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Gravitational search algorithm for determining controller parameters in an automatic voltage regulator system

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Abstract: This paper presents optimal tuning of the controller parameters of a proportional-integral-derivate (PID) controller for an automatic voltage regulator (AVR) system using a heuristic gravitational search algorithm (GSA) based on mass interactions and Newton's law of gravity. The determination of optimal controller parameters is considered an optimization problem in which different performance indexes and a performance criterion in the time domain have been used as objective functions to test the performance and effectiveness of the GSA. In the determining process of the parameters, the designed PID controller with the proposed approach is simulated under different conditions and the performance of the controller is compared with those reported in the literature. From the numerical simulation results it is clear that the GSA approach is successfully applied to reveal the performance and the feasibility of the proposed controller in the AVR system.

Key words: Gravitational search algorithm, optimization, automatic voltage regulator

1. Introduction

The proportional-integral-derivate (PID) controller is the most widely used control law in engineering field. In process control, more than 90% of the control loops are under the PID controller. It is quite obvious that the PID controller is widely used due to its simple structure and high performance in a wide range of operating conditions [1,2]. The PID controller exhibits relatively weak dynamic performance as evidenced by large overshoot and transient frequency oscillations. To design a PID controller is to specify parameters as K_p, K_i, and K_d [3]. Regrettably, it has been fairly difficult to tune the gains of the PID controller properly in industrial operations. In recent years, modern heuristic optimization techniques are proposed to tune the PID controller parameters instead of traditional methods that are inadequate because of possible changes in operating conditions. Some conventional methods are the Ziegler–Nichols method, the gain-phase margin method, and the Cohen–Coon method [4]. Heuristic methods include genetic algorithms (GAs) [5–9], evolutionary algorithms [10,11], modified ant colony optimization algorithms based on differential evolution [12], incremental learning algorithms [13], particle swarm optimization algorithms (PSO) [14–16] and ant colony algorithms [17–19].

The automatic voltage regulator (AVR) uses the exciter voltage of a generator, which is responsible for keeping the terminal voltage magnitude of a synchronous generator constant under normal operating conditions

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at different load levels [2]. Kim and Park [20] have determined the optimal PID controller parameters using metaheuristic methods. Results obtained from a simulation study show that a hybrid system composed of EU-GA-PSO is more satisfactory than GA and PSO. Zhu et al. [21] proposed a chaotic ant swarm algorithm for design of the controller in the AVR system. The design of the PID controller with chaotic ant swarm algorithm has been effective to improve the stability of the system according to results obtained from many simulation examples. Mukherjee and Ghoshal [22] explored the specifications of the optimal PID controller parameters using craziness based and velocity relaxed swarm optimization algorithm. Kim [23] designed a PID controller based hybrid GA-BF for AVR; in the optimization process the suggested approach was more effective than GA, PSO, and GA-PSO for tuning of PID controller parameters. Gozde and Taplamacioglu [24] investigated performance analysis of artificial bee colony (ABC) for an AVR system and reported that ABC is applied to different control applications. Mukherjee and Ghoshal [25] used heuristic methods to tune the PID controller parameter for an AVR and reported that a PID controller based on CRPSO-SLF provides better performance for step response of terminal voltage with less computational effort compared with the other heuristic algorithms. Zonkoly [26] used the PSO algorithm to tune the parameters of a coordinated power system stabilizer and the AVR in a multimachine power system; the performance of the proposed method was compared with some heuristic methods and mathematical optimization algorithms such as GA, quadratic programming methods, and linear programming, and proved to be efficient in determining the optimal values of the control parameters. A design of an AVR system using the PSO heuristic optimization method was presented by Zamani et al. [27], in which the proposed controller with the PSO algorithm had better performance characteristic and stability than the traditional controller under various scenarios. GA and bacterial foraging based on a novel hybrid approach was presented by Kim et al. [28], in which this hybrid approach (GA-BF) was tested using various test functions and was used to tune the parameters of a PID controller of an AVR system.

