value. This allows the system to stabilize faster without exceeding the speed level.

Fast Settlement Time: It has the shortest settling time. This allows the system to reach and stabilize to the desired speed level faster.

Low Oscillation: It shows less oscillation compared to other methods, resulting in a more stable system performance. As a result, according to Fig. 11, the DA method shows superior performance compared to the other methods. With low overshoot, fast settling time and low oscillation, DA is the most effective method for optimizing the PID controller in GT LFC. It is observed that DA improves efficiency, reduces costs and ensures system reliability in energy systems. Therefore, the use of DA inoptimizing the PID controller for GT LFC significantly improves system performance and provides a critical advantage in energy management.

5 CONCLUSIONS

In this study, a simplified mathematical model for LFC of a Rowen model gas cycle power plant with a 265 MW single shaft HDGT is used and analyzed with GA, PSO, SA and DA algorithms. Comparative analyses using different control methods and performance criteria (ISE, ITSE, ITAE and IAE) show that the advantages of the DA method are such as low overshoot, fast settling time and low oscillation. The DA method allows the system to stabilize faster without exceeding the speed level and a more stable system performance is achieved by reaching the desired speed level in a shorter time. The analysis results show that the PID controller optimized by the DA method provides more effective solutions for GT LFC than other methods. DA is found to be the most efficient solution for GT LFC with low overshoot rate and low IAE performance criteria. In conclusion, the use of the DA method for optimization of the PID controller in GT LFC increases efficiency, reduces costs and ensures system reliability in energy systems.

Therefore, the choice of the DA method in GT control systems has significantly improved the system performance and provided a critical advantage in energy management. This study proves that DA is an alternative and reliable solution for LFC in gas cycle power plants. To improve the effectiveness of the DA method in GT LFC, performance evaluation under different load conditions and artificial intelligence-based techniques, hybrid optimization approaches, multiobjective optimization strategies and industrial validation studies are suggested as future research.

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