

Article

Enhancing AVR System Stability Using Non-Monopolize Optimization for PID and PIDA Controllers

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Abstract

This work suggests a new use for the Non-Monopolize Optimization (NO) method to improve the dynamic stability and robustness of PID and PIDA controllers in Automatic Voltage Regulator (AVR) systems when there are load disruptions. The NO algorithm is a new search method that does not use metaphors and only looks for one answer. It utilizes adaptive dimension modifications to strike a balance between exploration and exploitation. Its addition to AVR control makes parameter tweaking more efficient, without relying on random metaphors or population-based heuristics. MATLAB/Simulink R2025a runs full simulations to check how well the system works in both the time domain (step response, root locus) and the frequency domain (Bode plot). We compare the results to those of well-known optimizers like WOA, TLBO, ARO, GOA, and GA. The suggested NO-based PID and PIDA controllers always show less overshoot, faster rise and settling periods, and higher phase and gain margins, which proves that they are more stable and responsive. A robustness test with a load change of $\pm 50\%$ shows that NO-tuned controllers are even more reliable. The results show that using NO to tune different controllers could be a good choice for real-time AVR controller tuning in modern power systems because it is lightweight and works well.

Keywords: automatic voltage regulator (AVR); PID and PIDA controllers; non-monopolize optimization (NO); power system stability; metaheuristic controller tuning



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1. Introduction

In modern power systems, maintaining terminal voltage stability is critical for efficient and reliable operation. These parameters significantly impair the performance of other operating equipment connected to power systems and have a substantial impact on the equipment's life expectancy, which in turn affects system productivity and operation. As a result, control devices have been implemented and integrated into power systems' grids to overcome any disturbance in the terminal voltage and sustain the operation limits or the reference settings. The generation unit is the primary source of power that supplies the load and enables system operation. If different power plants or generation units are connected,

they should be synchronized to supply the load with constant voltage and frequency and avoid any failure or system instability. Power plants may be renewable energy, such as solar, wind, hydrothermal, biomass, and tidal power plants, or may be non-renewable, such as fossil fuel gas turbines, diesel generators, steam turbines, nuclear power plants, and gas–steam combined cycle [1,2].

An Automatic Voltage Regulator (AVR) is used to regulate the terminal voltage of synchronous generators through controlling the excitation voltage on the rotor. The terminal voltage is directly proportional to the reactive power or power factor of the synchronous generators. The main objective of an AVR is to maintain the voltage within the reference or nominal values. The AVR should be stable, efficient, and robust to disturbances, such as load variations, faults, and short circuits. A controller is installed in the AVR system to enhance its stability and dynamic response. Controllers, such as Proportional–Integral–Derivative (PID) [3], Proportional–Integral (PI), Proportional–Integral–Derivative–Acceleration (PIDA) [4], Fuzzy Logic [5], and Fractional PID (FPID) [6], maintain the terminal voltage in a closed-loop system. They sense the voltage across the terminals and compare it to the reference, producing an error signal that should be minimized. Therefore, the objective of an AVR system is to minimize the error signal through an objective function, ensuring system stability with fast time and frequency responses. These controllers' parameters are tuned by optimization techniques and arithmetic algorithms according to the system's dimensions.

In recent years, optimization techniques have been widely applied to Automatic Voltage Regulator (AVR) controller tuning to improve stability, robustness, and dynamic performance. Traditional tuning methods often face limitations when dealing with system nonlinearities, parameter uncertainties, and the trade-off between the transient response and steady-state accuracy. To address these challenges, researchers have adopted meta-heuristic and hybrid optimization algorithms, which effectively balance exploration and exploitation to determine the optimal controller parameters. Nature-inspired and AI-driven algorithms have demonstrated superior performance by achieving faster convergence and avoiding local optima [7,8]. Incorporating these techniques into AVR systems enables significant improvements in overshoot reduction, settling time, and voltage regulation under dynamic operating conditions, establishing optimization-based controller design as a promising solution for modern power systems. Some of the intelligent algorithms are gradient-based optimization (GBO) [9], artificial rabbit optimization (ARO) [10], Sand Cat Swarm Optimization (SCSO) [11], the whale optimization algorithm (WOA) [12], particle swarm optimization (PSO) [13], and teaching–learning-based optimization (TLBO) [14].

Research studies have been conducted in this area to select the fastest and most robust optimization techniques to tune a controller's parameters for the fastest transient response and enhanced AVR performance in a grid under different disturbance and loading conditions [15]. A recent research paper surveyed AVR systems connected to a PID controller tuned using various optimization algorithms developed over the past two decades. A comparison was made between the grasshopper optimization algorithm (GOA) and vortex search algorithm (VSA), with both demonstrating better performance than the PSO algorithm [16]. Another study comparing the WOA and moth–flame optimization (MFO) using PID controllers showed that the WOA achieved superior performance, but the maximum overshoot was only reduced [17]. Researchers have continued to work on optimizing AVR systems due to their critical role in power generation units and substations. A hybrid optimization of the exponential distribution optimization algorithm (EDO) and transit search optimization algorithm (TSOA) was used to tune a PID controller, resulting in better time and frequency responses than GOA and TLBO. A hybrid fireworks algorithm (FWA) and WOA were also used to tune a PID2 controller for an AVR system to analyse the

stability, track the trajectory, reject disturbances, and manage parameter uncertainty. Recent papers have also studied AVR systems tuned by different controllers to improve the stability performance, as shown in Table 1. The table presents the types of optimizations, controllers, and comparisons with other optimization algorithms using the same controller [15].

Table 1. Recent research on AVR systems with an optimally tuned controller.

Optimization	Controller	Comparison	Ref.
Quadratic wavelet-enhanced gradient-based optimization (QWGBO)	RPIDD ² -FOPI	GBO, GSA, WOA, SMA, PDO	[9]
Artificial rabbits' optimization (ART)	PID	NZ, MNZ, TSA, DE with PCA	[10]
Sand cat swarm optimization (SCSO)	Fuzzy PIDF + FOPD	PSO under normal and uncertainty conditions	[11]
Whale optimization algorithm (WOA)	PID and PIDA	TLBO, LUS, HSA	[12]
TLBO, PSO	Fuzzy PIDF + PIDF	TLBO (PIDF), GA (PID), IWOA (PID), TLBO and PSO (FPID + FOPF)	[13]
TLBO, HSA, LUS	PID, PIDA	PSO, GSA, ABC, PSO, DE, MOL	[14]
Golf optimization algorithm (GOA) and vortex search algorithm (VSA)	PID	PSO	[16]
Hybrid of EDO and TS	PID	GOA, TLBO	[18]
Hybrid of FWA and WOA	PIDD2	FWWOA, SAGTO, PSO, WOA, TLBO	[19]
Ant lion optimization (ALO)	PID	BA, GWO, BBO	[20]
Artificial hummingbird algorithm (AHA)	FOPID	PSO, GWO, ABC, GA	[21]
PID-based search algorithm (PSA)	FPID	ZN (PID)	[22]
Jaya optimization algorithm	PID	DE, PSO, ABC, GOA, BBO, EO, ROA	[23]
EWOA	PID	WOA, TSO, TSA, SCA, RSO, RSA, BA	[24]
Hybrid simulated annealing (SA) and gorilla troops optimizer (GTO)	PID, PIDD2	GTO, HBA	[25]
Zebra optimisation algorithm (ZOA) and osprey optimization algorithm (OOA)	PID	ZOA, OOA	[26]
Artificial bee colony (ABC)	PID	PSO, DE	[27]
Manual tuning	PID	WOA, GOA, CS, GWO, SFS, TSA, SCA	[28]
Hybrid of harmony search (HS) and dwarf mongoose optimization (DMO)	PIDA, PID	LUS, HAS, TLBO	[29]
Current search (CS)	PIDA	PSO, GA	[30]
Bat algorithm (BA)	PIDA	CS, PSO, GA	[31]

