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Grasshopper Optimization Algorithm for Automatic Voltage Regulator System

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Abstract—**A novel design method is presented to determine optimum proportional-integral-derivative (PID) controller parameters of an automatic voltage regulator (AVR) system utilizing the grasshopper optimization algorithm (GOA). The proposed approach is a simple and effective algorithm that is able to solve many optimization problems even those with unknown search spaces effectively. The simplicity of algorithm provides high quality tuning of optimal PID controller parameters. The integral of time weighted squared error (ITSE) is used as the performance index to confirm the performance of the proposed GOA-PID controller. When compared to the other PID controllers based on Ziegler-Nichols (ZN), differential evolution (DE), and artificial bee colony (ABC) tuning methods, the proposed method is found highly effective and robust to improve AVR system's transient response.**

Keywords-automatic voltage regulator; grasshopper optimization algorithm; parameter tuning

I. INTRODUCTION

An automatic voltage regulator (AVR) system is used to maintain terminal voltage magnitude of a generator in an electrical power system. The magnitude of this voltage is maintained at a specified level by controlling the generator excitation [1]. Generally, it is hard to find optimal controller parameters with classical tuning methods such as Ziegler-Nichols (ZN), Cohen Coon, and gain-phase margin [2]. Therefore, several heuristic optimization methods have been proposed for tuning controller parameters, during the past two decades. In literature, the controller types used for improving the dynamic response of AVR system are proportional-integral-derivative (PID) [3]-[15], fractional order PID (FOPID) [16], [17], PID-acceleration (PIDA) [18], gray PID (GPID) [19], and fuzzy logic PID (FLPID) [20]. The heuristic optimization based tuning methods that have been applied to improve performance of the fore mentioned controller types are particle swarm optimization (PSO) [3]-[5], artificial bee colony (ABC) [6], [7], differential evolution (DE) [7], teaching learning based optimization (TLBO) [8], [9], gravitational search algorithm (GSA) [10], [11], bat algorithm (BA) [12], [18], pattern search algorithm (PSA) [13], firefly algorithm (FA) [14], bio-geography based optimization (BBO) [15], ant colony optimization (ACO) [16], cuckoo search (CS) algorithm [17], imperialist competitive algorithm (ICA) [19] and genetic algorithm (GA) [3], [4], [10], [16]-[20].

Grasshopper optimization algorithm (GOA) is a population-based single objective stochastic and heuristic optimization technique proposed by Saremi et al. [21], which imitates the behavior of grasshopper swarms in nature and models it mathematically for solving optimization problems with contentious variables. After the conducted tests with various test functions, namely unimodal, multimodal, composite and CEC2005 functions, and real problems in the field of structural design, it is shown that GOA can solve many optimization problems (even those with unknown search spaces) effectively [21]. Since GOA considers a given optimization problem as a black-box and does not need any gradient information of the search space, this makes it a highly suitable optimization technique for any properly formulated optimization problem in different fields.

GOA has attracted many researchers after its first proposal. In [22], [23] multi-objective versions, in [24] adaptive version, in [25] hybrid version of GOA have been proposed. GOA is also used for solving real problems such as structural design problems [21], cancer classification [26], distributed trajectory optimization [24], data clustering [27], short-term power load forecasting [25], and feature selection [28].

Since, the GOA algorithm is not affected by the nonlinear nature and/or magnitude of a problem, where usually other global optimization techniques show early convergence, it finds the best solution more efficiently with faster convergence. Considering these advantages of GOA algorithm, a GOA based PID (GOA-PID) controller proposed for a high-order AVR system in this work. It is worth to mention that there is no such study that has been proposed in the literature before. To confirm the proposed method's effectiveness and robustness, some comparative results between the proposed GOA-PID controller and DE-PID, ABC-PID, and ZN-PID controllers are presented.

The rest of this paper is organized as follows. Section 2 describes the AVR system and its transfer function model. Section 3 describes GOA-based optimization. Section 4 explains the application of GOA-PID controller in AVR system and provides the results of numerical simulations with comparisons. Finally, Section 5 concludes the paper with a brief summary of key findings of the work.

II. AVR SYSTEM

In a power system, the interaction between voltage control and frequency control of a power generation system

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is usually weak enough so that their analysis can be done separately. Since, a change in reactive power mainly affects the voltage magnitude of a generator at its terminals, the primary means of generator reactive power control is utilizing an AVR system to control the excitation of the generator [1]. Thus, the purpose of an AVR is to maintain the voltage magnitude of a generator at its terminals at a fixed level. An AVR system is shown in Fig. 1.

