Optimal control of automatic voltage regulator system using hybrid PSO-GWO algorithm-based PID controller

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Article Info

Article history:

Received Jan 14, 2024
Revised Mar 4, 2024
Accepted Mar 28, 2024

Keywords:

Automatic voltage regulator
Hybrid algorithm optimization
Particle swarm optimization and grey wolf optimizer
Power system
Proportional integral derivative controller

ABSTRACT

In this paper, a new hybrid optimization algorithm known as particle swarm optimization and grey wolf optimizer (PSO-GWO) based proportional integral derivative (PID) controller is suggested for automatic voltage regulator (AVR) system terminal tracking problem. The main objective of the suggested approach is to reduce crucial performance factors such as rise time, settling time, peak overshoot and peak time of the voltage of the power system in order to improve the AVR system's transient response. This analysis was compared to results obtained from existing heuristic algorithm-based approaches found in the literature, proving the improved PID controller's enhanced performance obtained through the suggested approach. Furthermore, the performance of the tuned controller with respect to disturbance rejection and its robustness to parametric uncertainties were evaluated separately and compared with existing control approaches. According to the obtained comparison results and from all simulations, using MATLAB-Simulink tool, it has been noted that the PID controller optimized using PSO-GWO algorithm has superior control performance compared to PID controllers tuned by ABC, DE, BBO and PSO algorithms. The main conclusion of the presented study highlights that the recommended strategy can be effectively implemented to improve the performance of the AVR system.

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1. INTRODUCTION

Electric power distribution networks are rapidly expanding due to the growing need for varied loads. The distribution system is linked to a wide range of power plants that reliably provide the necessary electricity. The control of electrical energy transmission from power plants to loads is essential, even when there are fluctuations in the load on the distribution network. Automatic voltage regulator (AVR) is a crucial equipment used in utility power system. Its main purpose is to manage the voltage across a synchronous generator by regulating the exciter voltage, as its name suggests. The intrinsic characteristics of high inductance cause the system to respond slowly and more complexly, making it more difficult to maintain stability and make rapid adjustments, especially when the load changes dynamically [1]. Therefore, improving AVR performance becomes imperative to ensure consistent and efficient response to sudden terminal voltage changes. Numerous strategies of voltage control have been used by researchers for the examination and improvement of the dynamic response of the AVR system. The most extensively used and preferred of these controllers is the traditional proportional integral derivative (PID) controller. PID controllers are widely used to optimize the dynamic behavior of AVR systems because of its reputation for simplicity, adaptability, and efficacy in regulating systems [1].

Determining the optimal values of gains of a PID controller poses a difficult task. Traditionally, these parameters are calculated by methods such as error and trial or established techniques such as Cohen-Coon (CC), Ziegler-Nichols (ZN) [2], [3]. Unfortunately, these approaches cannot ensure that the PID settings are ideal and may cause undesired overshoots and extended oscillations in the system. Additionally, the extensive mathematical calculations involved in these methods make it difficult to find the best PID controller settings. In contrast, fuzzy logic and neural networks are two artificial intelligence methods that have been utilized in order to tackle the PID controller parameter optimization problem [4]. However, artificial neural networks face challenges in terms of heavy training processes and long convergence times. In the case of fuzzy-logic controllers, the creation of membership functions successfully frequently requires knowledge of data analysis, model tuning, and design [5]. The need for more effective and adaptable tuning techniques in under complex and dynamic power system conditions is reflected in the move towards scalable heuristic optimization algorithms for establishing PID controller parameters in AVR systems. When compared to conventional tuning techniques, these algorithms provide advantages in terms of scalability, efficiency, and flexibility.

Different heuristic optimization techniques have been introduced for tuning PID controller, encompassing approaches such as: biogeography based optimization (BBO) [6], particle swarm optimization (PSO) [7], artificial bee colony (ABC) [8], differential evolution (DE) [6], arithmetic optimization algorithm (AOA) [9], novel enhanced aquila optimizer (NEAO) [10], novel improved slime mould algorithm (NISM) [11], reptile search algorithm (RSA) [12], chaotic firefly algorithm (CFA) [13], Algorithm grasshopper optimization (GOA) [14], slime mould algorithm (SMA) [15], runge kutta optimizer (RKO) [16], pattern search algorithm (PSA) [17], adaptive neuro fuzzy inference system [18], fractional order model predictive controller [19] and evolutionary algorithms [20]. These techniques are applied to achieve optimal tuning of the PID controller within an AVR system.