In this paper, Non-Monopolize Optimization (NO) is proposed to tune PID and PIDA controllers and enhance the performance of an Automatic Voltage Regulator (AVR) system. The proposed method is benchmarked against several state-of-the-art optimization techniques through comprehensive simulations, including a step response, frequency response (Bode plots), and root locus analysis. The robustness is further validated under load variations of $\pm 50\%$, demonstrating stable dynamic performance under fluctuating operating conditions. While numerous metaheuristic optimization techniques have been applied to AVR systems, many suffer from premature convergence, high computational costs, or

improvements limited to either the time-domain or frequency-domain performance, with insufficient robustness to load disturbances. To bridge this gap, the NO algorithm introduces a lightweight, metaphor-free, and adaptive search mechanism that achieves superior transient and frequency responses while maintaining high robustness, thereby providing a more reliable and efficient solution for modern power systems.

This paper is organized into six sections. Section 1 introduces AVR systems and their impact on power systems. Section 2 discusses the components of AVR systems. Section 3 presents the controllers used in the MATLAB simulation and outlines the optimization techniques applied. Section 4 examines various objective functions used in AVR systems to minimize errors and enhance stability. Section 5 presents the simulation results, including a comparison with previously studied methods to evaluate the stability, response, and robustness of the AVR system. Finally, Section 6 concludes the paper and summarizes the key findings.

2. AVR System Components

An AVR system senses the terminal voltage using voltage sensors or voltage transformers (VTs) placed across the generator terminals and sends this signal back to the AVR. It then compares the reference voltage with the measured voltage from the VTs using an error detector (comparator) to obtain the error voltage. This error is processed by the controller to achieve better stability and a higher frequency response. The amplifier gain amplifies the error signal to adjust the excitation of the synchronous generator's rotor, thereby minimizing the terminal voltage error and regulating it to match the reference or nominal voltage. The components of an AVR system include four gain elements, as listed in Table 2. The total transfer function of the AVR system was drawn in MATLAB Simulink and is illustrated in Figure 1 [1,2].

Table 2. AVR system components.

AVR Component	Gains	Values
1. Amplifier	$\frac{K_A}{1+s T_A}$	$\frac{10}{1+0.1 s}$
2. Exciter	$\frac{K_E}{1+s T_E}$	$\frac{1}{1+0.4 s}$
3. Generator	$\frac{K_g}{1+s T_g}$	$\frac{1}{1+s}$
4. Voltage sensor	$\frac{K_S}{1+s T_S}$	$\frac{1}{1+0.01 s}$

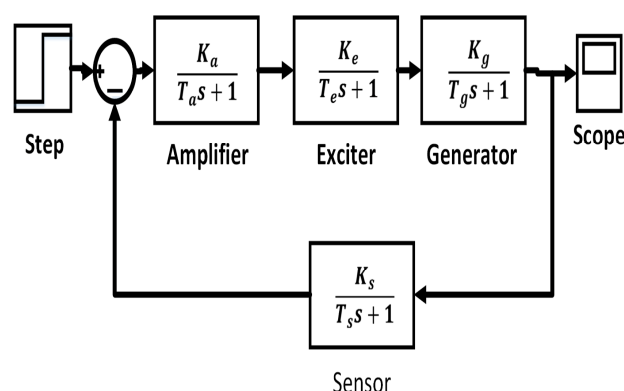


Figure 1. AVR system components model.

3. The Controllers and the Optimization Techniques

The controllers are installed to improve power system performance, and the objective functions are optimized to achieve the minimum error functions in the power system.

3.1. The Controllers

The controllers in this paper are the conventional-type PID and PIDA controllers, to study the effects of controller parameters on the frequency response as well as the time response. PID is a simple and robust controller and is widely used in diverse industries. It consists of three main gains, the proportional gain (K_p), integral gain (K_i), and derivative gain (K_d), and is found in Equation (1) below. The proportional gain depends on the current error, which produces an output directly proportional to the error. It mainly reduces the rise time while the integral gain improves the steady state error of the system. The integral gain can accumulate past errors over time. The derivative gain reduces the maximum overshoot as well as stability margin enhancement, as it predicts the future based on the rate of change in the error [3].

$$G(S) = K_p + \frac{K_i}{S} + K_d S \quad (1)$$

PIDA is a third-order control system, with the addition of acceleration gain (K_a) to the PID controller, which is expressed in the transfer function Equation (2). d and e are filter elements inside the controller. Equation (2) is simplified further to form a third-order polynomial function where the numerator consists of the four main gains (K_p , K_d , K_i , and K_a) and the two α and β parameters in the dominator, as represented in Equation (3) [4].

$$G(S) = K_p + \frac{K_i}{S} + \frac{K_d S}{(S + d)} + \frac{K_a S^2}{(S + d)(S + e)} \quad (2)$$

$$G(S) = \frac{K_a S^3 + K_d S^2 + K_p S + K_i}{S^3 + \alpha S^2 + \beta S} \quad (3)$$

3.2. Non-Monopolize Search Optimization (NO)

The Non-Monopolize Optimization (NO) is a metaphor-free and single-solution-based algorithm designed to efficiently solve complex problems without depending on population-based analogies or metaphors. This optimization solves the problem of premature convergence or lack of adaptive behaviour, unlike traditional metaphor-free optimization techniques. It introduces a mechanism by adjusting each decision variable (dimension or controller parameter) of the current solution based on its behavioural characteristics. It is performed through a mixture of localized exploitation and adaptive exploration to reach the optimal search space (objective function). The steps for implementing the NO algorithm to meet these objectives are as follow [32]:

1. Initiate the parameters (maximum iteration (T), position (X), dimensions (Ds), and boundaries).
2. Calculate the objective function with the initial positions for all the dimensions within the boundaries where $X(RP)$ is a random position within the boundaries).
3. If the iteration is less than half of maximum iteration, solve for the position as in Equation (4).

$$X_{new(j)} = rand.X(RP) \quad (4)$$

4. If the iteration is more than half of maximum iteration, solve for the position as in Equation (5).

$$X_{new(j)} = X_{(j)} - (rand.X(SelectedRP)) * eps - (X_{(j)} - NO) \quad (5)$$

5. When the maximum iteration is reached, use the positions as the controller's parameters for all the controller's dimensions (a PID controller has three dimensions while a PIDA controller has six dimensions).

This optimization escapes the local optima and prevents premature convergence. As a result, it is crucial to tune the controller parameters for enhanced power system stability in an AVR system. The NO algorithm has diverse advantages over the existing metaphor-free algorithms [32]:

- Dimension-Specific Adaptation: It operates at a dimensional level, unlike others that use the whole system, to enable the best adaptability and controllability in high-dimensional cases.
- Stochastic Controlled Search: The operator's randomness is balanced by a strategic local search for a better exploration–exploitation trade-off.
- Improved convergence through bypassing the local optima through the inherent operator's randomness.
- Lower computational complexity through using a single solution-based algorithm. It means a smaller memory is needed and has lower computational power.

