

Research Article

Hunger Games Search Algorithm for Transient Response and Stability Enhancement of a Fractional-Order PID-Based Automatic Voltage Regulator (AVR) System

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Article Info	Abstract
Article History Received Feb 04, 2025 Revised May 02, 2025 Accepted May 10, 2025	Due to its larger stability margin, better transient response, and superior robustness to system uncertainties compared to conventional PID controllers, the fractional-order PID (FOPID) controller is gaining increasing attention. This paper proposes a FOPID controller optimized using the Hunger Games Search Algorithm (HGSA) to enhance the performance of an Automatic Voltage Regulator (AVR) system. The FOPID controller introduces two additional parameters, λ and μ , in addition to the conventional proportional (K_p), integral (K_I), and derivative (K_D) gains, thereby offering greater tuning flexibility and smoother control action. HGSA determines the optimal FOPID gains to improve the AVR system's transient response and stability. Key transient performance metrics, such as overshoot, rising time, and settling time, are used to evaluate effectiveness. The performance of the proposed HGSA-optimized FOPID controller is compared with that of other optimization algorithms reported in recent literature. The results demonstrate that the HGSA-based FOPID controller significantly reduces system overshoot by 7.75% to 57.88%, achieves improved rise time, and yields the lowest fitness function value, indicating better convergence characteristics. These outcomes confirm that HGSA is an effective optimization technique for enhancing transient performance, terminal voltage stability, and robustness of AVR systems.
Keywords	
Automatic Voltage Regulator (AVR) System	
Fractional-order proportional integral derivative (FOPID)	
Hunger Games Search Algorithm (HGSA)	
Transient response	
Robustness Analysis	
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1. Introduction

The stability of the electric power system is a fundamental concern in electrical engineering, as it directly affects the reliability and quality of electricity delivered to consumers [1]. An ideal power system must deliver voltage at a constant magnitude and frequency to meet load demands and prevent power quality issues, which can cause operational problems and equipment damage on both the consumer and utility sides.

While the power system cannot control the current drawn by loads, it can regulate the voltage. Fluctuations or instability in supply voltage can significantly impact electrical equipment, shortening its lifespan or causing outright failure. Additionally, power losses are influenced by the magnitude of the supplied voltage, meaning any variation leads to changes in reactive power and increased system losses, with substantial economic consequences.

Several methods have been proposed in the literature to address voltage instability [2-4]. Among these, the Automatic Voltage Regulator (AVR) plays a key role by adjusting the excitation of the synchronous generator to maintain terminal voltage at the desired level. A block diagram of the closed-loop

AVR system is illustrated in Figure 1.

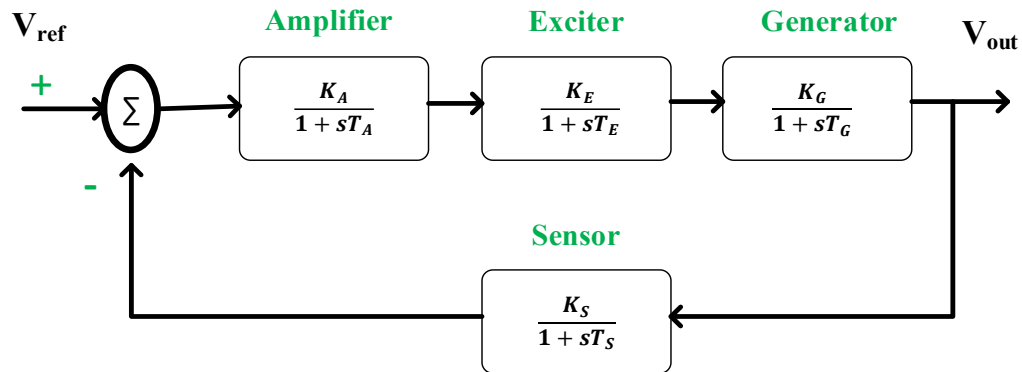


Figure 1. Block Diagram of the AVR System

However, due to the dynamic nature of loads and the high inductance of synchronous generators, maintaining optimal performance in an AVR system is challenging. Integrating a well-designed controller is crucial to managing continuous variations in terminal voltage.

This paper proposes a Fractional-Order PID (FOPID) controller for regulating the generator's terminal voltage by controlling excitation. To determine the required excitation level, the FOPID controller processes the error signal, i.e., the difference between the reference and the actual terminal voltage. Unlike the conventional PID controller, FOPID introduces two additional parameters (λ and μ), which enable finer tuning flexibility and enhance robustness and stability.

The key contribution of this paper is the application of the Hunger Games Search Algorithm (HGSA) for the optimal tuning of the FOPID controller parameters in an AVR system. The HGSA-based FOPID is benchmarked against other optimization techniques to validate its performance across transient response metrics (overshoot, rise time, settling time), minimized fitness function, and system stability.

2. Literature Review

Many studies have explored enhancing AVR system performance using classical and intelligent control strategies [5]. Traditionally, the Proportional–Integral–Derivative (PID) controller has been widely employed due to its simplicity, robustness, and well-established tuning methods, such as the Ziegler–Nichols (ZN) method, trial-and-error, and the Cohen–Coon (CC) method [6]. However, the PID controller's limited parameter set can constrain performance in highly dynamic or uncertain environments.

The Fractional-Order PID (FOPID) controller, with its additional fractional parameters λ and μ , offers greater flexibility in tuning and improved control performance. This makes it well-suited for AVR systems that operate under diverse and rapidly changing load conditions [7]. However, tuning the FOPID controller is more complex than tuning a conventional PID due to the increased number of parameters. As a result, researchers have turned to metaheuristic optimization algorithms to identify optimal controller gains.

In recent literature, various optimization algorithms have been applied to PID and FOPID controllers.

For instance, swarm intelligence algorithms such as the Grasshopper Optimization Algorithm (GOA) [7], Particle Swarm Optimization (PSO) [8, 9], and Artificial Bee Colony (ABC) [8] have been widely adopted. Evolutionary strategies like Differential Evolution (DE) [9] and Biogeography-Based Optimization (BBO) [10] have also shown effectiveness in this domain. In addition, bio-inspired algorithms such as the Whale Optimization Algorithm (WOA) [11], the Salp Swarm Algorithm (SSA) [11], and the Improved Kidney-Inspired Algorithm (IKA) [12] have been employed to enhance AVR system performance. Pattern Search Algorithm (PSA) [13], the Marine Predator Algorithm (MPA) [14], as well as newer methods like the Tree Seed Algorithm (TSA) and Modified Ziegler-Nichols (MZN) [15, 16], have also been investigated.

Most of these algorithms have been applied to conventional PID controllers. Only a few, including WOA and SSA, have been specifically employed for tuning FOPID controllers. These latter studies highlight the increased complexity and potential of FOPID tuning but suggest that further improvements are needed regarding convergence speed and robustness.

Several advanced control strategies have been explored in the literature to enhance the dynamic performance of AVR systems. Suid and Ahmad [17] presented a sigmoid-based PID (SPID) controller tuned using a nonlinear sine-cosine algorithm (NSCA), which demonstrated improved control accuracy and transient response. Sahin, et al. [18] introduced the sigmoid-based fractional-order PID (SFOPID) controller, whose parameters were optimized using the Dandelion Optimizer (DO) to enhance both robustness and dynamic response. Badr, et al. [19] proposed a fuzzy-based PID controller to improve AVR system performance, with its optimal parameters obtained using the Equilibrium Optimizer Algorithm (EOA). Furthermore, Kundu, et al. [20] investigated the performance of PID, artificial neural network (ANN), and adaptive neuro-fuzzy inference system (ANFIS) controllers for AVR regulation. In another approach, Furat and Cücü [21] employed sliding mode controllers (SMC) to manage terminal voltage under parameter uncertainties and load disturbances.

Despite the notable progress in controller design and optimization, existing strategies still exhibit limitations. Challenges such as limited convergence speed, sensitivity to parameter variations, and inconsistent performance across varying load conditions persist. Moreover, to the authors' knowledge, the Hunger Games Search Algorithm (HGSA) has not yet been applied to FOPID tuning in AVR systems. This paper addresses this research gap by applying HGSA for the first time to optimize the five parameters of the FOPID controller, aiming to improve transient response, convergence speed, and overall system stability.