Among the available metaheuristics algorithms, the gravitational search algorithm (GSA), one of the recently improved heuristic algorithms, based on Newton's law of gravity and mass interaction is proposed by Rashedi et al [29]. Masses are regarded as individuals of the population in this approach. GSA has a simple structure and effective calculation ability. Exploration and exploitation abilities can be improved with its flexible and well-balanced structure [30]. The gravitational constant is decreased with time to arrange the accuracy of the search, which is defined as the most significant feature of the GSA. Thus, the solution process of the GSA is accelerated [31,32]. Furthermore, the algorithm needs less memory [32]. Nowadays, many researchers have used this algorithm for solving various problems in the literature [33–40].

In the present study, performance analysis of the proposed method is tested to tune the gains of the PID controller in a practical high-order AVR. The integral time squared error (ITSE), integral time absolute error (ITAE), integral squared error (ISE), integral absolute error (IAE), and a performance creation in the time domain are used as objective functions to test the performance of the proposed approach. The designed PID controller with the proposed heuristic approach is simulated under various operating conditions and the performance of the controller is compared with those reported in [24].

2. Model of an AVR system

The PID controller is widely used to improve the dynamic response of the system and to decrease the steady-state error. The proportional part of the controller is used to reduce error under disturbance conditions. An enhancement of the transient response and stability of the system is achieved by the derivative part of the controller, which adds a finite zero to the open-loop plant transfer function of the system. An integral part of controller that adds a pole to the origin and increases the system type by one is used to eliminate steady-state error [2,4,24]. Equation (1) shows the transfer function of the PID controller:

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

The AVR system plays an important role in keeping the terminal voltage of the generator at a specified level. Normal and fault conditions of operation are taken into account to design the AVR. Therefore, the security of the power system is seriously affected by the stability of the AVR system. The real model of this system is depicted in Figure 1 [24]. The AVR system involves generators, amplifiers, exciters, and sensors, which define the four main components in an AVR system. The reasonable transfer function of these components using the PID controller is shown in Figure 2 [1,2,4,21].

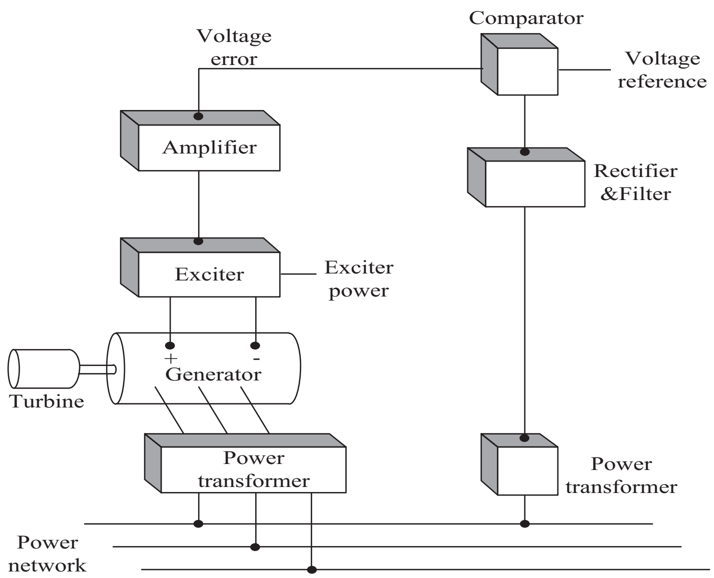

Figure 1. The model of the AVR system.

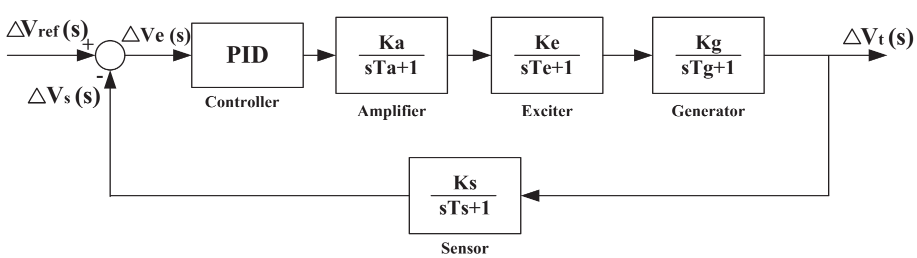

Figure 2. Block diagram with the transfer function model of the system.