In this paper, the NO algorithm is applied to tune the controller parameters utilizing its distinctive features of non-metaphorical design, specific dimensions, and adaptive local search for higher accuracy, efficiency, and stability in controller tuning compared to the existing metaphor-free algorithms.

4. Objective Function

The objective function aims to minimize the voltage error (ΔV_e) between the reference voltage and the terminal voltage of the generator. The most common objective functions in AVR systems for error minimization are Integrated Absolute Error (IAE), Integrated Squared Error (ISE), Integrated Time-weighted Squared Error (ITSE), and Integral Time-weighted Absolute Error (ITAE). These are represented by Equations (6), (7), (8), and (9), respectively.

In control system optimization, the IAE weights all errors equally, but this typically results in a slower response and longer settling time. The ISE is more sensitive to initial errors and penalizes large deviations more heavily. The ITSE balances the need to suppress large errors and sustain penalized late errors. It is used more in research and mathematical modelling. The ITAE is the most widely used objective function in industries due to its ability to produce low overshoot and short settling times. It is characterized by a fast response and quick error reduction as it adds a weighting factor based on the time. As a result, the ITAE is the best objective function used in AVR systems, and it is used in process industries [33]. The final transfer function of the system, after integrating the controller whose parameters are optimized using the selected objective function, is shown in Figure 2.

$$IAE = \int_0^t |\Delta V_e| dt \quad (6)$$

$$ISE = \int_0^t (\Delta V_e)^2 dt \quad (7)$$

$$ITSE = \int_0^t t (\Delta V_e)^2 dt \quad (8)$$

$$\text{ITAE} = \int_0^t t |\Delta V_e| dt \quad (9)$$

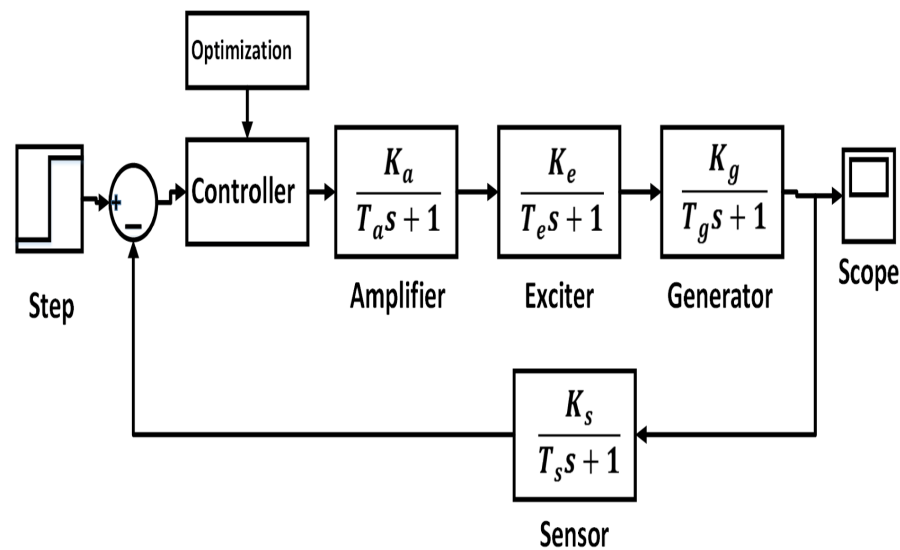


Figure 2. AVR system with controller's parameters optimized.

5. Results

After performing the step response simulation in MATLAB Simulink, several key analyses were conducted for each controller type, including a 1 p.u. step response, Bode plots, and root locus diagrams. A comprehensive comparison of the PID and PIDA controllers was carried out to identify the most effective optimization technique for tuning the controller parameters. The goal was to achieve optimal power system stability, high time-domain performance, fast frequency response, and strong robustness under load variations.

The transient response was evaluated based on the terminal voltage of the synchronous generator. The best time response, or the benchmark, was indicated by a minimal overshoot (M_p) that was nearly equal to zero, the shortest rise time (T_r), a reduced settling time at 5% or 2% (T_s), and an improved steady-state error (E_{ss}) that was nearly equal to 1. The time-domain performance was further assessed using a root locus analysis, from which the eigenvalues and damping ratios were extracted. The fastest time response had the highest damping ratio, nearly equal to one (close to the x-axis), and more negative real parts for the eigenvalues that indicate more system stability.

The frequency response was assessed using Bode diagrams, which provide the peak margin, gain margin, phase margin, and delay margin. The best frequency stability was characterized by the highest gain margin, the biggest phase margin (180 degrees), infinite delay margin, and zero peak margin. The controller parameters for each optimization technique were compared under the same conditions to determine the best AVR system performance. Furthermore, a robust analysis was performed on the best optimization technique to emphasize the power system's stability and the speed of time response under various loading conditions. The stability should be within 5% of the nominal voltage or reference, and the time response should be within the normal condition ranges with minimal overshoot, rise time, settling time, and unity steady-state error.

5.1. AVR Connected to PID Controller

The PID controller was tuned using several optimization techniques, including the Non-Monopolize Optimization (NO), whale optimization algorithm (WOA), teaching—learning-based optimization (TLBO), golf optimization algorithm (GOA), artificial bee colony (ABC), and artificial rabbits' optimization (ARO). The controller gains (K_p , K_i , and

K_d) were constrained within the range $[0, 1]$, and the optimization was conducted with a maximum of 100 iterations.

Figure 3 shows the step responses of the AVR system using the PID controller that was tuned by the different optimization techniques. The corresponding controller parameters and performance metrics are summarized in Table 3. The results indicate that the NO provided the lowest overshoot among all the techniques. The settling times were generally similar across all methods. Final evaluation of each optimization technique's effectiveness was based on both the time and frequency response metrics.