3. Materials and Methods

3.1. The AVR System

The automatic voltage regulator system consists of four main components, synthesized together to regulate the excitation of the synchronous generator and maintain terminal voltage stability at the generation

stage. These four main components are the amplifier, the exciter, the generator, and the sensor, and this is demonstrated in Figure 1.

The amplifier is used to amplify the low power of the error signal, thereby regulating the exciter. The sensor's functionality is to measure the output voltage of the synchronous generator, allowing it to be subtracted from the reference voltage to obtain the value of the error signal. Practically, a voltage transformer is used as a sensor. To facilitate the comprehension of the mathematical modeling of the AVR system, all of these four components have been linearized in the literature and written in the form of a first-order transfer function, and this is as illustrated in the following equations (1)-(4) [22-24]. The transfer function of the amplifier is simplified to be:

$$G_A(s) = \frac{K_A}{1+sT_A} = \frac{10}{0.1s+1} \quad (1)$$

The transfer function of the exciter is simplified to be:

$$G_E(s) = \frac{K_E}{1+sT_E} = \frac{1}{0.4s+1} \quad (2)$$

The transfer function of the generator is simplified to be:

$$G_G(s) = \frac{K_G}{1+sT_G} = \frac{1}{s+1} \quad (3)$$

The transfer function of the sensor is simplified to be:

$$G_S(s) = \frac{K_S}{1+sT_S} = \frac{1}{0.01s+1} \quad (4)$$

where the four constants (K_A, K_E, K_G, K_S) located in the numerator of the previous equations are the symbols of the amplifier gain, exciter gain, generator gain, and sensor gain, respectively. Whereas the four constants (T_A, T_E, T_G, T_S) located in the denominator of the same equations are the time constants of the corresponding system components. The accepted range of values for each parameter, as presented in the literature, is demonstrated in Table 1.

Table 1. The range and the selected values of the AVR system parameters

Parameter Name	Symbol	Accepted Range	Selected Value	Unit
Amplifier gain	K_A	10-40	10	-
Exciter gain	K_E	1-10	1	-
Generator gain	K_G	0.7-1	1	-
Sensor gain	K_S	1-2	1	-
Amplifier time constant	T_A	0.02-0.1	0.1	Second
Exciter time constant	T_E	0.4-1	0.4	Second
Generator time constant	T_G	1-2	1	Second
Sensor time constant	T_S	0.001-0.06	0.01	Second

The step response of the benchmark AVR system before synthesizing the FOPID controller is illustrated in Figure 2.

Figure 2 and Table 2 both indicate that the terminal voltage has a high value, contributing to overshoot and a prolonged settling time. The overshoot value indicates that the terminal voltage exceeds the set-point, or in other words, the steady-state value by (65.1935%), while the settling time of (7.0190 seconds) is the duration taken by the AVR system to settle or to achieve stability. These insights imply that the system is experiencing undesired oscillations in the synchronous generator's output voltage. Hence, the FOPID controller is proposed to improve the values of the transient response parameters.

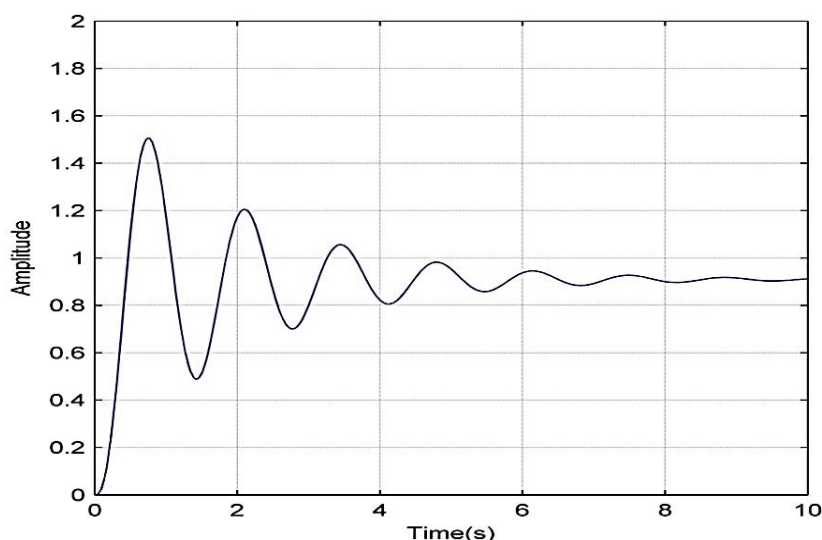


Figure 2. The step response of the AVR system before adding the controller

Table 2. The values of the transient response of the AVR

Parameter	Value
Percentage Overshoot	65.1935
Rise Time	0.2620
Settling Time	7.0190

3.2. Fractional-Order PID Controller Inception and Its Significance

The conventional PID controller is the most widely used in the literature, and it can generally be used to improve the performance of various control systems and applications. However, the fundamental issue is that PID controllers are linear. Accordingly, their performance is often considered inadequate when applied to nonlinear systems because it is subjected to variations. Hence, it was obvious to researchers that some amendments needed to be made to the PID controller. Fractional calculus is a significant branch of mathematics with numerous applications across various knowledge domains, including physics, chemistry, social sciences, engineering, and finance [25]. The application of fractional calculus to solve problems in control engineering has recently become a fascinating topic for researchers [26]. Fractional calculus was established in 1695 after a discussion between Leibniz and L'Hôpital [27, 28]. The mathematical theory of fractional calculus is significant because it generalizes the ordinary integration and differentiation to arbitrary non-integer orders. In other words, fractional calculus, as a framework, includes the commonly

encountered integration and differentiation but with another unique feature: handling non-integer orders. Traditionally, in differential calculus, the order of the derivative of a given function $f(x)$ is represented in the form of $\frac{d^n f(x)}{dx^n}$, where n is a positive integer.

The theory has been extended to become $\frac{d^\alpha f(x)}{dx^\alpha}$, where α could be a fraction too, and generally, it could be a real or complex number, positive or negative number, rational or irrational number [29, 30].

Fractional-order PID controller ($PI^\lambda D^\mu$) is an effective control strategy used to enhance the performance of the conventional PID controller. The control strategy uses fractional ordering to accomplish acceptable set-point tracking and smooth control action.

$$G_{PID}(s) = \frac{u(s)}{e(s)} = K_P + \frac{K_I}{s} + K_D s \quad (5)$$

$$G_{FOPID}(s) = \frac{u(s)}{e(s)} = K_P + K_I s^{-\lambda} + K_D s^\mu \quad (6)$$

The transfer function of the FOPID controller is integrated with the 4 components of the AVR system to form the final transfer function of the closed-loop AVR system, as shown in equation (7).

$$G(s) = \frac{V_{out}}{V_{ref}} = \frac{G_{FOPID}(s) * G_A(s) * G_E(s) * G_G(s)}{1 + G_{FOPID}(s) * G_A(s) * G_E(s) * G_G(s) * G_S(s)} \quad (7)$$

Figure 3 depicts the AVR system, where V_{out} is the output voltage of the generator, while V_{ref} is the set point (the reference voltage).

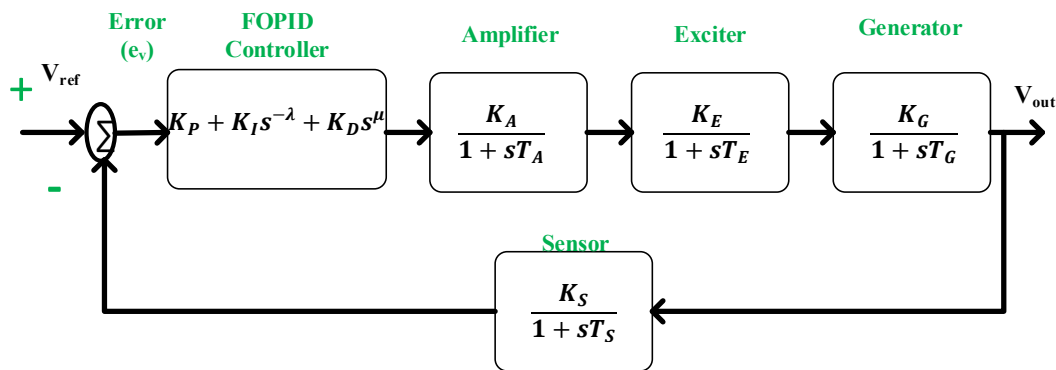


Figure 3. Block diagram of the AVR system with FOPID

3.3. Hunger Games Search Algorithm and its application in the AVR system

Meta-heuristic algorithms are algorithms designed to solve optimization problems across various fields. Several things, such as nature, the behaviors of birds, insects, animals, and humans, as well as other science-based inspirations like physics, chemistry, and biology, inspire them.