The literature review shows that the heuristic techniques are now the go-to method for the controller PID optimization in AVR systems. A similar goal unites the researchers: reducing important transient response characteristics would improve system performance. Finding the best values for the coefficients of the PID controller is essential to optimizing these settings. It is important to remember, nonetheless, that current algorithms do not always offer methodical ways to get the ideal improvements needed to raise the AVR system's performance. For example, although grey wolf optimizer (GWO) and PSO show significant potential for solving various optimization problems, they are hampered by limitations such as memory constraints and computational loads. Although alternative optimization approaches may yield better results, they have drawbacks such as minimal local stagnation, premature convergence and challenges in controlling parameter selection [21], [22]. Additionally, certainly, identifying the most efficient solution for PID controller parameters in AVR system poses a formidable challenge due to the complex and nonlinear characteristics inherent in power systems. Therefore, exploring new heuristic optimization algorithms remains a crucial and notable challenge for researchers.

In this study, we use new approach know as hybridation between two algorithms, we use new hybrid optimization algorithm known as particle swarm optimization and grey wolf optimizer (PSO-GWO). This hybrid algorithm is applied to optimize the suggested PID controller for the AVR system, effectively calculating the PID's optimal values coefficients. The use of this hybrid approach has gained popularity in recent years in solving engineering design challenges and performing numerical optimization computations. PSO and GWO algorithms are implemented for many studies in the literature. The PSO and GWO algorithms have been widely implemented in various studies, with some focusing on load frequency control (LFC) optimization problems [23], [24]. Experimental investigations indicate that the hybrid PSO-GWO algorithm exhibits superior robustness and convergence characteristics. Furthermore, a comparative analysis is conducted, evaluating the performance of the suggested PSO-GWO algorithm against other algorithms such as ABC, PSO, DE and BBO. The comparative results indicate that the use of the PSO-GWO algorithm in the design of the controller PID improves the tracking of the voltage reference within the AVR system. The primary contributions of this research paper are:

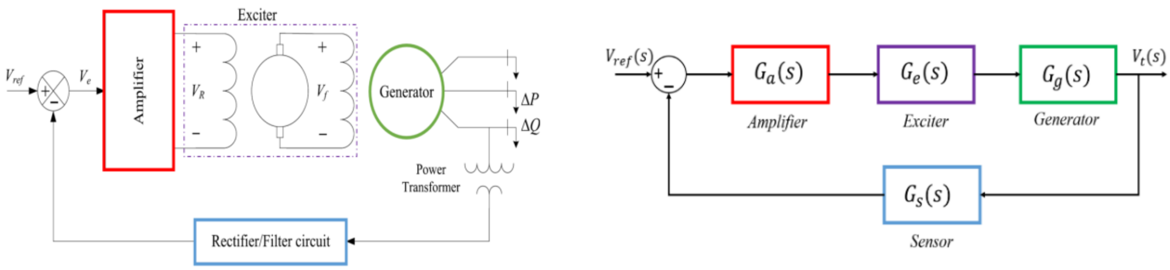
a. The study introduces for the first time the PSO-GWO technique based PID controller for the AVR system. This represents the most significant aspect of the originality of the research.
b. The values obtained for tr, tp, ts and Mp% using the PSO-GWO technique were evaluated against the results obtained using various optimization algorithms previously reported in the literature, including BBO [8], PSO [7], ABC [6] and DE [6]. The results of this comparative analysis unequivocally underline the effectiveness of the suggested PSO-GWO approach.
c. The robustness of the PID controller, optimized with PSO-GWO, was evaluated under parameter variations within the AVR system.

This paper begins with an introduction to the the AVR system and its key components relevant to control design and the proposed PID controller scheme in section 2. Section 3 details the optimization hybrid (PSO-GWO) and elaborates on the problem formulation. For simulation results and discussions, refer section 5. The paper concludes in the last section.