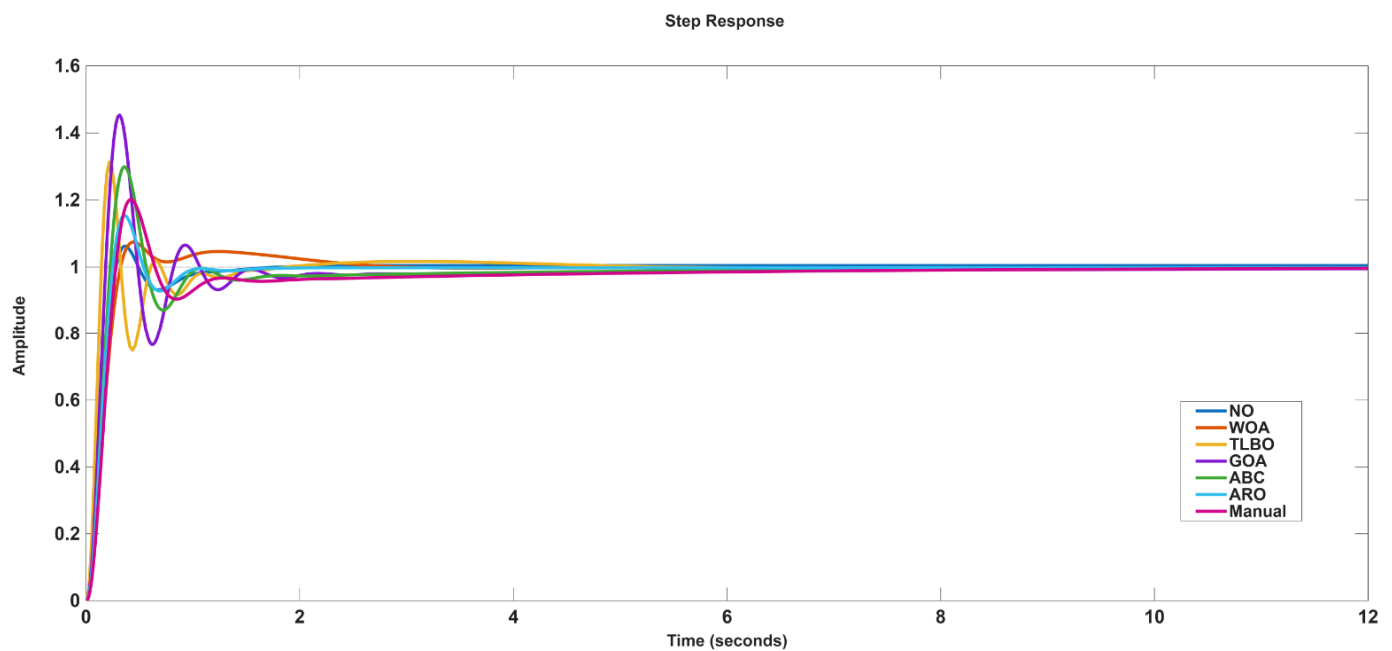


Figure 3. Step response of AVR system using PID controller.

Table 3. Step response performance of AVR system using PID controller.

Optimization	K_P	K_i	K_d	Overshoot	Rise Time	Settling Time
NO-PID	0.84449	0.61533	0.37661	1.0622	0.185	0.612
WOA-PID [12]	0.7847	0.9961	0.3061	1.07	0.26	0.555
TLBO-PID [14]	0.96854	1	0.89825	1.232	0.095	0.5726
GOA-PID [16]	2.5264	0.3988	0.4635	1.454	0.118	1.332
ABC-PID [27]	1.6524	0.4083	0.3654	1.250	0.156	0.92
ARO-PID [10]	1.0386	0.6748	0.3808	1.154	0.164	0.804
Manual-PID [28]	1.2261	0.2902	0.2836	1.171	0.192	1.118

Figure 4 presents the Bode diagram for the NO-PID controller only. The other optimization techniques are illustrated in Figure 5 for the frequency response analysis. The phase, gain, delay, and peak margins are calculated, analysed, and presented in Table 4. The NO-PID controller demonstrated the best frequency-domain performance, with the highest gain, phase, and delay margins, and the lowest peak margin.

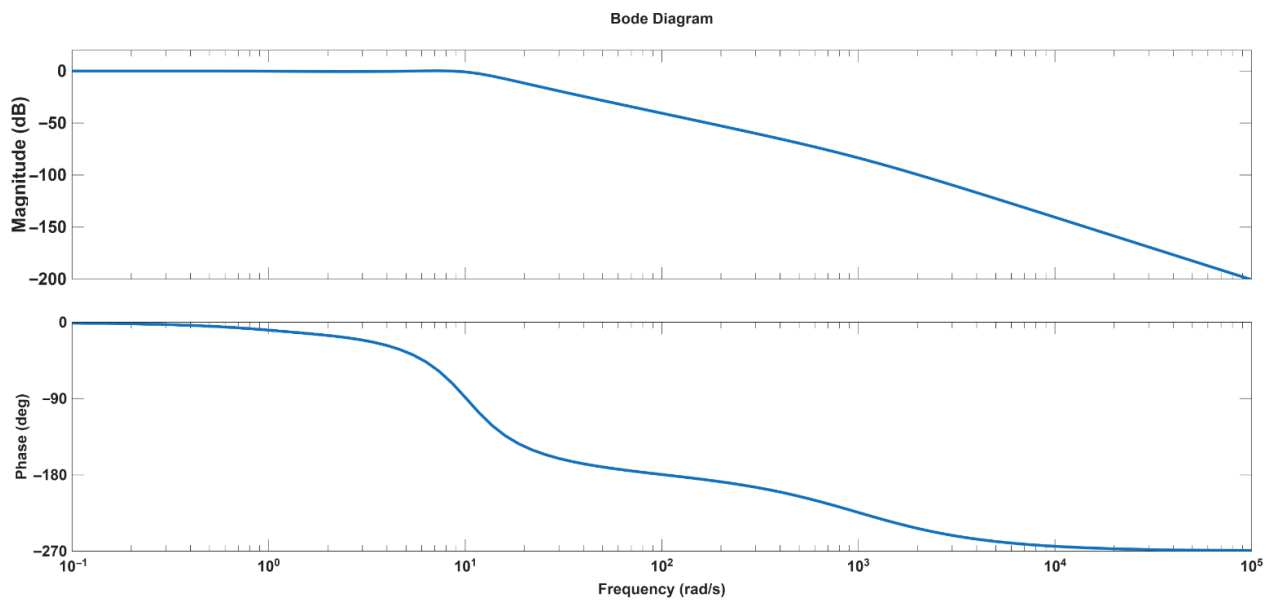


Figure 4. Bode diagram for AVR system using NO-PID controller.

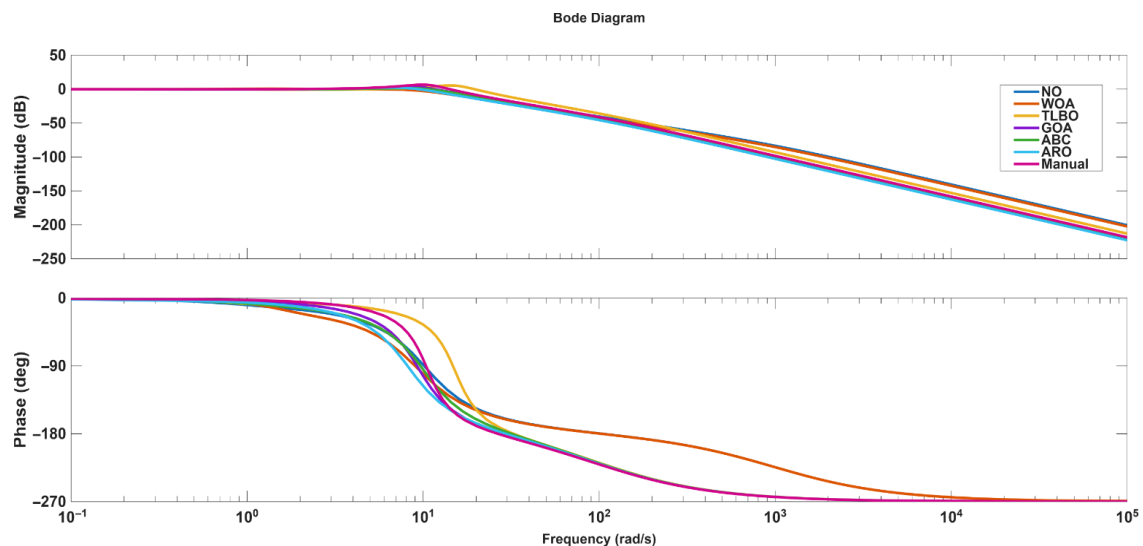


Figure 5. Bode diagram for AVR system using different optimizations with PID controller.

Table 4. Bode diagram performance of AVR system using PID controller.