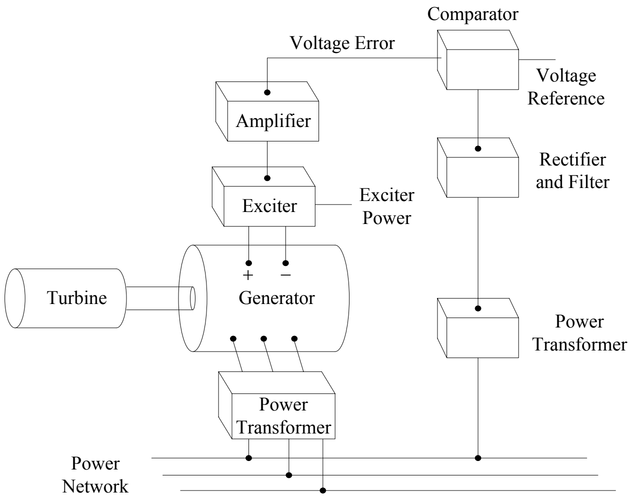

Figure 1. AVR System.

As seen from the figure, AVR system is mainly composed of four components; amplifier, exciter, sensor and generator. Thus, it can be modeled by the transfer function of its all components as shown in Fig. 2.

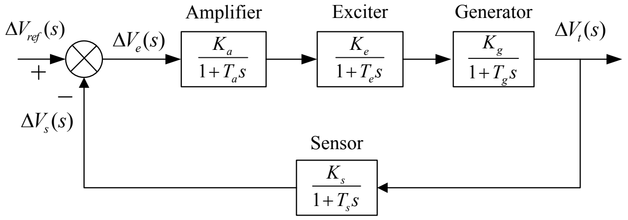

Figure 2. Transfer function model of AVR system.

Here, $\Delta V_{ref}(s)$, $\Delta V_s(s)$, $\Delta V_e(s)$, and $\Delta V_t(s)$ are reference input voltage, output voltage of the sensor, error voltage and terminal voltage of the generator, respectively. The transfer functions of AVR system is given in (1).

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{K_a K_e K_g (1+sT_s)}{(1+sT_a)(1+sT_e)(1+sT_g)(1+sT_s)+K_a K_e K_g K_s} \quad (1)$$

The boundary values of AVR system components and the used values in AVR system are given in Table 1. The used values in this paper are chosen as the same values in [7]. Although it is stable, without a controller, the terminal step voltage response of AVR system is highly oscillatory as shown in Fig. 3.

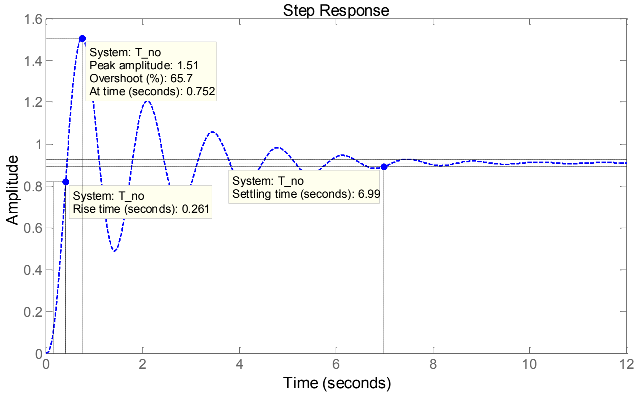

Figure 3. Step response of AVR system without controller.

The system has two real poles at $s=-99.971$ and -12.489 and two complex poles at $s=-0.5198\pm 4.6642i$ with a damping ratio of 0.111. The system has a rise time of 0.261 s, a peak time of 0.752 s, a settling time of 6.99 s, an overshoot of 65.7% and a steady state value of 0.909 pu. From these figures it is clear that the dynamic response of AVR system needs to be improved and the steady state error needs to be eliminated by using a PID controller. The boundary values of PID controller parameters to be used in AVR system are given in Table I, as well.

TABLE I. BOUNDARY VALUES OF AVR SYSTEM WITH PID CONTROLLER.