The components of the AVR system and the boundary values of the system are described in Table 1. The transfer function of the system with the controller is described in Eq. (2):

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{\left(s^2 K_d + sK_p + K_i\right)\left(K_a K_e K_g\right)\left(1 + sT_s\right)}{s\left(1 + sT_a\right)\left(1 + sT_e\right)\left(1 + sT_g\right)\left(1 + sT_s\right) + \left(K_a K_e K_g K_s\right)\left(s^2 K_d + sK_p + K_i\right)} \tag{2}$$

Table 1. Parameter limits of the AVR system and the PID controller.

Model	Parameter limits	Used parameter values in the AVR system
Controller	$0.2 \leq K_p, K_i, K_d \leq 2.0$	Optimal values (K_p, K_i, K_d)
Amplifier	$10 \leq K_a \leq 40$, $0.02 \leq T_a \leq 0.1$	$K_a = 10$, $T_a = 0.1$
Exciter	$1 \leq K_e \leq 10$, $0.4 \leq T_e \leq 1.0$	$K_e = 1$, $T_e = 0.4$
Generator	K_g (0.7–1.0), $1.0 \leq T_g \leq 2.0$	$K_g = 1$, $T_g = 1$
Sensor	$0.001 \leq T_s \leq 0.06$	$K_s = 1$, $T_s = 0.01$

3. GSA

The heuristic optimization method was first improved by Rashedi et al. [29], motivated by Newton's laws of gravity and motion. The algorithm has many advantages that are reported in [29] and the authors compared the GSA with other stochastic methods using 23 benchmark test functions; they inferred that GSA was stronger compared with those methods. In this approach, entire agents are used as objects and their performance is computed by using a fitness function denoted by their masses. The gravitational force attracts every object to other objects. The motion of entire agents globally towards the agents with heavier masses is provided by this force. The heavy masses are described as good solutions of the optimization problem [29]. The proposed algorithm can be depicted as follows:

At the beginning of the algorithm variables are described with M masses:

$$X_i = \left(x_i^1, ..., x_i^d, ..., x_i^M\right) \qquad for, i = 1, 2, \ldots, M \tag{3}$$

where x_i^d is the position of the i^{th} mass in the d^{th} dimension and M is the dimension of the search space. The *best* and *worst* fitness values according to the minimization or maximization problem are described as follows:

The minimization problem is:

$$best\,(k) = \min_{j \in \{1,..,M\}} fit_j\,(k) \tag{4}$$

$$worst\,(k) = \max_{j \in \{1,..,M\}} fit_j\,(k) \tag{5}$$

And the maximization problem is:

$$best\,(k) = \max_{j \in \{1,...,M\}} fit_j\,(k) \tag{6}$$

$$worst\,(k) = \min_{j \in \{1,...,M\}} fit_j\,(k) \tag{7}$$

where $fit_j(k)$ is defined as the fitness value of the j^{th} agent at time k. The *best(k)* fitness and *worst(k)* fitness values indicate the powerful and the powerless agent for the maximization or minimization problem in the search space. The gravitational constant is computed in (8) and (9):

$$G\,(k) = G\,(G_0, k) \tag{8}$$

$$G\,(k) = G_0 e^{\left(-\alpha \frac{k}{K}\right)} \tag{9}$$

Gravitational constant (G_0) will be decreased with time to adjust the accuracy of the search. The initial values of the G_0 and α are specified by the user. The k and K are the current iteration and the total number of iterations, respectively. Inertial masses are defined for each agent at a specified iteration:

$$M_{pi} = M_{ai} = M_{ii} = M_i \tag{10}$$

$$m_i(k) = \frac{fit_i(k) - worst(k)}{best(k) - worst(k)} \tag{11}$$

$$M_i(k) = \frac{m_i(k)}{\sum_{j=1}^{M} m_j(k)} \tag{12}$$

where M_{ai}, M_{pi}, M_{ii}, and $M_i(k)$ are the active mass, the passive mass, the inertia mass of the i^{th} agent, and the mass of the i^{th} agent at iteration k, respectively. The sum of force acting on the i^{th} agent $(F_i^d(k))$ is computed as in Eq. (13):

$$F_i^d(k) = \sum_{j \in kbest j \neq i} rand_j F_{ij}^d(k) \tag{13}$$

where $rand_j$ is a randomly defined number in the interval [0,1]. The force acting on the i^{th} mass $(M_i(k))$ from the j^{th} mass $(M_j(k))$ at the current iteration k is defined according to gravitational theory. The mathematical equation of this theory is offered in Eq. (14). Figure 3 shows the sum of the forces acting on an object.