Optimization	Peak Margin (dB)	Phase Margin (Degrees)	Gain Margin (dB)	Delay Margin (s)
NO-PID	0.1974	176.05	41.24	7.082
WOA-PID [12]	0.569	155	22.699	1.04
TLBO-PID [14]	3.42	59.5	12.57	0.0553
GOA-PID [16]	6.588	175.581	14.586	1.78
ABC-PID [27]	2.87	69.4	18.6	0.111
ARO-PID [10]	1.477	159.565	20.32	0.875
Manual-PID [28]	1.696	167.82	41.09	1.42

The root locus diagram is calculated in Figure 6 for the NO-PID. The eigenvalues and damping ratios for all the techniques are presented in Table 5. The NO-PID controller achieved the highest damping ratio and more negative poles, indicating the fastest time response compared to the other techniques.

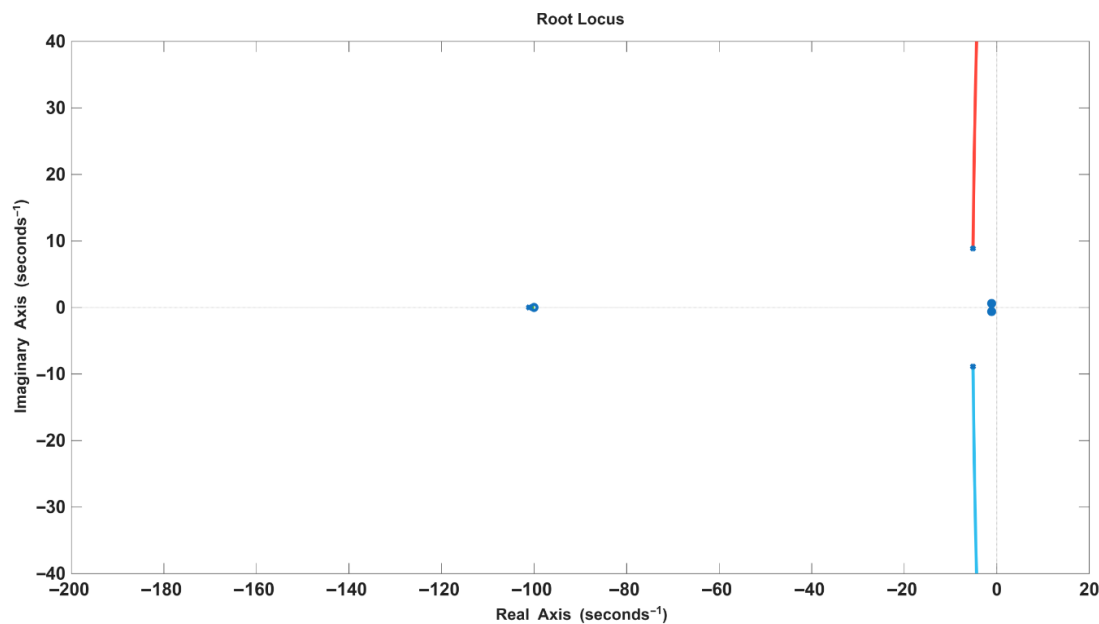


Figure 6. Root locus of AVR system using NO-PID controller.

Table 5. Eigen values (damping ratio) of AVR system using PID controller.

Optimization	Eigen Values (Damping Ratio)		
NO-PID	−101 (1)	$-5.15 \pm 8.89j$ (0.501)	$-1.12 \pm 0.614j$ (0.877)
WOA-PID [12]	−101 (1)	$-5.24 \pm 7.64j$ (0.565)	$-1.09 \pm 1.3j$ (0.642)
TLBO-PID [14]	−102 (1)	$-5.02 \pm 14.7j$ (0.323)	$-0.52 \pm 0.86j$ (0.511)
GOA-PID [16]	−100 (1)	-5.46 (1), -0.163 (1)	$-2.63 \pm 10.22j$ (0.249)
ABC-PID [27]	−101 (1)	-4.74 (1), -0.25 (1)	$-3.75 \pm 8.4j$ (0.4)
ARO-PID [10]	−100 (1)	-1.58 (1), -1.09 (1)	$-4.38 \pm 9.113j$ (0.433)
Manual-PID [28]	−101 (1)	-4.05 (1), -0.252 (1)	$-3.89 \pm 7.096j$ (0.48)

5.2. AVR Connected to PIDA Controller

The PIDA controllers had different margins compared to the PID controllers. The margins of PIDA controllers were as follows:

$$50 \leq K_a \leq 150$$

$$450 \leq K_d \leq 550$$

$$750 \leq K_p \leq 850$$

$$350 \leq K_i \leq 450$$

$$550 \leq \alpha \leq 650$$

$$900 \leq \beta \leq 1000$$

For the PIDA controller, the transient response was also tested using various optimization methods: NO, WOA, TLBO, hybrid harmony search and dwarf mongoose optimization (HS/DMOA), current search (CS), BAT algorithm, and genetic algorithm (GA). This was conducted by a comparison with previous works in the literature [12,14,29–31]. Figure 7 illustrates the step response of the PIDA controllers. Table 6 contains the controller parameters and performance outcomes. Among these, the NO-PIDA achieved the lowest overshoot, while all techniques yielded similar rise times around 0.5 s. Both the NO and WOA showed the best settling times.

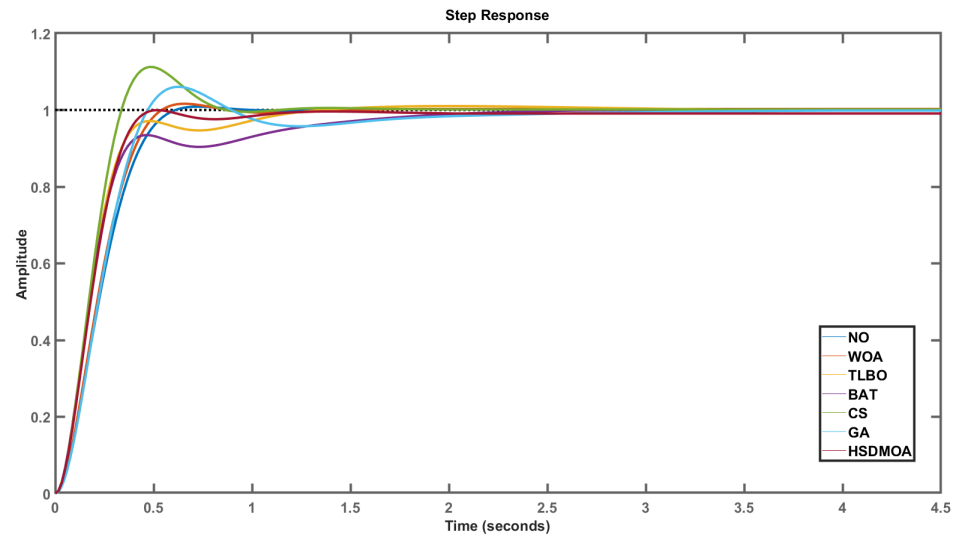


Figure 7. Step response of AVR system using PIDA controller.

Table 6. Step response performance of AVR system using PIDA controller.