Model	Parameter Ranges	Used Values in AVR System
Controller	$0.2 \le K_p, K_i, K_d \le 2.0$	Optimal values of K_p, K_i, K_d
Amplifier	$10 \le K_a \le 40$, $0.02 \le T_a \le 0.1$	$K_a = 10$, $T_a = 0.1$ s
Exciter	$1.0 \le K_e \le 10$, $0.4 \le T_e \le 1.0$	$K_e = 1.0$, $T_e = 0.4$ s
Generator	$0.7 \le K_g \le 1.0$, $1.0 \le T_g \le 2.0$	$K_g = 1.0$, $T_g = 1.0$ s
Sensor	$1.0 \le K_s \le 2.0$, $0.001 \le T_s \le 0.06$	$K_s = 1.0$, $T_s = 0.01$ s

III. GRASSHOPPER OPTIMIZATION ALGORITHM (GOA)

GOA is a recently proposed single objective, population based heuristic algorithm, which imitates the behavior of grasshopper swarms in nature and models it mathematically to solve optimization problems with contentious variables [21]. The algorithm simulates repulsion and attraction forces between grasshoppers. While repulsion forces permit grasshoppers to explore the search space, attraction forces urge them to exploit the promising regions. GOA was equipped with a coefficient, which decreases the comfort zone of the grasshoppers to balance exploration and exploitation phases over the course of optimization. This helps GOA not to become trapped in local optima and find a precise estimate of the global optimum. Since the best solution obtained so far by the swarm considered as a target to be chased, grasshoppers have a great chance to find the global optimum via improving the target over the course of iterations. The position updating equation of GOA is given as in

$$X_i^d = r\left(\sum_{\substack{j=1\\ j\neq i}}^{N} r\frac{ub_d - lb_d}{2} s\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{d_{ij}}\right) + T_d \quad (2)$$

here, X_i^d is the current solution's position in d-th dimension, r is a diminishing coefficient, which narrows the comfort zone, repulsion zone, and attraction zone, ub_d is the upper bound in d-th dimension, lb_d is the lower bound in d-th dimension, s is a function, which defines the social forces between grasshoppers, d_{ij} is the absolute value of the distance between j-th grasshopper x_j and i-th grasshopper x_i, T_d is the target value in d-th dimension, which is the best solution found so far. Equation (2) shows that the next position of a grasshopper depends on its current position, the position of all other grasshoppers, and the position of the target. The social forces function in (2) is defined as in

$$s = fe^{\frac{-d}{l}} - e^{-d} \quad (3)$$

here, f shows the strength of attraction and l is the attractive length scale. The function s is shown in Fig. 4, to demonstrate its effect on the social interaction (attraction and repulsion) between grasshoppers.

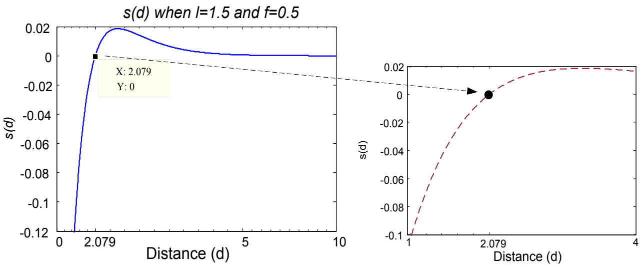

Figure 4. Social forces function s when l=1.5 and f=0.5 (Left), and its range when distance d is in a range of [1, 4] (Right) [21].

In this figure, distances from 0 to 10 are considered. Repulsion occurs in the interval [0, 2.079]. When a grasshopper is 2.079 units away from another grasshopper, there is neither attraction nor repulsion, which is called the comfort zone or comfortable distance. Fig. 4 also shows that the attraction value increased from 2.079 to about 4, and then gradually decreased. It is obvious that varying the parameters f and l in (3) will cause different social behaviors in artificial grasshoppers, however in this study they are chosen as 0.5 and 1.5, respectively. Since, this function returns values close to zero with distances greater than 4 as Fig. 4 shows, the distance of grasshoppers represented in a range of [1, 4]. The shape of the function s in this interval is shown in Fig. 4 (right). The conceptual model of social interactions between grasshoppers and the comfort zone using the function s is shown in Fig. 5.