2. AUTOMATIC VOLTAGE REGULATOR SYSTEM MODELING AND proportional integral DERIVATIVE CONTROLLER

2.1. Automatic voltage regulator system modeling

The AVR system's function in any power system with synchronous generators is to keep the voltage amplitude at a predetermined level, thereby improving the quality and stability of the power system through control of the generator exciter. A standard configuration of a basic AVR system is depicted in Figure 1(a). As shown in the diagram, the AVR system consists of four crucial components: the amplifier, the exciter, the generator, and the sensor [25]. The structure of the closed-loop studied AVR system is shown in Figure 1(b).



(a) (b)

Figure 1. AVR system (a) overview and (b) closed loop structure

The transfer functions of each component can be combined to model the transfer function of the AVR system [25] as expressed in (1) to (4):
The amplifier model :

$$G_a(s) = \frac{K_a}{1+sT_a} \tag{1}$$

The exciter model:

$$G_e(s) = \frac{K_e}{1+sT_e} \tag{2}$$

The generator model:

$$G_g(s) = \frac{K_g}{1+sT_g} \tag{3}$$

The sensor model:

$$G_s(s) = \frac{K_s}{1+sT_s} \tag{4}$$

In (5) expresses the linearized transfer function of the AVR system without the presence of the PID:

$$G_{AVR}(s) = \frac{V_t(s)}{V_{ref}(s)} = \frac{G_e(s)G_a(s)G_g(s)}{1+G_a(s)G_e(s)G_g(s)G_s(s)} \tag{5}$$

Table 1 provides a detailed overview of commonly used time constants and gains, presenting both the ranges and selected values for these constants.

To analyze the dynamic behavior of this system, a unit response is carried out. The AVR system's unit step response without the controller PID is shown in Figure 2, which also shows how the terminal voltage varies. In this representation, the terminal voltage is expressed in per-unit (p.u.) with respect to a base unit quantity system. This approach makes it possible to represent the values of power, impedance, current and voltage in electricity in the form of unit quantities.

Table 1. Constants of the AVR system

Ranges of constants	Values	Ranges of constants	Values
$10.0 \leq K_a \leq 40.0$	10	$0.02 \leq T_a \leq 0.1$	0.1
$1 \leq K_e \leq 10$	1	$0.5 \leq T_e \leq 1$	0.4
$0.7 \leq K_g \leq 1$	1	$1 \leq T_g \leq 2$	1
$K_s = 1$	1	$0.001 \leq T_s \leq 0.06$	0.01

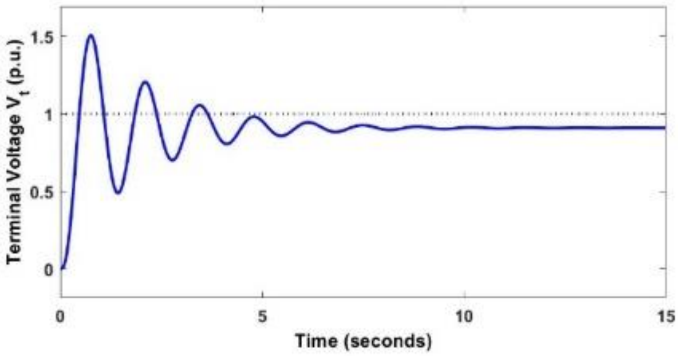


Figure 2. Step response without controller PID

The output voltage does not accurately follow the desired reference, as presented in Figure 2, requiring the implementation of a controller to eliminate steady-state errors and reduce settling time. The openloop characteristics of the AVR system, including M_p% (overshoot percentage), t_s (settling time), t_r (rise time), and E_{ss} (steady-state error), are detailed in Table 2. The zero and the poles of the studied AVR system are described are described in Table 3. Analyzing the poles of the transfer function provides valuable insights into the stability characteristics of the system. Specifically, the AVR system features a pair of conjugate poles, helping to damp oscillations within the system.

Table 2. AVR system response

Criteria	Value
Mp%	65.7720% (peak=1.5065 p.u.)
Tr	0.2606 s
Ts	7.5112 s
Tp	0.7532 s
Ess	0.09088 p.u.