The Hunger Games search algorithm is a population-based and animal-inspired optimization technique. It was developed in 2021 [31]. Animals depend on their senses and computational rules to interact with their surrounding environment (wildlife) and make decisions. Moreover, these inputs and

computational rules help the animals to develop their cognition, which improves their prospects of survival, reproduction, and foraging. The feeling of hunger impels and motivates the animals to increase the process of food searching (foraging) and environmental exploration. Although several factors affect the animals' behavior, hunger is considered the most prominent factor that profoundly influences their choices and behavior when they experience a lack of food. This is because hunger can lead to starvation, illness, and death.

Animals adopt many strategies to survive in nature, but the most applied is engaging in foraging and exploring food without being exposed to danger. Social life is a crucial factor for animals to survive, as it enables them to search for food and hunt in groups, protect one another, and evade predators. This behavior is called cooperative behavior. The other behavior is when each animal individually searches for food and protects itself without assistance, which is known as non-cooperative behavior. This behavior often occurs in cases of limited food and resources. Eventually, the process of evolution is based on the health of the animals, where healthy animals have better opportunities for searching for food and surviving over their weaker counterparts, which is why this optimization technique is called HGSA. The main objective of the algorithm is to achieve high-quality solutions and faster convergence.

The steps of the HGSA are explained along with its mathematical modeling:

1. Initializing the population randomly, the position is initialized for each search agent using the following equation:

$$X_{N \times D} = rand(N, D) * (Upper\ Bound - Lower\ Bound) + Lower\ Bound \quad (8)$$

where *rand* is any random number between [0,1], N is the total number of search agents, and D is the search space dimension. The upper and lower bounds are the search space boundaries.

2. Calculate the fitness values for each agent as depicted in Figure 4. Apply the objective function on the initial population to evaluate the fitness of the solutions, then rank the obtained solutions from best to worst. Since the target of this optimization process is to minimize the fitness function. Therefore, the best solution is the solution having the least fitness value, and the worst solution is the solution having the highest fitness value.
3. Update the following three parameters:
 - a) *BF*: Best fitness value is the best solution to the current iteration.
 - b) *WF*: Worst fitness value is the worst solution until the current iteration.
 - c) X_b : Location of the best agent (individual) in the current iteration.
4. Determine the hunger value for each individual (animal) according to the fitness value of each individual as shown in the following equation:

$$hungry(i) = \begin{cases} 0, & AllFitness(i) == BF \\ hungry(i) + H, & AllFitness \neq BF \end{cases} \quad (9)$$

The hunger value of the animal is equal to zero if its fitness value is the least obtained; otherwise, all the other animals have a hunger value. H can be obtained using the following two equations.

$$TH = \frac{F(i) - BF}{WF - BF} * r_6 * 2 * (UB - LB) \quad (10)$$

$$H = \begin{cases} LH * (1 + r), TH < LH \\ TH, TH > LH \end{cases} \quad (11)$$

where $F(i)$ is the fitness value of each animal, UB and LB are the upper and lower limits of the space. In equation (10), the numerator of the fraction describes the food amount that the animal requires not to be hungry; the hunger value varies each iteration. While the denominator represents the individual's foraging capacity, r and r_6 are random numbers between $[0,1]$. In equation (11), TH indicates hunger, which depends on food quality and search capability, and LH indicates the lower bound of hunger.

5. Calculate the weights of hunger (W_1 and W_2) using the following two equations:

$$W_1(i) = \begin{cases} hungry(i) \cdot \frac{N}{SHungry} * r_4, r_3 < 1 \\ 1, r_3 > 1 \end{cases} \quad (12)$$

$$W_2(i) = (1 - \exp(-|hungry(i) - SHungry|)) * r_5 * 2 \quad (13)$$

N is the number of animals, r_3 and r_4 are random numbers in the range between $[0,1]$. $SHungry$ and $hungry(i)$ are the sum of the hunger feelings of all the individuals (animals) and the hunger value for each individual, respectively.

6. Calculate parameter E and update the parameter R for all the search agents using the following three equations:

$$E = \text{sech}(|F(i) - BF|) \quad (14)$$

$$R = 2 * shrink * rand - shrink \quad (15)$$

$$shrink = 2 * \left(1 - \frac{t}{T}\right) \quad (16)$$

where E is a variation control for all the positions, $F(i)$ is the fitness value of each animal, sech is a hyperbolic function, R is the range of exploration $[-a, a]$, t is the number of the current iteration, and T is the maximum number of iterations. The R and shrink values are gradually decreasing until they reach zero.

7. Update the position of each agent using the following equation:

$$X(t+1) = \begin{cases} Game_1: X(t) \cdot (1 + randn(1)), r_1 < l \\ Game_2: W_1 \cdot X_b + R \cdot W_2 \cdot |X_b - X(t)|, r_1 > l, r_2 > E \\ Game_3: W_1 \cdot X_b - R \cdot W_2 \cdot |X_b - X(t)|, r_1 > l, r_2 < E \end{cases} \quad (17)$$

$Game_1$ represents the mathematical model used to calculate non-cooperative behavior, which occurs when each animal searches for food without cooperating with the other animals. Whereas $Game_2$ and

$Game_3$ represent the mathematical model used to calculate cooperative behavior, which occurs when social animals cooperate while they search for food.

Where $X(t + 1)$ is the new position of each animal (individual), $X(t)$ is the old position of each animal. $randn, r_1$, and r_2 represent random numbers with values between $[0,1]$. The value of parameter E determines the game used in calculating cooperative behavior.

8. Increment the counter, then repeat all the steps from 2 to 7 until the stopping criterion is met.

9. Return the best fitness value (BF) and the position of the best individual (X_b).

The proposed HGSA is employed to determine the optimal values of the FOPID parameters by minimizing the fitness function, thereby enhancing the performance of the AVR system. The position of each search agent in the algorithm represents a possible solution for the FOPID gains (K_P , K_I , K_D , λ , and μ). The search agents (individuals) are ranked based on the obtained fitness values, where lower fitness values indicate better regulation of the synchronous generator output voltage. The position of the best search agent provides the optimal values of the FOPID gains, which enhances the AVR system terminal voltage stability.

According to Yang, et al. [31], the authors conducted a qualitative analysis using four predetermined indicators. The proposed HGSA was tested on numerous benchmark functions, and the obtained results demonstrated that the searching ability of HGSA is considered efficient and superior to that of other optimization algorithms. Furthermore, the HGSA adaptive mechanism provides an outstanding balance between exploitation and exploration. Accordingly, these advantages have urged and intrigued us to conduct this research. The flowchart illustrates the methodology of employing the proposed optimization technique (HGSA) to optimize the FOPID controller for the AVR system depicted in Figure 5.

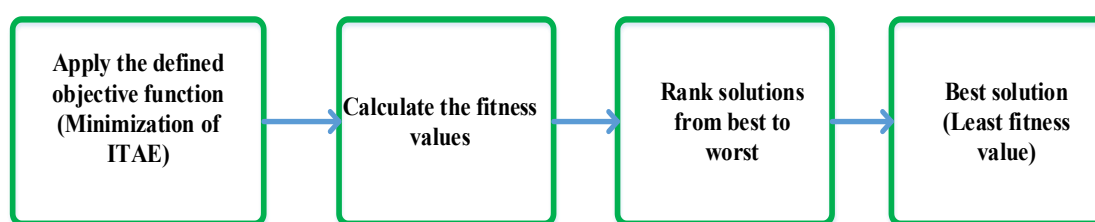


Figure 4. Fitness Evaluation of each solution

3.4. The Objective Function

Choosing an expedient objective function to be applied is necessary to evaluate the fitness of the obtained solutions in any optimization problem. Four main objective functions have been extensively used in literature to determine the optimal values of the controller gains, whether it was a PID or FOPID controller, to improve the performance of the AVR system, and this is as demonstrated in the following lines:

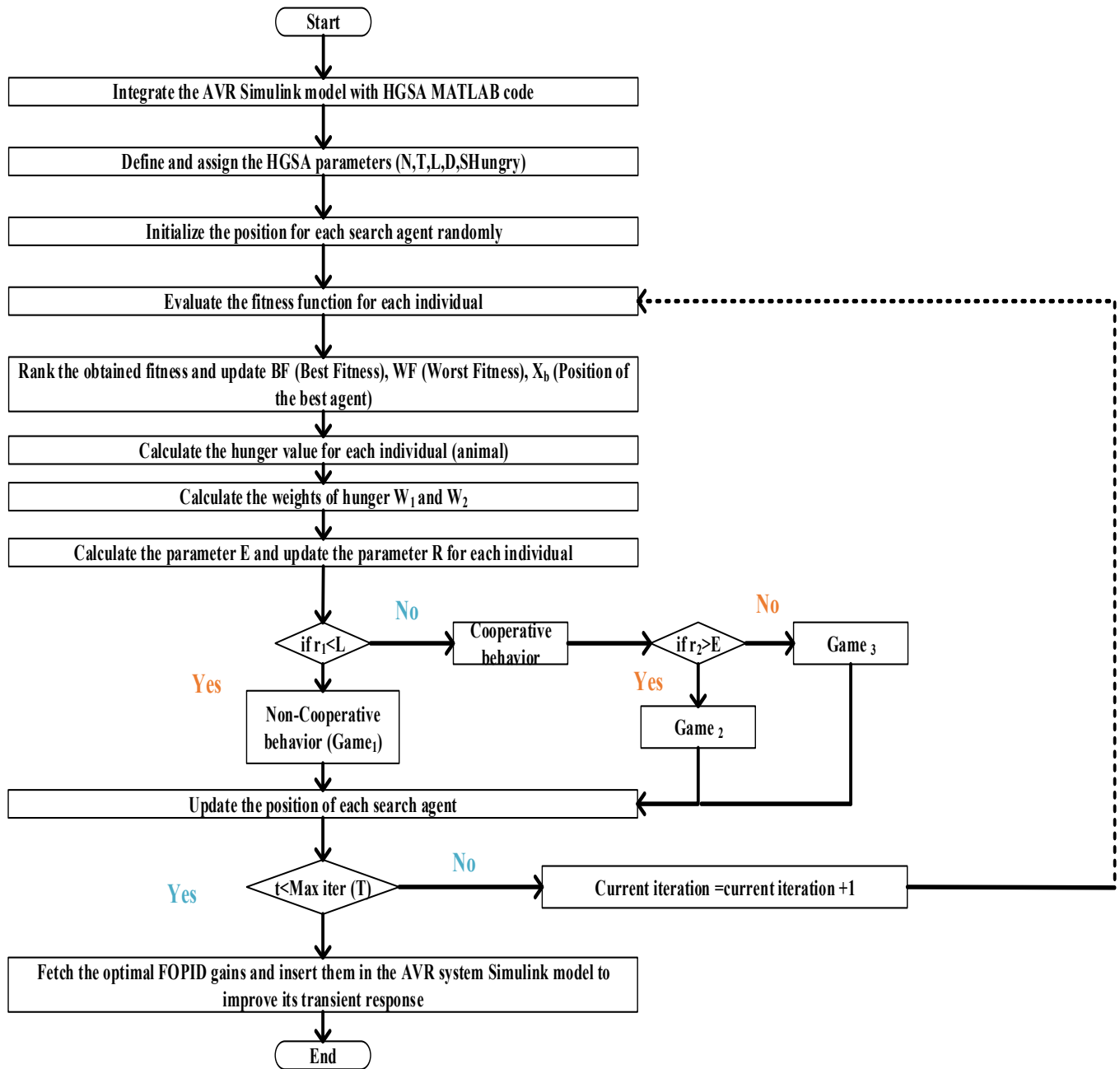


Figure 5. Flowchart of HGSA for AVR FOPID design

1. Integral Absolute Error (IAE).

$$IAE = \int_0^t |e_v(t)| dt = \int_0^t |v_{ref} - v_t| dt \quad (18)$$

2. Integral Square Error (ISE).

$$ISE = \int_0^t |e_v(t)|^2 dt = \int_0^t |v_{ref} - v_t|^2 dt \quad (19)$$

3. Integral Time Absolute Error (ITAE).

$$ITAE = \int_0^t t |e_v(t)| dt = \int_0^t t |v_{ref} - v_t| dt \quad (20)$$

4. Integral Time Square Error (ITSE).

$$ITSE = \int_0^t t |e_v(t)|^2 dt = \int_0^t t |v_{ref} - v_t|^2 dt \quad (21)$$

Where t stands for the simulation time and $e_v(t)$ The steady-state error can be obtained mathematically by subtracting the synchronous generator's terminal voltage (out voltage) from the set point (reference voltage). Figure 6 illustrates the block diagram for utilizing HGSA to optimize the five parameters of the FOPID, thereby improving the performance of the AVR system. In this study, ITAE is chosen to be the objective function to be minimized throughout this optimization process, consequently minimizing the AVR system transient response parameters (E_{ss} , $\%Mp$, t_r , and t_s). ITAE can be easily implemented, and its results are much better than those of its counterparts [32, 33]. Nevertheless, ISE and ITSE can often outperform ITAE and retain better final results, but they are regarded as violent functions with impractical results, and this is due to the squaring of the steady-state error.

To ensure that the retained improvements are attributed to the effectiveness of the proposed optimization algorithm rather than the objective function. ITAE is used as the objective function to calculate fitness values in this study. The results are compared with previous studies that used the same objective function to ensure a fair and consistent comparison.

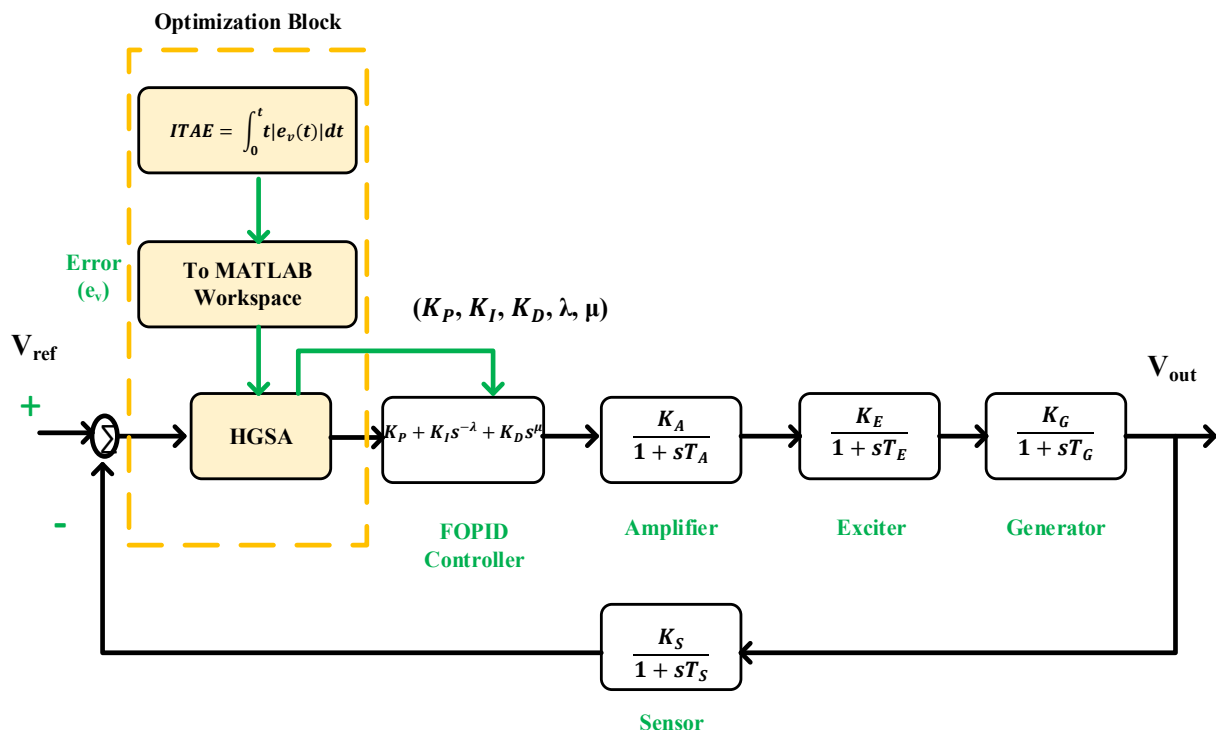


Figure 6. HGSA-based FOPID tuning in the AVR System

To highlight the most important points that need to be noted. The optimal AVR system design can be accomplished by optimizing the five FOPID gains (K_p , K_I , K_D , λ , and μ). The software used to model the AVR system is MATLAB/SIMULINK. Whereas the code of HGSA is executed using MATLAB after

assigning the values of the number of search agents, the maximum number of iterations, and the number of variables. After the termination of the optimization process using the ITAE objective function, the obtained results of the five variables (gains) are fetched and introduced to the FOPID controller block in the AVR system SIMULINK model to achieve the optimal design of the AVR system and improve the system's transient response, convergence, and stability.