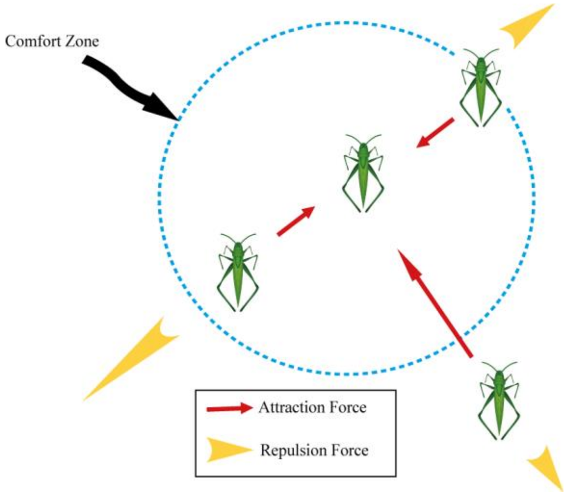

Figure 5. Social interactions between grasshoppers and the comfort zone [21].

The parameter r in (2) is required to be decreased in proportion to the number of iterations to balance exploration and exploitation. This encourages exploitation as the iteration count increases. This parameter also reduces the comfort zone in proportion to the number of iterations and is calculated as in

$$r = r_{\max} - t\frac{r_{\max} - r_{\min}}{T} \quad (4)$$

where $r_{\max}$ is the maximum value, $r_{\min}$ is the minimum value, t indicates the current iteration, and T is the maximum number of iterations. In this paper, 1 and 0.00001 are used for $r_{\max}$ and $r_{\min}$ respectively.

IV. IMPLEMENTATION OF THE PROPOSED GOA-PID CONTROLLER IN AVR SYSTEM

In this section, the proposed GOA tuned PID controller, which is called GOA-PID controller, is presented to make the transient response of an AVR system better. The block diagram of AVR system with GOA-PID controller is shown in Fig. 6.

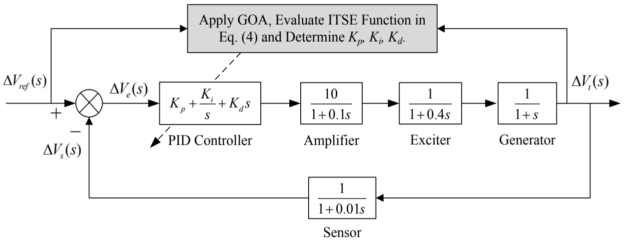

Figure 6. AVR system with GOA-PID controller.

To analyze and design the proposed controller the considered performance index in this paper is the integral of time multiplied squared error (ITSE) and it is given as in

$$ITSE = \int_{0}^{t_{sim}} t(\Delta V_t - \Delta V_{ref})^2 \; dt \, . \tag{5}$$

here, t_{sim} is the simulation run time and equals to 20 s, in this paper. After the simulation process, the tuned and optimized PID controller parameters obtained by classical and heuristic tuning methods are given in Table II.

TABLE II. OPTIMIZED PID PARAMETERS.

Controller type	Kp	Ki	Kd
ZN-PID	1.0210	1.8743	0.1390
DE-PID [7]	1.9499	0.4430	0.3427
ABC-PID [7]	1.6524	0.4083	0.3654
Proposed GOA-PID	1.3825	1.4608	0.5462

The transfer functions of AVR system with its PID controller tuned by ZN, DE, ABC, and the proposed GOA method are given in (6)-(9), respectively. The step responses of AVR system with different controllers are shown in Fig. 7.

$$\frac{0.0139s^3 + 1.493s^2 + 10.4s + 18.74}{0.0004s^5 + 0.045s^4 + 0.555s^3 + 2.9s^2 + 11.21s + 18.74} \tag{6}$$

$$\frac{0.03427s^3 + 3.622s^2 + 19.54s + 4.43}{0.0004s^5 + 0.045s^4 + 0.555s^3 + 4.937s^2 + 20.5s + 4.43} \tag{7}$$

$$\frac{0.03654s^3 + 3.819s^2 + 16.56s + 4.083}{0.0004s^5 + 0.045s^4 + 0.555s^3 + 5.164s^2 + 17.52s + 4.083} \tag{8}$$

$$\frac{0.05462s^3 + 5.6s^2 + 13.97s + 14.61}{0.0004s^5 + 0.045s^4 + 0.555s^3 + 6.972s^2 + 14.83s + 14.61} \tag{9}$$

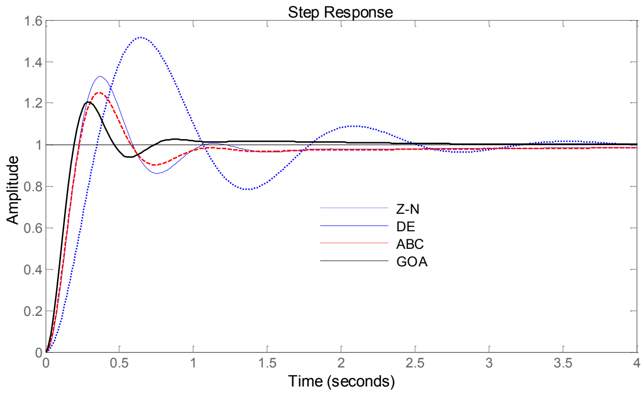

Figure 7. Step response of AVR system with different controllers.