Table 3. AVR system zero-poles

Zero-poles	Value
Real poles	-98.8170+0.0000i
	-12.6261+0.0000i
Complex poles	-0.5285+4.6649i
	-0.5285-4.6649i
Zero	-100+0.0000i

2.2. Proportional integral derivative CONTROLLER
2.2.1. Essentials of proportional integral derivative controller

PID controllers are, in fact, widely used in industrial applications because of their simple design and efficient operation. The schematic structure of the considered controller PID is represented in Figure 3, where the parameters are: K_P (proportional), K_I (integral), and K_D (derivative). The transfer function model of the PID controller is expressed in (6) [20]:

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \quad (6)$$

2.2.2. Automatic voltage regulator system with proportional integral derivative controller

To improve the transient behavior and minimize the steady-state error in the generator voltage, the incorporation of a high-performance controller is crucial. The system of AVR in this study is controlled by a PID controller. The AVR system's closedloop control configuration using the PID controller is presented in Figure 4. With the presence of the PID, the transfer function of the AVR system in the closedloop setup is expressed in (7):

$$G_{AVR}(s) = \frac{V_t(s)}{V_{ref}(s)} = \frac{G_{PID}(s)G_e(s)G_a(s)G_g(s)}{1+G_{PID}(s)G_a(s)G_e(s)G_g(s)G_s(s)} \quad (7)$$

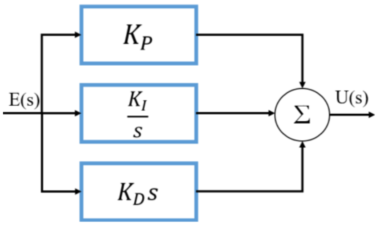


Figure 3. PID structure

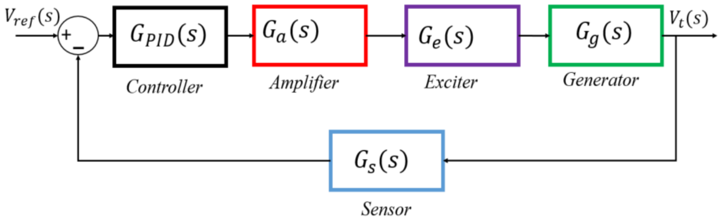


Figure 4. AVR system with the PID controller

3. PROPOSED ALGORITHM AND PROBLEM FORMULATION

3.1. Proposed algorithm

3.1.1. Particle swarm optimization

PSO is a swarm-intelligence based optimization approach that uses particles to move them about in the space of search to determine the best way to solve the issue. It drew inspiration from the social interactions observed in birds. PSO, a meta-heuristic optimization methodology, offers a population based search approach for global optimization, with the main benefit of being simple to use and requiring few parameters to be adjusted [26].

3.1.2. Grey wolf optimization

A newly created meta-heuristic algorithm called the GWO imitates the swarming hunting behavior of wolves. The male and female pack leaders in GWO are referred to as alpha (α) and are the first and best individuals. The second and third top wolf are referred to (β) and (δ). The grey wolf's lowest rank is omega (ω), which is subordinate to all other governed wolves [27].

3.1.3. Hybrid particle swarm optimization and grey wolf optimizer algorithm

PSO-GWO is a recent swarm-based meta-heuristic endowed with several advantages, including simple implementation and low memory utilization. The key idea is to combine the exploration and exploitation capabilities of PSO and GWO to produce variants with strength and memory consumption. They operate simultaneously in various ways. The PSO-GWO algorithm is employed to simultaneously utilize and investigate the positions of the initial three agents within the search space. In (8) to (10) shows the mathematical expressions:

$$X_1 = X_\alpha - A_1 \cdot |C_1 \cdot X_\alpha - X| \quad (8)$$

$$X_2 = X_\beta - A_2 \cdot |C_2 \cdot X_\beta - X| \quad (9)$$

$$X_3 = X_\delta - A_3 \cdot |C_3 \cdot X_\delta - X| \quad (10)$$

$$X_{123}(t+1) = \frac{X_1(t)+X_2(t)+X_3(t)}{3} \quad (11)$$

Where A_1, A_2, A_3, C_1, C_2, and C_3 stand for the top three wolves' coefficient vectors, while $X_i(i=1,2,3)$ stand for the positions of the top three wolves relative to the corresponding prey. X_{123} designates the location of the current solution.