Optimization	K_a	K_d	K_P	K_i	α	β	Overshoot	Rise Time	Settling Time
NO-PIDA	111.586	506.09	777.98	365.18	623.3	903.97	1	0.353	0.488
WOA-PIDA [12]	103.02	500.65	777.4	397.74	550.12	915.04	1.02	0.328	0.453
TLBO-PIDA [14]	150	550	850	421.6	550	990	1.01	0.2732	0.81
HS/DMOA-PIDA [29]	129.207	527.12	905.56	356.81	508.91	890.24	1	0.274	0.932
CS-PIDA [30]	101.01	498.95	799.12	394.01	589.54	965.05	1.0182	0.524	1.34
BAT-PIDA [31]	149.98	549.53	755.11	350	550.23	1000	1	0.3	1.182
GA-PIDA [30]	99.1	577.56	784.01	342.15	592.97	912.45	1.06	0.451	2.5422

The frequency response analysis for the NO-PIDA controller is shown in Figure 8 and compared to the others as indicated in Figure 9. The analysis of the frequency response that was conducted on the optimization techniques used for the PIDA controller and the margins are indicated in Tables 6 and 7. The NO-PIDA had the highest phase margin, gain margin, delay margin, and negligible peak margin. Although several methods had similar phase and delay margins, the NO-PIDA had a notably higher gain margin.

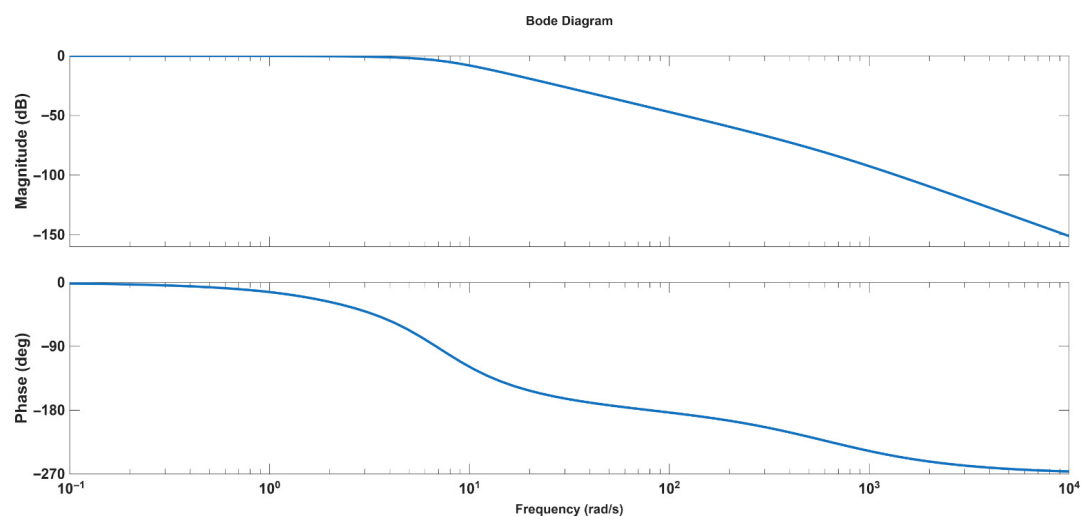


Figure 8. Bode diagram of AVR system using PIDA controller.

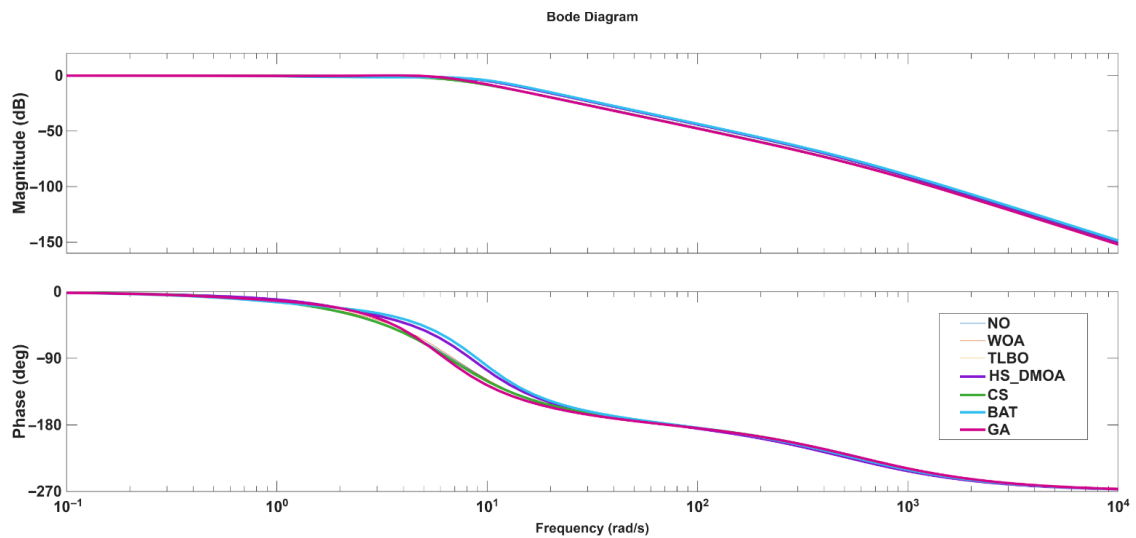


Figure 9. Bode diagram of different optimization techniques using PIDA controller.

Table 7. Bode diagram performance of AVR system using PID controller.

Optimization	Peak Margin	PHASE Margin	Gain Margin	Delay Margin
NO-PIDA	0	180 degrees	43.07	Inf
WOA-PIDA [12]	0	180 degrees	41.5	Inf
TLBO-PIDA [14]	0	180 degrees	39.1	Inf
HS/DMOA-PIDA [29]	0	180 degrees	38.79	Inf
CS-PIDA [30]	0	180 degrees	42	Inf
BAT-PIDA [31]	0	180 degrees	39.2	Inf
GA-PIDA [30]	0.15	123 degrees	42	0.5 s

To assess the time response further, the root locus for the NO-PIDA is presented in Figure 10. The eigenvalues and damping ratios are listed in Table 8 for the different optimization techniques using the PIDA controller. The NO-PIDA controller demonstrated the best time response characteristics, featuring more negative poles and one of the highest damping ratios, approaching a value of 1—indicative of excellent time response and stability.