A. *Transient Response Analysis*

Maximum overshoot, settling time, rise time and peak time are the performance features that define the transient response of a unit step input. Therefore the obtained results of these features are given in Table III to emphasize the efficiency of the proposed GOA-PID controller compared to the other controllers.

TABLE III. TRANSIENT RESPONSE ANALYSIS RESULTS OF AVR SYSTEM.

Controller type	Maximum overshoot	Settling time (2% band)	Rise time	Peak Time
ZN-PID	1.515	3.052	0.237	0.644
DE-PID [7]	1.330	2.650	0.152	0.360
ABC-PID [7]	1.250	3.094	0.156	0.360
Proposed GOA-PID	**1.205**	**0.971**	**0.130**	**0.286**

For maximum overshoot, GOA-PID has better results by 20.46% compared to ZN-PID, 9.40% compared to DE-PID, and 3.60% compared to ABC-PID. For settling time of 2% band, GOA-PID has better results by 68.18% compared to ZN-PID, 63.36% compared to DE-PID, and 68.62% compared to ABC-PID. For rise time, GOA-PID has better results by 45.15% compared to ZN-PID, 14.47% compared to DE-PID, and 16.67% compared to ABC-PID. For peak time, GOA-PID has better results by 55.59% compared to ZN-PID, 20.55% compared to both DE-PID and ABC-PID. Also, the performance index values for different controllers are given in Table IV.

TABLE IV. PERFORMANCE COMPARISON OF DIFFERENT CONTROLLERS

Controller type	ZN-PID	DE-PID [7]	ABC-PID [7]	Proposed GOA-PID
ITSE value	0.1070	0.0223	0.0180	**0.0063**

As seen from this table, the proposed controller gives the minimum ITSE value compared to the other controllers. These results confirm that the proposed controller tuned by GOA has better performance than the other controllers tuned by ZN, DE, and ABC.

B. *Robustness Analysis*

To illustrate the robustness of the proposed method the time constant of generator T_g has been changed from 0.5 s to 1.5 s with 0.50 s steps excluding those, which are already given in Table III for T_g equal to 1 s. The comparative simulation results obtained for AVR system are given in Table V. From the table, it can be seen that GOA has less change in terminal voltage with better performance compared to ZN, DE and ABC in terms of maximum overshoot, settling time, rise time, and peak time when a change in a system parameter occurs. These results validate the robustness of the proposed GOA based controller for AVR system.

TABLE V. TRANSIENT RESPONSE ANALYSIS OF AVR SYSTEM UNDER PARAMETER CHANGES

T_g	Controller type	Maximum overshoot	Settling time (2% band)	Rise time	Peak Time
0.50	ZN-PID	1.435	1.532	0.164	0.427
	DE-PID [7]	1.407	3.296	0.099	0.247
	ABC-PID [7]	1.341	3.686	0.099	0.245
	Proposed GOA-PID	**1.337**	**0.864**	**0.081**	**0.191**
1.50	ZN-PID	1.569	4.705	0.294	0.810
	DE-PID [7]	1.284	2.245	0.197	0.468
	ABC-PID [7]	1.203	2.367	0.207	0.472
	Proposed GOA-PID	**1.141**	**2.001**	**0.177**	**0.390**

V. CONCLUSION

A novel parameter tuning method based on GOA algorithm is presented to determine the optimal PID controller parameters of an AVR system for the first time. In the parameter tuning procedure, the GOA algorithm is repeatedly run to give the optimal parameters of the PID controller based on the integral of time multiplied squared error (ITSE) performance index. By simulation results it is confirmed that the proposed GOA-PID controller can perform fast and efficient search for the optimal controller parameters. In addition, the GOA-PID controller is compared with ZN-PID, DE-PID, and ABC-PID, controllers with their results taken from the transient analysis and robustness analysis. These results showed that the proposed GOA-PID controller performs better than the other tuning methods.

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