4. Results and Discussions

This section presents and discusses the results and the significance of designing the FOPID using the proposed HGSA. The number of search agents and the maximum number of iterations of the HGSA are 50 and 100, respectively. The lower bounds and the upper bounds of the FOPID five parameters (K_P , K_I , K_D , λ , and μ) are chosen to be 0.1 and 2, respectively. ITAE is selected to be the objective function to be minimized throughout the optimization process. The process terminates after reaching the maximum number of iterations, which serves as the stopping criterion. MATLAB and SIMULINK are used to model the AVR system, optimize the FOPID controller, and execute all the simulations. The computer used to carry out these simulations has a processor *Intel Core™ i5* at 2.30 GHz with 4.00 GB installed memory (RAM).

4.1. HGSA Performance Evaluation

The main objective of using HGSA in the AVR system is to employ this meta-heuristic optimization technique on the FOPID controller as a tuning method to obtain the optimum values of its gains, which consequently ameliorates the performance of the system through having an optimal transient response and guaranteeing the supply of constant voltage to the end users. HGSA is used to minimize the value of the fitness function and determine the optimum FOPID gains. Figure 7 illustrates one of the most important criteria used to evaluate and assess the performance of any optimization technique, which is the convergence curve of the proposed technique. The x-axis represents the number of iterations, and the y-axis represents the best fitness value obtained at the corresponding iteration.

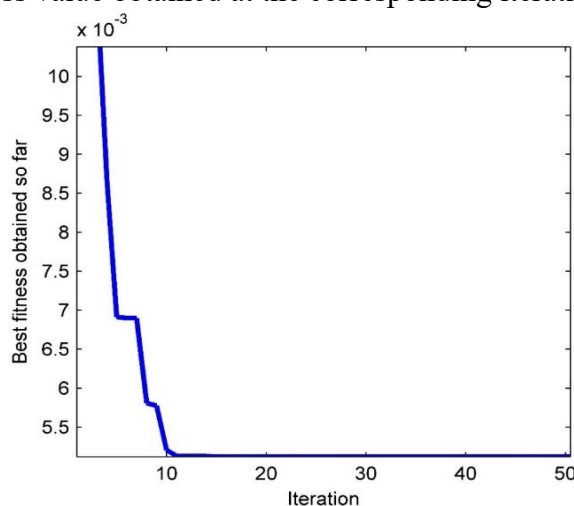


Figure 7. HGSA convergence curve

Figure 7 illustrates that as the number of iterations increases, the magnitude of the fitness function plummets. To obtain a precise and comprehensive evaluation of the proposed optimization algorithm's performance in the optimization process, several parameters can be used, depending on the type and domain of the application or the optimization problem. Regarding this optimization problem, two vital parameters are required to assess the algorithm's performance, as per the literature (previous studies). The first parameter is the convergence rate, which refers to the speed at which the solution converges towards the optimal solution. An optimization algorithm with a good convergence rate requires fewer iterations to reach a solution.

The second parameter is the fitness function value, which virtually indicates the solution's value accomplished by the optimization method after convergence. Since the quantity that we are aiming to minimize in this optimization process is the error. Therefore, the solution with the nearest value to zero is optimal. The final solution obtained for the fitness function is 0.0051203, achieved after 11 iterations.

The results obtained by the proposed algorithm support the hypothesis that HGSA is an effective optimization technique, exhibiting high convergence speed and yielding well-minimized solutions. Table 3 shows a numerical comparison between the optimal fitness values of the recent optimization methods in the literature and the minimized fitness value achieved by HGSA.

Table 3 demonstrates that the quality of the obtained convergence solution surpasses the mentioned optimization techniques, as it has the lowest fitness value among them. Accordingly, HGSA improves the performance of the AVR system.

Table 3. Solution Quality Comparison

Optimization Algorithm	Optimal Fitness Value
HGSA-FOPID (proposed)	5.1203×10^{-3}
GOA-PID [7]	6.332×10^{-3}
MPA-FOPID [14]	1.5077×10^{-2}
DE-PID [8]	2.235×10^{-2}
ABC-PID [8]	1.803×10^{-2}
PSO-PID [9]	7.172×10^{-3}
BBO-PID [10]	7.773×10^{-3}
SSA-FOPID [11]	4.195×10^{-2}
PSA-PID [13]	6.421×10^{-3}
IKA-PID [12]	6.161×10^{-3}

4.2. Transient Response

The following values are the optimal gains of the FOPID controller obtained by the proposed optimization technique (HGSA): $K_p = 2$, $K_I = 2$, $K_D = 0.59285$, $\lambda = 0.1$, and $\mu = 1.3804$. The transient response of the AVR system is illustrated in Figure 8. The AVR system takes a unit step as an input signal to evaluate its transient response.

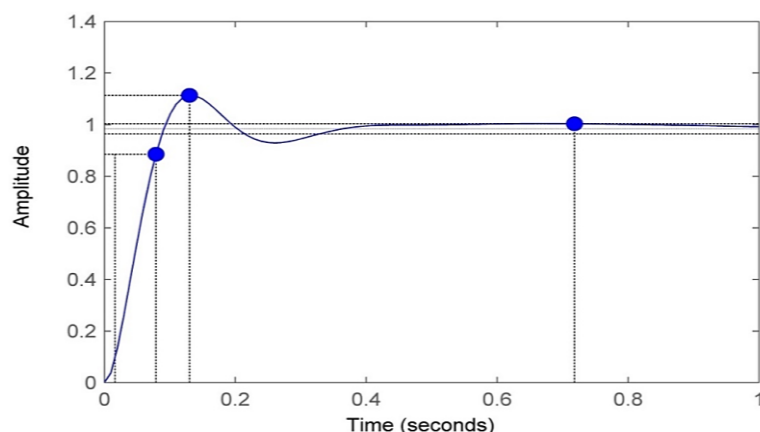


Figure 8. Step response of the HGSA-AVR system

This study considers three main predetermined criteria as observed facts used to assess the system's transient response. The first criterion is the percentage overshoot. The second criterion is the rise time, which is the time required for the system response to increase from 10% to 90% of its steady-state or final value. The third criterion is the settling time, defined as the time required for the system response to reach and remain within 2% or 5% of the steady state (final value) of the positive or negative values. According to the literature, the 2% definition is applied in this research study.

Table 4 illustrates the transient response analysis by comparing the obtained results of the proposed HGSA with those of recent optimization methods reported in the literature. The optimal design of the studied system is determined according to the three previously mentioned criteria: Percentage overshoot, rise time, and settling time. Figure 9 also presents a graphical comparison between the results of the proposed optimization algorithm (HGSA) and some recent optimization algorithms mentioned in Table 4, providing a visualization of the aspects of HGSA.