In (12) and (13) show how the PSO technique can be used to update the wolves' positions and speeds, which are denoted by x_i^k and v_i^k:

$$v_i^{k+1} = (v_i^k + r_1 c_1(x_1 - x_i^k) + r_2 r_2(x_2 - x_i^k) + r_3 r_3(x_3 - x_i^k) \quad (12)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (13)$$

Where the revised positions and speeds of the top three wolves are indicated by x_i^{k+1} and v_i^{k+1}, respectively. $r_{i(i=1,2,3)} \in [0, 1]$ are random number, besides, the optimization parameters, denoted by c_1, c_2, and c_3 and are set to 0.5.

The objective is to optimize the proposed controller in the studied AVR system. It is important to note that the controller's parameters were set utilizing a hybrid PSO-GWO. In order to get the best values depending on the system requirements, the PSO-GWO MATLAB code includes the lowest and highest values of PID gains. For this study, a number of steps were utilized to determine the optimal values for the PID controller's parameters, illustrated in Figure 5.

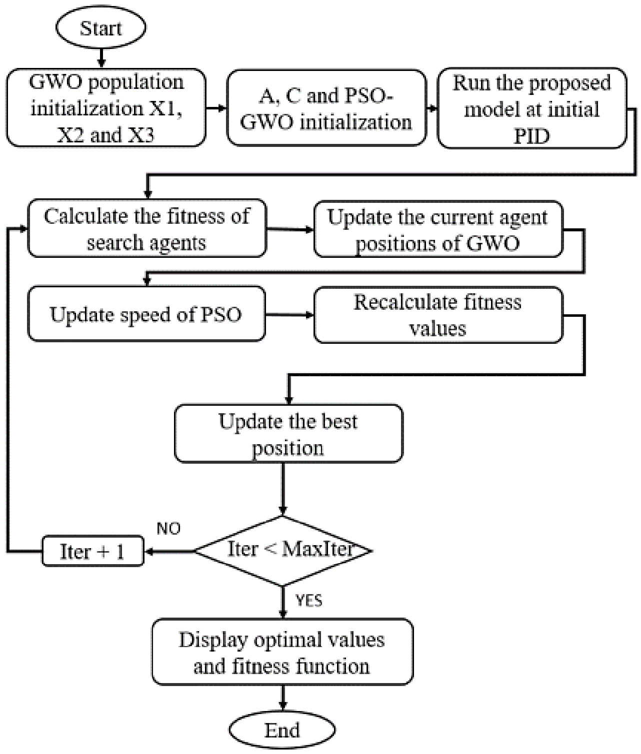


Figure 5. Flowchart for hybrid PSO-GWO algorithm

3.2. Problem formulation

Evaluation of AVR system performance involves consideration of key parameters such as peak time (t_p), settling time (t_s), rise time (t_r), maximum overshoot percentage (M_p%) and the steady state error (E_{ss}) as a function of time. Optimal system performance is obtained when the step response has minimum values for Mp%, ts, tr, tp and E_{ss}. In an AVR optimization problem, the objective function is defined as the error e(t) that is depends on the voltage V_t(t) as:

$$e(t) = V_{ref}(t) - V_t(t) \quad (14)$$

The error is typically formulated in the form of four main performance criteria in the design of control systems integral time absolute error (ITAE), integral absolute error (IAE), integral square error (ISE), integral time square error (ITSE). In the literature, the most commonly preferred objective function to evaluate the effectiveness of the AVR system is integral of time-weighted absolute error (ITAE). It reduces oscillation, settling time and overshoot. As a result, the objective function used by AVR system can be written as (15):

$$mi\,n(ITAE) = \int_0^{t_{sim}} \left(\left|V_{ref}(t) - V_t(t)\right|\right).t.dt \quad (15)$$

In this context, where "t_{sim}" represents the simulation duration. Subject to:

$$K_{cpmin} \leq K_{cpi} \leq K_{cpmax} \quad (16)$$

K_{cpi} are the controller parameters to be optimized and K_{cpmin}, K_{cpmax} are the controller parameters lower and upper limits respectively. This study has opted to use a gain range extending from 0.1 to 2.5 in order to enable meaning ful comparisons with other studies in the literature and to identify the ideal PID controller characteristics.

4. RESULTS AND DISCUSSION

The testing system was established by configuring it as a Simulink model in MATLAB (R2021a) software, running on a computer equipped with an Intel Core i7 processor and 32GB of RAM. Furthermore, the proposed algorithm PSO-GWO code is executed as an m MATLAB file, connecting with the Simulink model representing the AVR system under study to facilitate the optimization procedure. Table 4 contains a list of the PID controller's gain that were determined using various approaches.