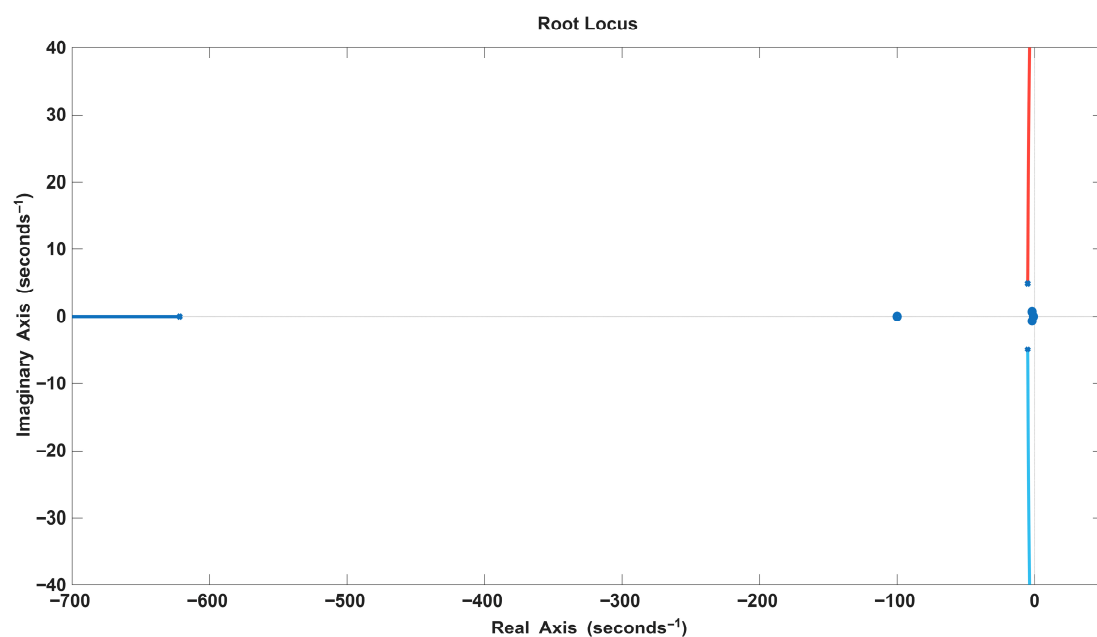


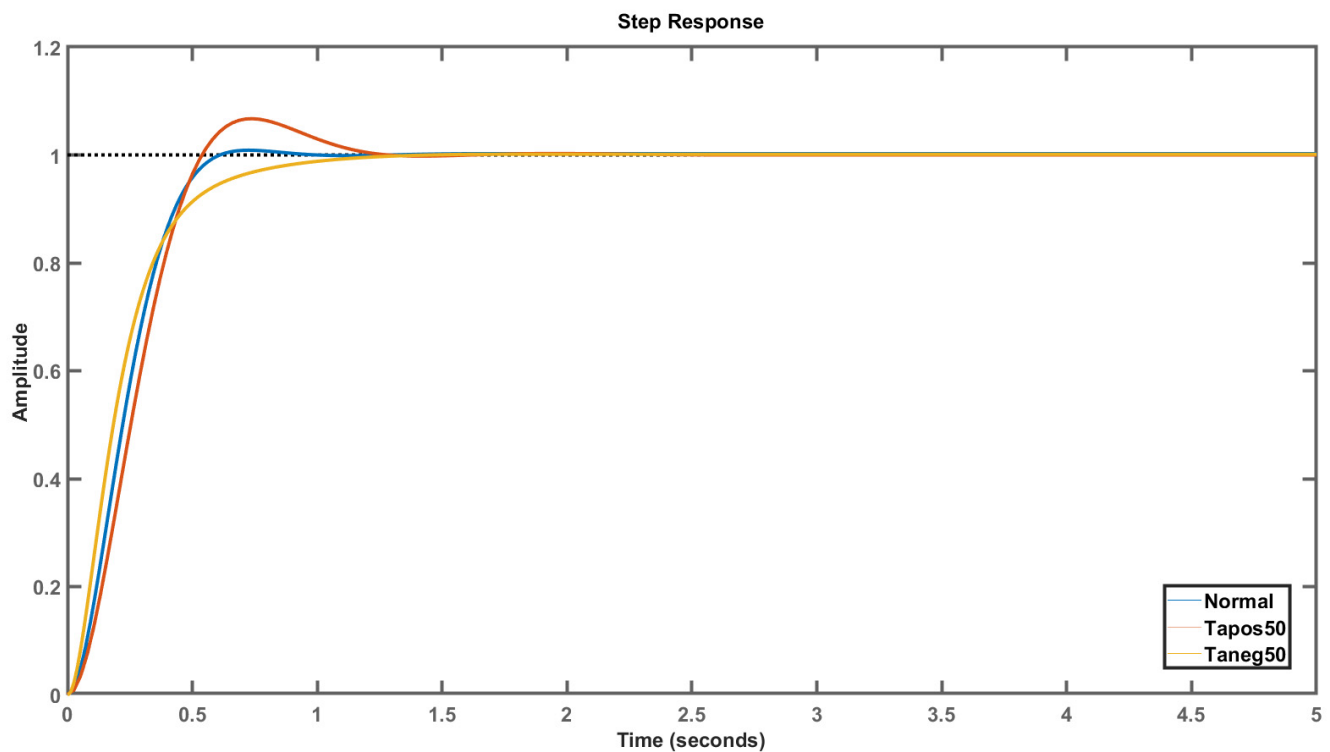
Figure 10. Root locus of AVR system using NO-PIDA controller.

Table 8. Eigen values (damping ratio) of AVR system using PID controller.

Optimization	Eigen Values (Damping Ratio)				
NO-PIDA	−622 (1)	−101(1)	−0.856 (1)	$-5.08 \pm 4.92j$ (0.719)	$-1.78 \pm 0.734j$ (0.924)
WOA-PIDA [12]	−548 (1)	−101 (1)	−2.28 (1)	$-4.93 \pm 5.1j$ (0.695)	$-1.21 \pm 0.33j$ (0.964)
TLBO-PIDA [14]	−548 (1)	−101 (1)	−0.855 (1)	$-5.47 \pm 7.29j$ (0.6)	$-1.23 \pm 1.08j$ (0.6)
HS/DMOA-PIDA [29]	−507.1 (1)	−100 (1)	−0.542 (1)	$-5.39 \pm 6.82j$ (0.62)	$-1.76 \pm 1.4j$ (0.784)
CS-PIDA [30]	−588 (1)	−101 (1)	−0.926 (1)	$-4.92 \pm 4.6j$ (0.73)	$-1.91 \pm 0.55j$ (0.96)
BAT-PIDA [31]	−548 (1)	−101 (1)	−0.936 (1)	$-5.51 \pm 7.37j$ (0.6)	$-1.23 \pm 0.7j$ (0.87)
GA-PIDA [30]	−591 (1)	−101 (1)	−5.44 (1)	$-3.71 \pm 4.57j$ (0.631)	$-0.82 \pm 0.3j$ (0.938)

5.3. Robust Analysis of NO for PIDA Controller

The operating point and the power system parameters depend on the load variation. As a result, a study was performed on the AVR parameters to reflect a variation in loads, with variations from 50% to −50% of their nominal values (time constant). The NO-PIDA was studied as it had the best power system stability and fastest time and frequency responses. The variations in the load on the amplifier, generator, exciter, and sensor are presented in Figure 11, Figure 12, Figure 13, and Figure 14, respectively. Table 9 shows the performance (maximum overshoot, settling time, and rise time) of the AVR system using the NO-PIDA, and Table 10 shows the maximum deviation and its percentage for the variation in load. The results emphasize the robustness of AVR system, where the maximum deviation is acceptable and power system stability is achieved during transients.

**Figure 11.** Time-changing constant (T_a) using NO-PIDA controller.

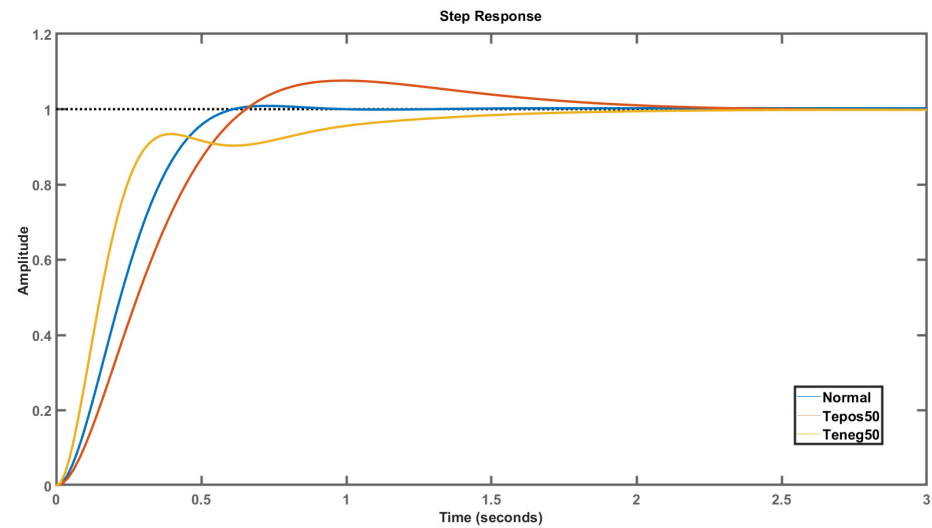


Figure 12. Time-changing constant (T_e) using NO-PIDA controller.