Table 4. Transient Response Analysis

Optimization Method and Controller Type	%M _p	t _r	t _s
HGSA-FOPID (proposed)	13.8369	0.0617	0.8717
GOA-PID [7]	20.5306	0.1300	0.9706
DE-PID [8]	32.8537	0.1516	2.6495
ABC-PID [8]	25.0071	0.1557	3.0939
PSO-PID [8]	30.0634	0.1610	3.3994
PSO-PID [9]	18.8183	0.1493	0.8145
BBO-PID [10]	15.5187	0.1485	1.4457
SSA-FOPID [11]	15.50	0.0981	0.551
WOA-FOPID [11]	22.50	0.111	0.931
PSA-PID [13]	16.8449	0.1445	0.8039
IKA-PID [12]	15.0	0.128	0.753
MNZ [16]	18.0382	1.0117	6.0492
TSA [16]	15.5700	0.1310	0.7580

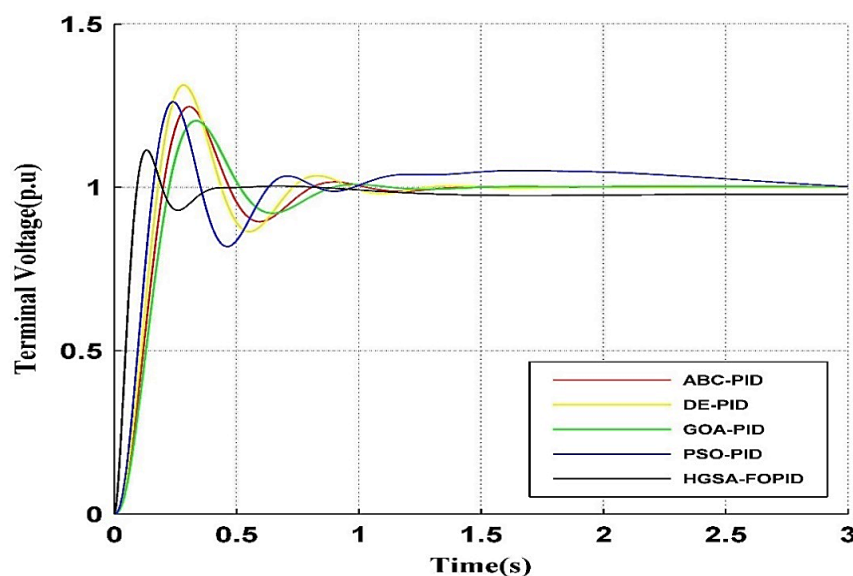


Figure 9. Graphical comparison between HGSA and the other optimization algorithms

The superiority of HGSA in optimizing the FOPID controller is quite evident after comparing it to the other previously studied optimization algorithms based on the predetermined transient response performance criteria, as illustrated in Table 4 and Figure 9. To further indicate and clarify the outcomes of HGSA. For instance, HGSA obtains 32.60%, 57.88%, 44.67%, 53.97%, 26.47%, 10.84%, 10.73%, 38.50%, 17.86%, 7.75%, 23.29% and 11.13% less maximum overshoot than that of GOA-PID [7], DE-PID [7], ABC-PID [8], PSO-PID [7], PSO-PID [9], BBO-PID [10], SSA-FOPID [11], WOA-FOPID [11], PSA-PID [13], IKA-PID [12], MNZ [16] and TSA [16] respectively. In other words, the proposed optimization technique (HGSA) based on the AVR design significantly reduces the system's overshoot, ranging from 7.75% to 57.88%. Moreover, the proposed algorithm surpasses all the previously mentioned optimization methods in terms of rising time and achieves a better settling time than 7 of the mentioned optimization techniques. Therefore, all these givens consolidate the fact that the proposed optimization algorithm outperforms the other optimization algorithms employed in the previous studies for the standard AVR system configuration.

4.3. Stability Analysis

To evaluate the stability of the demonstrated HGSA-AVR system, several criteria can be used to assess and measure the system's stability [34, 35]. The Bode diagram and pole-zero map are chosen in this study as illustrated in Figures 10 and 11, respectively. The Bode diagram is the most used method for stability analysis, and consequently, the obtained results are explained in this study.

A Bode diagram generally displays the gain and the phase shift for every frequency, or in other words, the system's frequency response and stability. It consists of 2 main plots:

1. Magnitude Plot.
2. Phase Plot.

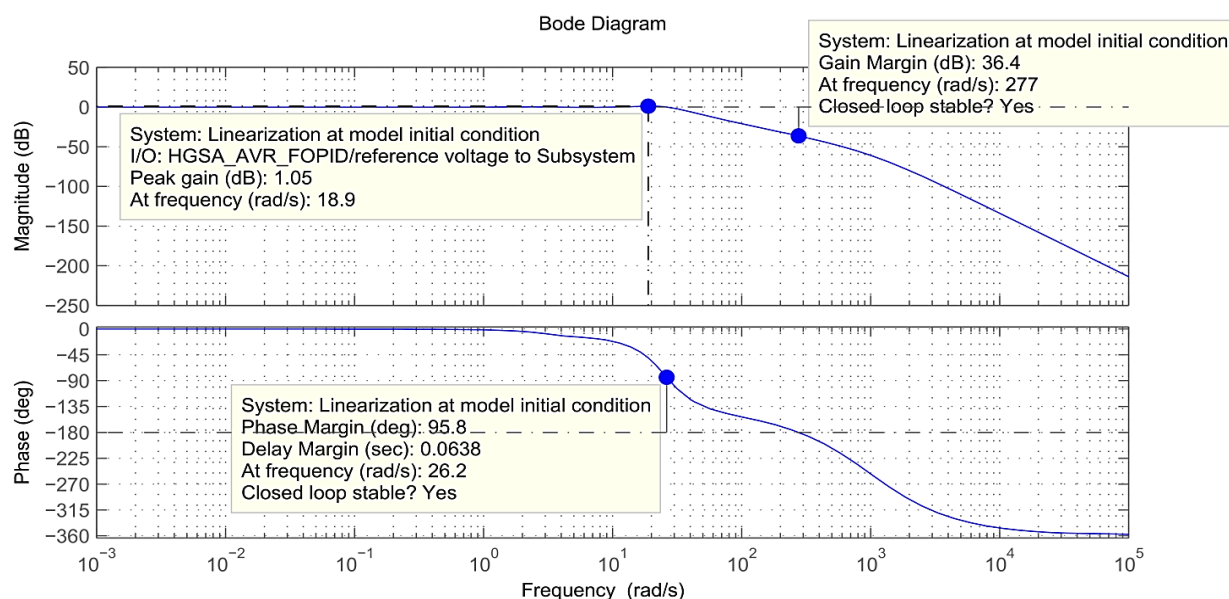


Figure 10. Bode diagram of the HGSA-AVR system

Figure 10 illustrates the Bode diagram of the HGSA-AVR system. It is evident from the graphical representation that the system's gain margin equals 36.4dB, and the phase margin equals 95.8 degrees. These two important pieces of information indicate the system's stability. Table 5 compares the results obtained from previous studies with those of the proposed system design.

Table 5. Stability Metrics Comparison

Optimization Algorithm	Phase Margin (Degrees)	Delay Margin (Seconds)	Bandwidth
HGSA-FOPID (proposed)	95.8	0.0638	26.2
GOA-PID [7]	73.4	0.095	15.958
DE-PID [8]	58.4	0.092	12.80
ABC-PID [8]	69.4	0.111	12.879
PSO-PID [8]	62.2	0.103	12.182
PSO-PID [9]	79.3	0.121	13.915
BBO-PID [10]	81.6	0.122	14.284
SSA-FOPID [11]	89.3	0.091	17.0
PSA-PID [13]	79.7	0.115	14.636
IKA-PID [12]	76.7	0.095	16.785
TSA [16]	77.4	0.0999	16.232

To highlight the most important information drawn from Table 5, the proposed HGSA outperforms the other optimization techniques in Table 5 in terms of phase margin and bandwidth. The values obtained for these two metrics indicate that the system is more stable than its literature counterparts and can handle higher frequencies. Accordingly, the proposed HGSA can enhance the system's stability and effectively regulate the terminal voltage.

The Pole-Zero map also assesses the system's stability and proves the point. A pole-zero map is a graphical representation of the poles and zeros of the system in a complex plane. The system's stability is determined by the locations of its poles.

The system is stable only if all its poles are located at the left-hand side of the s-plane; otherwise, it is unstable even if the system has only one pole at the right-hand side of the s-plane. Figure 11 indicates the stability of the proposed HGSA-based AVR system.