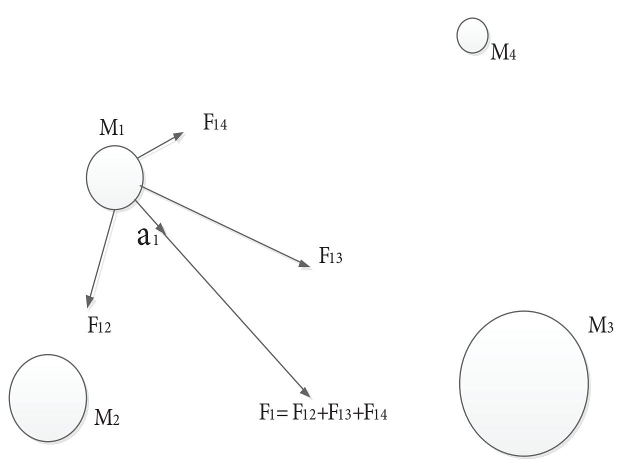

Figure 3. All the forces acting on an object.

$$F_{ij}^d(k) = G(k) \frac{M_i(k) \times M_j(k)}{R_{ij}(k) + \varepsilon} \left(x_j^d(k) - x_i^d(k)\right) \tag{14}$$

$R_{ij}(k)$ is the Euclidean distance between agents i^{th} and j^{th}. Euclidean distance is defined as $R_{ij}(k) = \left(\|X_i(k), X_j(k)\|_2\right)$ and ε is the small constant.

In an attempt to find the acceleration of the i^{th} agent at t time in the d^{th} dimension, the law of motion is used directly for the calculations. $a_i^d(k)$ is expressed as in Eqs. (15) and (16).

$$a_i^d(k) = \frac{F_i^d(k)}{M_{ii}(k)} \tag{15}$$

$$a_i^d(k) = \frac{F_i^d(k)}{M_{ii}(k)} = \sum_{j \in kbest j \neq i} rand_j G(k) \frac{M_j(k)}{R_{ij}(k) + \varepsilon} \left(x_j^d(k) - x_i^d(k) \right) \tag{16}$$

The velocity of an agent is identified as a function of its acceleration value added to its velocity. The new velocity of an agent is obtained as in Eq. (17):

$$v_i^d(k+1) = rand_i \times v_i^d(k) + a_i^d(k) \tag{17}$$

Here, $rand_i$ is a number that is randomly distributed in the interval [0,1]. The new position of the i^{th} agent in d^{th} dimension is expressed as in Eq. (18):

$$x_i^d(k+1) = v_i^d(k+1) + x_i^d(k) \tag{18}$$

The GSA algorithm flowchart is illustrated in Figure 4.

4. Simulation results

In this study, the GSA heuristic approach is used to tune the optimal parameters of the PID controller of an AVR system. In order to examine the performance of the offered heuristic approach, it is compared with [24] and the ABC algorithm under various operating scenarios. In the present study, ITSE and a performance criterion in the time domain are used to tune the optimal values of the controller parameters as objective functions, represented in Eqs. (19) and (20), respectively. The performance criterion in the time domain contains steady state error E_{ss}, rise time t_r, settling time t_s, and overshoot M_p. β is the weighting factor, which is selected from 0.5 to 1.5 in steps of 0.5 in the present study. Moreover, the time constants of the AVR system are changed together in the range of +25%– +100% in order to analyze the robustness of the proposed stochastic optimization algorithm.