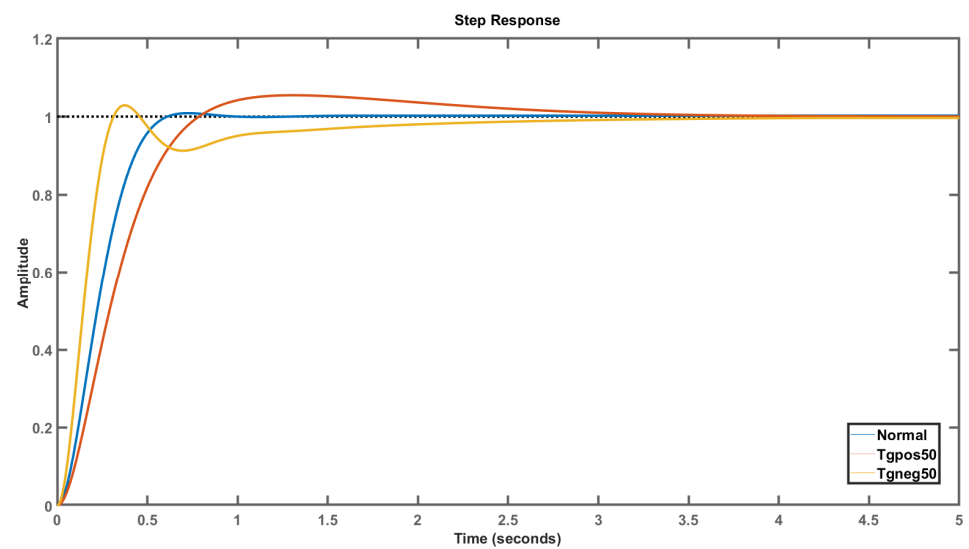


Figure 13. Time-changing constant (T_g) using NO-PIDA controller.

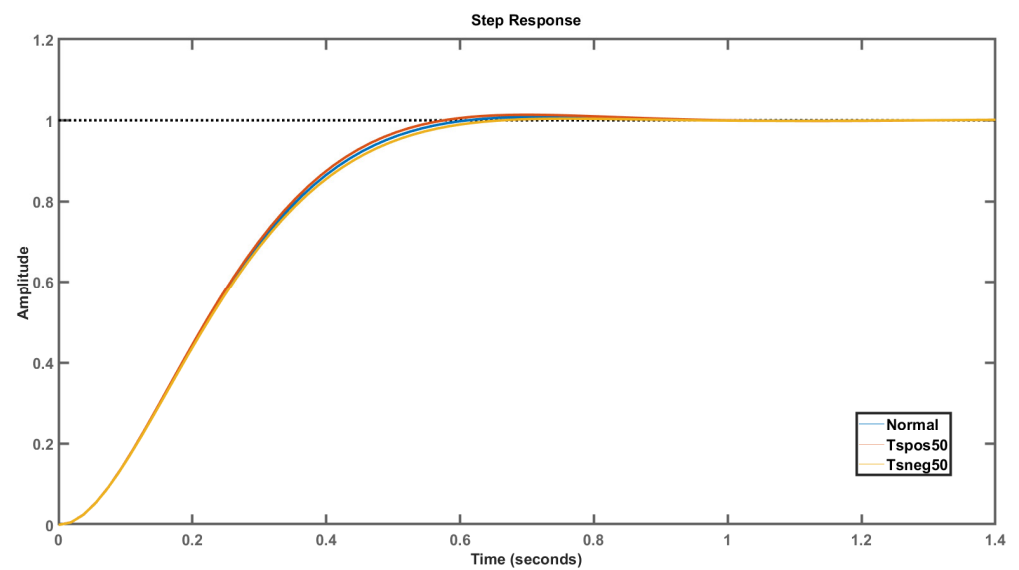


Figure 14. Time-changing constant (T_s) using NO-PIDA controller.

Table 9. Dynamic response performance of AVR system using NO-PIDA.

Time Constant	Change %	M_p	T_r	T_s
T_a	50%	1.066	0.355	0.713
	−50%	1	0.412	0.526
T_e	50%	1.076	0.432	1.235
	−50%	1	0.256	0.748
T_g	50%	1.054	0.493	1.474
	−50%	1.029	0.199	0.892
T_s	50%	1.014	0.343	0.413
	−50%	1.004	0.362	0.497

Table 10. Maximum deviations of AVR system using NO-PIDA.

Time Constant	Deviation	M_p	T_r	T_s
T_a	Max	0.066	0.059	0.225
	Percentage (%)	6.6	16.7	46.1
T_e	Max	0.076	0.097	0.747
	Percentage (%)	7.6	27.47	153
T_g	Max	0.054	0.154	0.986
	Percentage (%)	5.4	43.62	202
T_s	Max	0.014	0.009	0.075
	Percentage (%)	1.4	2.5	15.36

6. Conclusions

This paper shows how to fully combine the Non-Monopolize Optimization (NO) method with the tuning of both PID and PIDA controllers for AVR systems to adjust the terminal voltage in the synchronous generator. The NO algorithm is different from other metaheuristics since it has a tuning process that does not use metaphors and is expeditious. It had the best transient stability and fastest time response and frequency response compared to other techniques that use the same controllers. With the PID controller, compared to the others, the NO showed the lowest overshoot of 1.0622 p.u., the highest gain margin of 41.24 dB and phase margin of 176.05 degrees, and the biggest damping ratio. The results show a significant output for the simple PID controller compared to other modern controllers. The NO-PIDA controller had the best transient stability of 1 p.u. overshoot, the fastest frequency stability with a 43.07 dB gain margin and a 180-degree phase margin, and the highest dynamic behaviour with more negative eigenvalues and damping ratios near to 1.

A robust analysis of the NO-PIDA controller was performed to study a loading variation of $\pm 50\%$ on the transient stability, and showed a stable, robust, and efficient AVR system model. These results show that the NO could be a good alternative to the complicated, multi-agent optimizers used in power systems. In the future, this technology may be expanded to work with several machines, different modern controllers, and its performance may be tested on experimental testbeds to see if it can be used in grid-connected generators and smart microgrids.

In future research, the proposed NO approach could be further enhanced by combining it with other optimization techniques to achieve even better AVR system performance. Beyond MATLAB/Simulink simulations, a transition to real-time implementation is planned to validate the findings experimentally and assess their industrial applicability. A hardware-based AVR system will be developed with embedded control platforms, sensors, and power

electronic components to monitor the parameters and regulate the terminal voltage. Experimental testing will include step and frequency response evaluations, with particular attention to noise sensitivity, unmodelled system dynamics, and statistical error margins under different dynamic load conditions. These investigations will provide deeper insights into the reliability and robustness of the proposed method, ensuring its suitability for practical power system applications.

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