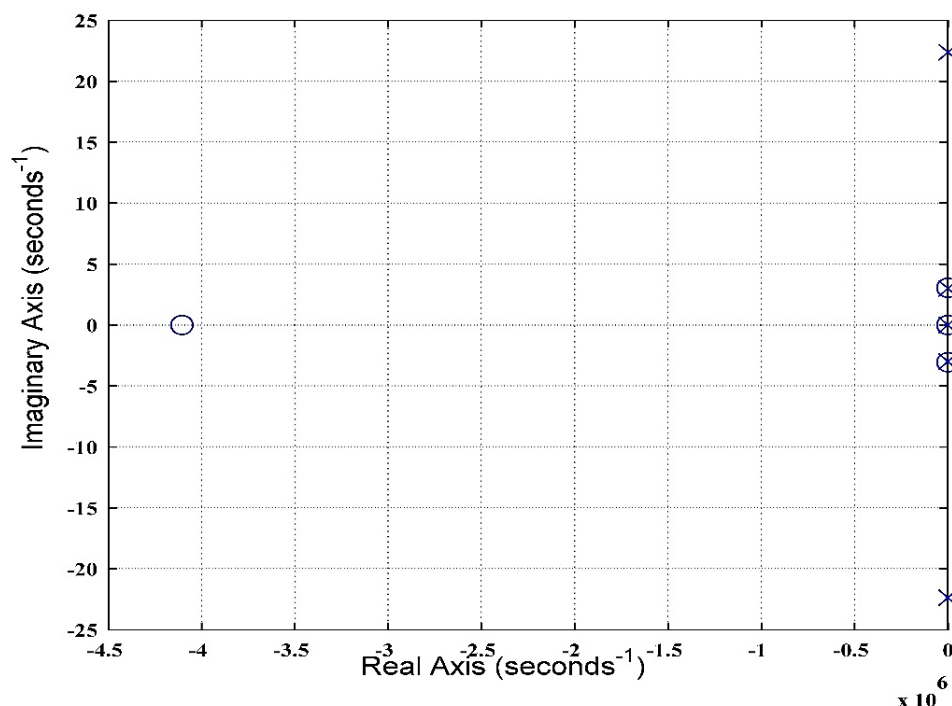


Figure 11. Pole-Zero Map of HGSA-AVR system

4.4. Robustness Analysis

The results obtained in the previous sections demonstrate that the proposed AVR system design outperforms its counterparts in earlier studies under normal or nominal conditions. However, testing the proposed AVR system design's performance during abnormal operating states is imperative to verify the system's reliability. In control systems, robustness analysis is used to assess the system's ability to meet expectations in terms of stability and desired performance when it experiences variations in its parameters or uncertainties. Virtually, the performances of the AVR system are tested and assessed for the four system's components: amplifier, exciter, generator, and sensor time constants (T_A , T_E , T_G , T_S). Nevertheless, the FOPID controller parameters have the same values as the nominal operating condition without any changes. The performance is evaluated through the step response of the AVR system after varying the mentioned time constants' values from -50% to 50% of the nominal value with a step size of 25%. The results of the robust analysis of the HGSA-FOPID controller-based AVR system are illustrated in Figures 12-15 and 6, respectively.

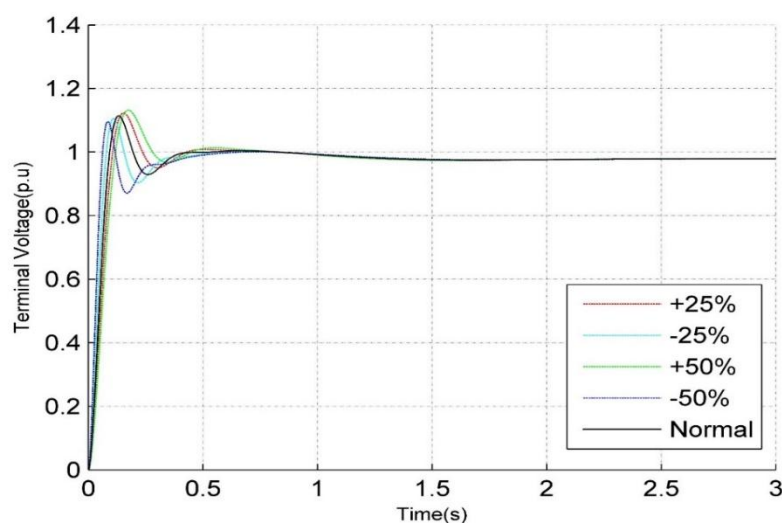


Figure 12. Step responses of the AVR system after varying the amplifier's time-constant

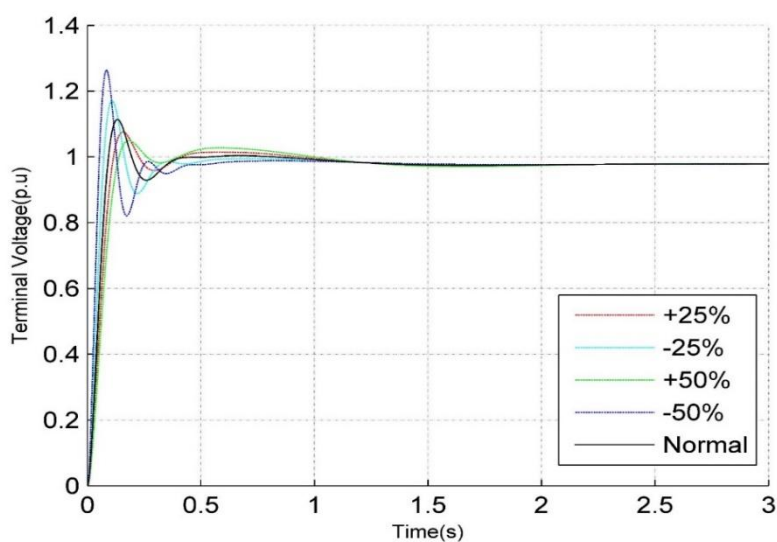


Figure 13. Step responses of the AVR system after varying the exciter's time-constant

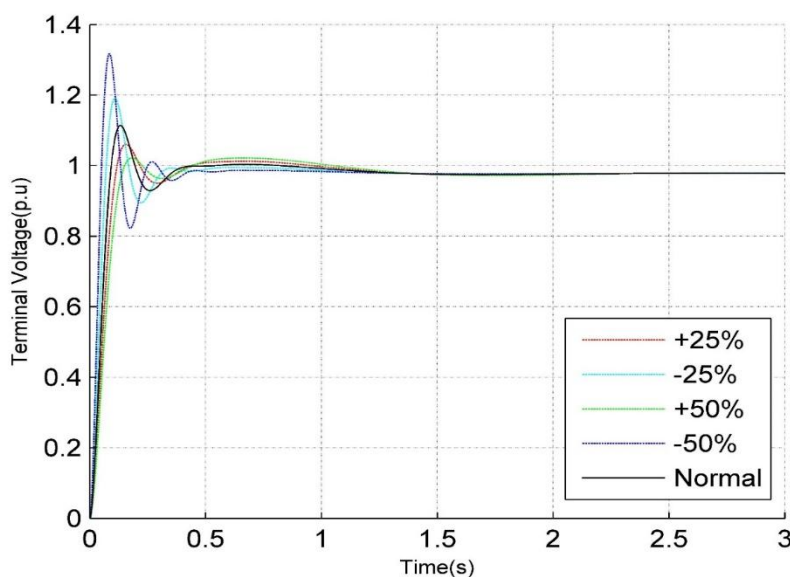


Figure 14. Step responses of the AVR system after varying the generator's time-constant

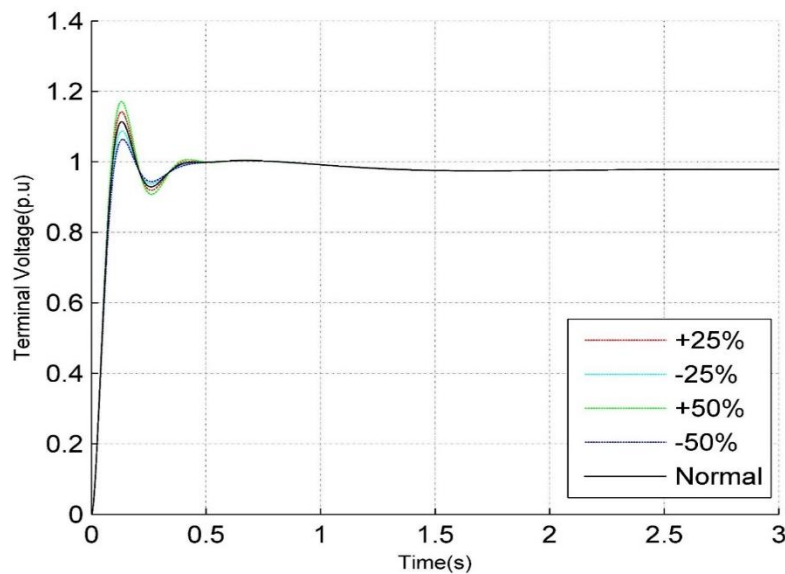


Figure 15. Step responses of the AVR system after varying the sensor's time-constant