Table 4. PID controller parameters

Controller	K_P	K_I	K_D
PSO-GWO-PID (proposed)	1.1035	0.9122	0.4378
PSO-PID [7]	1.7774	0.3827	0.3184
ABC-PID [6]	1.6524	0.4083	0.3654
BBO-PID [8]	1.2464	0.5893	0.4562
DE-PID [6]	1.9499	0.4430	0.3427

4.1. Comparison with conventional proportional integral derivative

In this subsection, the simulation responses in the time domain were compared with results obtained using various optimization algorithms presented in the literature including BBO [8], PSO [7], ABC [6] and DE [6] to exhibit the superiority and effectiveness of the PSO-GWO-PID controller that has been suggested for the AVR system. Table 4 summarizes the PID controller gain derived from various techniques. For comparison study, Figure 6 presents the simulation results that show the step response of the terminal voltage of the studied AVR system under the impact of all controllers. It is clear from the figure that the proposed hybrid PSO-GWO-PID controller gives superior results compared to other approaches.

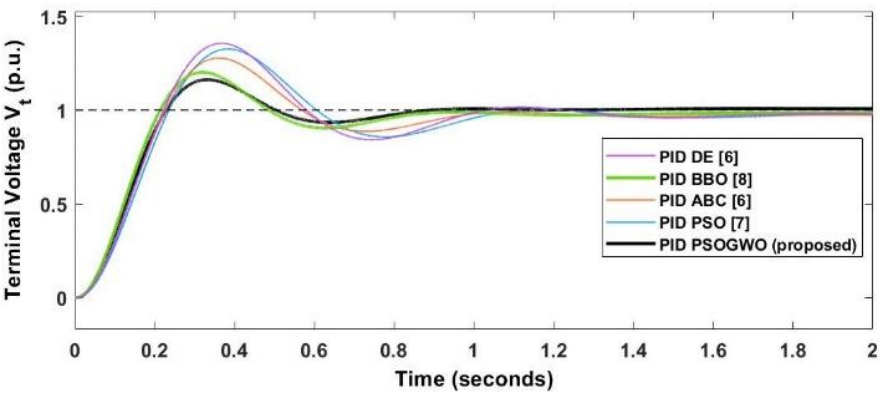


Figure 6. AVR system terminal voltage

The comparative analysis of transient responses, as well as the performance characteristics of tr, ts, tp and Mp% are detailed in Table 5. The table also provides values of the ITAE. The table indicates that the PSO-GWO-PID controller provides the lowest values for all four transient performance indices and both objective functions. In comparison to other PID controllers tuned using various techniques, the proposed approach displays a more stable, quicker, and less fluctuating structure.

Table 5. Results for different controllers: transient response

Controllers	Mp%	ts	tr	tp	ITAE
PSO-GWO-PID (proposed)	15.3719 (peak=1.1621)	0.8043	0.1358	0.3017	0.0383
PSO-PID [7]	35.7944 (peak=1.3256)	1.2536	0.1516	0.3831	0.1111
DE-PID [6]	38.5483 (peak=1.3563)	1.5235	0.1433	0.3669	0.1082
BBO-PID [8]	20.1538 (peak=1.1848)	0.8178	0.1403	0.3192	0.0648
ABC-PID [6]	31.1159 (peak=1.2772)	0.9209	0.1461	0.3602	0.0964

4.2. Disturbance response of the automatic voltage regulator control system

In synchronous generators, disturbances are an efficient way to record changes in load, thus it is critical to evaluate how resilient and transiently responsive the controllers are to these disturbances. The disturbance model is applied as shown in Figure 7, where it is injected into the system at rates of ±10% at 4 and 6 seconds.

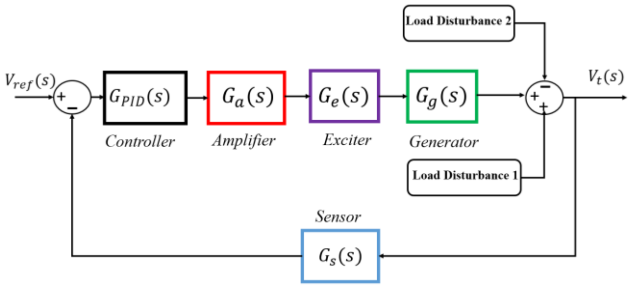


Figure 7. Disturbance model for AVR system

Figure 8 shows the AVR system's responses using the PSO-GWO-based PID controller. The results are compared to studies from the literature. Figure 8 shows that, in terms of rising time, settling time and maximum overshoot, the considered controller performs better and responds quicker than PSO-PID [7], DE-PID [6], ABC-PID [6], and BBO-PID [8]. These comparative results demonstrate that, in comparison to alternative techniques, the suggested method has improved temporal response characteristics.

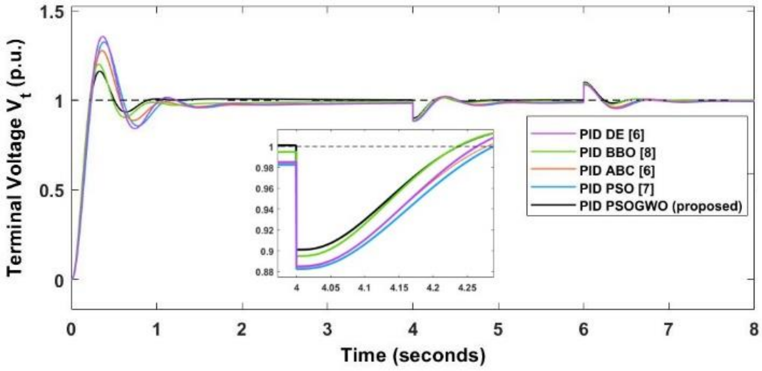


Figure 8. Terminal voltage response of the AVR control system: disturbance response

4.3. Robustness analysis

To evaluate the resilience of the AVR system with the proposed PID controller tuned by the PSO-GWO approach, the temporal constants of the generator, the amplifier, the exciter, and the sensor were systematically changed in 25% steps, ranging from +50% to -50%. The results of the robustness analysis are summarized in Table 6. Similarly, Figures 9(a) to (d) graphically represent the transient responses of the AVR system with the suggeted approach PSO-GWO-PID controller under various time constants. The values shown in Table 6 are all within acceptable limits, indicating that the suggeted PSO-GWO-PID based AVR system exhibits robustness. These results suggest that the system can maintain stable and satisfactory performance even under variations in the time constants of its constituent components.

Table 6. Robustness analysis results of the AVR system

	(%)	ts(s)	tp(s)	tr(s)	Peak value PSO-GWO (pu)	Peak value PSO (pu)	Peak value DE (pu)	Peak value ABC (pu)	Peak value BBO (pu)
T_A	-50	0.7950	0.2603	0.1320	1.0485	1.2120	1.2427	1.110	1.0712
	-25	0.7724	0.2968	0.1413	1.1140	1.2775	1.3082	1.190	1.1367
	+25	0.9051	0.3643	0.1622	1.1993	1.3628	1.3935	1.280	1.2220
	+50	0.9786	0.3946	0.1724	1.2293	1.3928	1.4235	1.330	1.2520
T_E	-50	1.0129	0.2213	0.0985	1.2087	1.3722	1.4029	1.240	1.2314
	-25	0.7410	0.2781	0.1261	1.1805	1.3440	1.3747	1.220	1.2032
	+25	0.8889	0.3848	0.1765	1.1509	1.3144	1.3451	1.250	1.1736
	+50	0.6758	0.4388	0.2003	1.1450	1.3085	1.3392	1.260	1.1677
T_G	-50	0.9955	0.2218	0.0913	1.3091	1.4726	1.5033	1.340	1.3318
	-25	1.0825	0.2781	0.1215	1.2200	1.3835	1.4142	1.270	1.2427
	+25	0.8966	0.3861	0.1833	1.1220	1.2855	1.3162	1.220	1.1447
	+50	0.8874	0.4440	0.2165	1.0940	1.2575	1.2882	1.200	1.1167
T_S	-50	0.8399	0.3351	0.1561	1.1383	1.3018	1.3325	1.210	1.1610
	-25	0.8345	0.3319	0.1520	1.1609	1.3244	1.3551	1.230	1.1836
	+25	0.8323	0.3307	0.1499	1.1748	1.3383	1.3690	1.260	1.1975
	+50	0.8310	0.3298	0.1481	1.1878	1.3513	1.3820	1.270	1.2105