Table 6. Transient response metrics of the AVR system for parameters' uncertainties

Time constant	% Variation	% M_p	t_r	t_s
T_A	-50	12.0281	0.0408	0.8689
	-25	12.9304	0.0519	0.8714
	+25	14.7534	0.0707	0.8733
	+50	15.6731	0.0791	0.8729
T_E	-50	29.1609	0.0352	0.3854
	-25	19.6454	0.0485	0.2935
	+25	9.9431	0.0752	0.9611
	+50	7.2530	0.0890	1.0165
T_G	-50	34.6655	0.0342	0.3620
	-25	21.7731	0.0477	0.2868
	+25	8.3618	0.0765	0.9890
	+50	4.3828	0.0923	1.0679
T_S	-50	8.7249	0.0663	0.8799
	-25	11.1492	0.0638	0.8759
	+25	16.7063	0.0600	0.8670
	+50	19.6808	0.0587	0.8611

Figures 12-15 and Table 6 indicate that the system exhibits small and subtle variations in the transient response metrics, even in the presence of significant parameter uncertainties. Furthermore, the results obtained from the HSGA robustness analysis, as demonstrated in Table 6, prove that the system can maintain stability during off-nominal operating conditions. In conclusion, the obtained transient response results are within an acceptable range; consequently, the proposed HGSA-FOPID-based AVR system can be regarded as a robust control system, as it exhibits good and satisfying performance under acute variations in system parameters.

4.5. Disturbance Response of the AVR System

The main aim of this section is to test and evaluate the capabilities of the proposed HGSA-FOPID-based AVR system when experiencing abrupt load changes represented as sudden disturbances. As illustrated in Figure 16, load disturbance is synthesized on the synchronous generator output voltage. The first value of the load disturbance is 1.1 p.u, which is equivalent to a 10% increase in the nominal value (1 p.u) after time equals 3 seconds, while the second value of the load disturbance is 0.9 p.u, which is equivalent to a 10% decrease in the nominal value after time equals 5 seconds. The transient responses of the different AVR system designs versus the proposed HGSA-FOPID are illustrated in Figure 17.

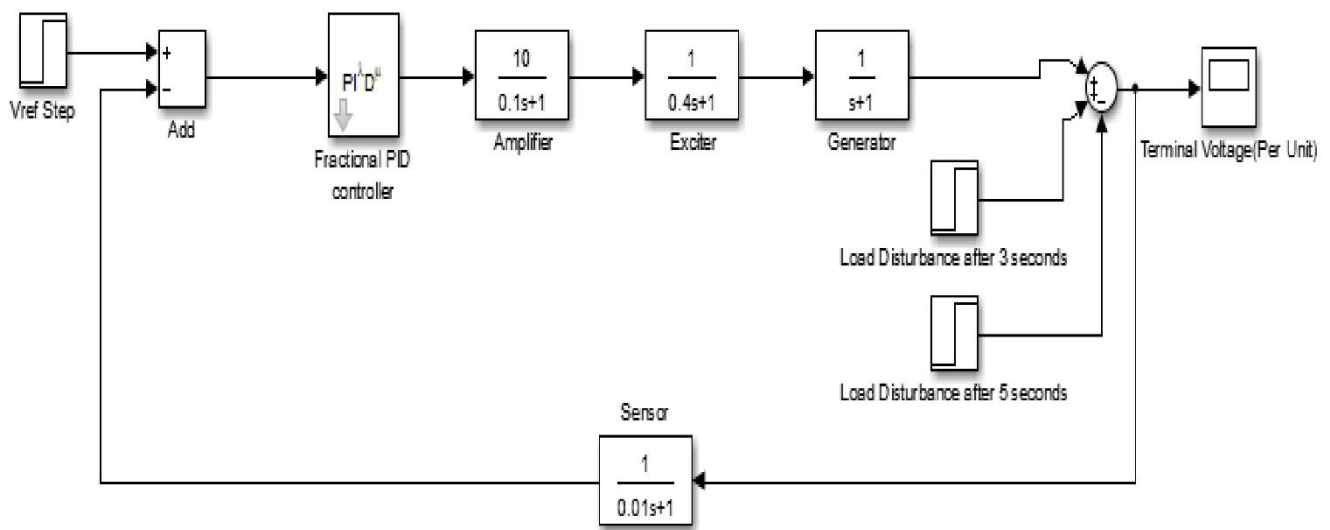


Figure 16. Load disturbance Simulink model for the proposed HGSA-FOPID-based AVR system

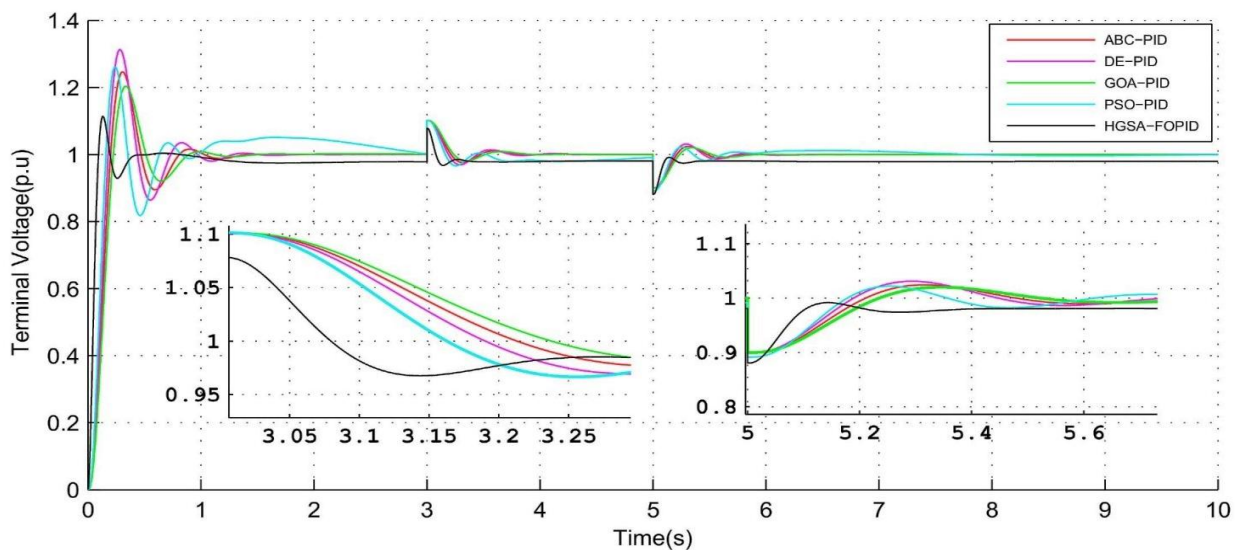


Figure 17. Transient responses of the AVR system design experiencing load disturbance

Figure 17 proves that the proposed HGSA-FOPID controller takes the least duration to decrease the terminal voltage from 1.1 p.u to 1 p.u and increase the terminal voltage from 0.9 p.u to 1 p.u. As graphically

presented in Figure 17, the proposed AVR design is the first to drop and rise in the two load disturbances. Therefore, the HGSA-FOPID-based AVR system performs better than the previous AVR designs.

5. Conclusions

The primary issue with fluctuations in the generator's output voltage (terminal voltage) is that it can result in significant economic repercussions for both customers and the utility, directly impacting the power system's stability. To avoid these problems, AVR is used as a control strategy to improve the system's stability.

This study proposes the Hunger Games Search Algorithm (HGSA) to optimize the five parameters, or gains, of the FOPID controller in the AVR system. To illustrate the aspects of the proposed algorithm, the performance of HGSA is compared with that of several techniques used in recent literature. The final results indicate that HGSA can achieve better transient response, convergence speed, and stability of the automatic voltage regulator system. For future research, different objective functions and new optimization techniques can be explored to further improve the AVR system's transient response and stability. Furthermore, other controllers can be employed on the AVR system to improve performance.

Funding: This work was supported by Cairo University through internal funding and access to research resources.

Declaration of Competing Interest: The authors declare they have no known competing interests.

Research Involving Human/Animal Participants: This article does not involve any studies conducted by authors on animals or human participants.

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