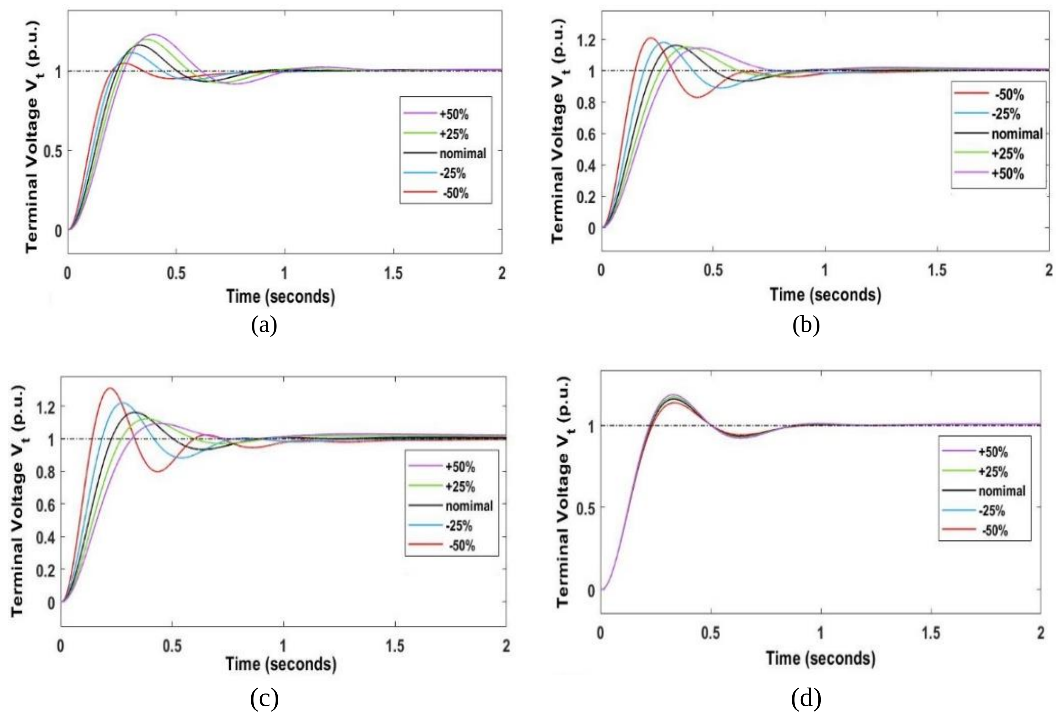


Figure 9. Effect of: (a) amplifier T_a uncertainties-PSO-GWO, (b) exciter T_e uncertainties-PSO-GWO, (c) generator T_g uncertainties-PSO-GWO, and (d) sensor T_s uncertainties-PSO-GWO

5. CONCLUSION

This paper presents a PID control approach that uses the PSO-GWO method, a new hybrid optimization method to enhance AVR system regulation. The PSO-GWO method is used to determine the optimal values of the PID controller coefficients based on the objective function ITAE. The results indicate that, compared to existing methods for AVR documented in the literature; BBO, PSO, ABC and DE, the suggested technique PSO-GWO optimized PID controller is effective in achieving better control outcomes under the same conditions and exhibits superior performance in terms of steady and transient responses, exhibiting improvements in overshoot maximum and steady state status error. The PSO-GWO algorithm exhibits competitive results with existing methods in the transient response study, which takes into account characteristics like rising time, peak time, peak overshoot and settling time. In contrast, the PSO-GWO algorithm performs better in terms of disturbance response and steady state errors than other algorithms. According to the results, the suggested PSO-GWO algorithm optimized PID controller for the AVR system appears to be resilient to changes in system parameters. This suggests that for synchronous generator AVR systems, PID controllers based on the PSO-GWO algorithm outperform PID controllers based on the previously described techniques in the literature. In future studies, the suggested approach will be extended to apply to tuning controllers beyond the conventional PID controller in the frequency and voltage control of the power system. These include more advanced control systems for example fuzzy PID controller, fractional order PID (FOPID) controller and sliding mod controllers.

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