In order to demonstrate the efficiency and robustness of the proposed algorithm, it was applied to different objective functions such as IAE, ISE, ITAE, and ITSE. Objective functions are shown in Eqs. (19) and (21)–(23). A block diagram of an AVR system with the optimized PID controller using the proposed heuristic approach is shown in Figure 5.

$$J = ITSE = \int_0^t t e^2(t)\,dt \tag{19}$$

$$Min \quad J(K_p, K_i, K_d) = \left(1 - e^{-\beta}\right)(M_p + E_{ss}) + e^{-\beta}(t_s - t_r) \tag{20}$$

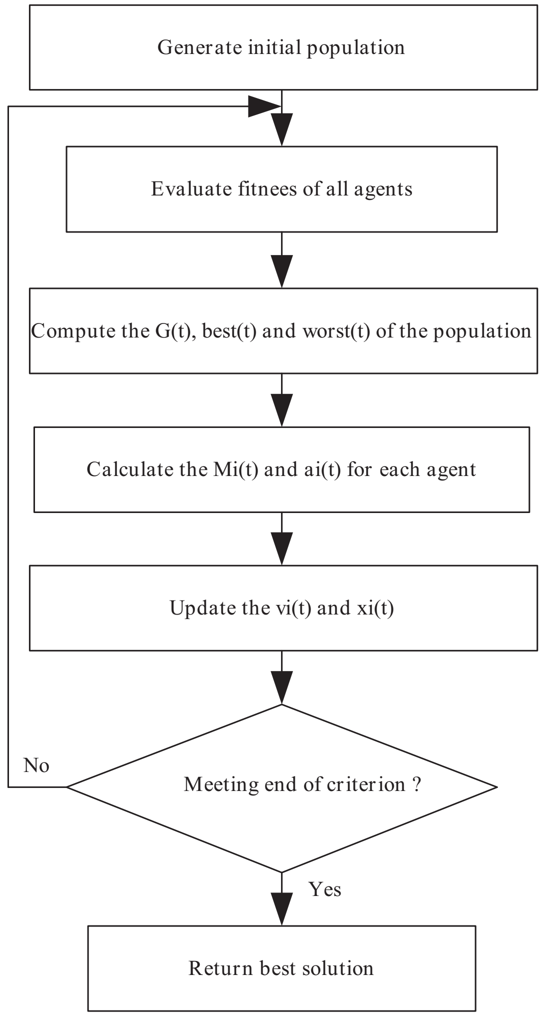

Figure 4. The flowchart of the GSA [29].

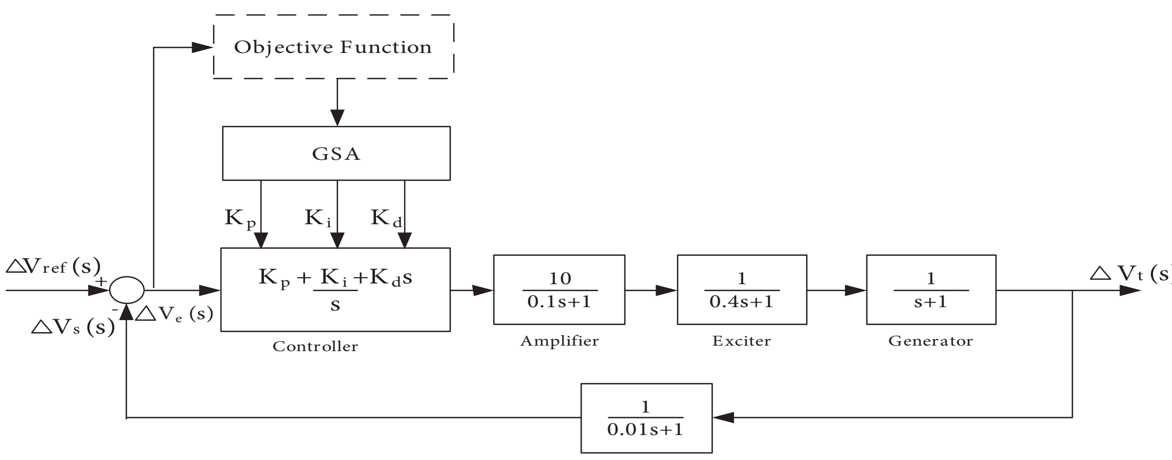

Figure 5. An AVR system with a proposed controller.

$$J = IAE = \int_0^t |e(t)|\, dt = \int_0^t |r(t) - y(t)|\, dt \tag{21}$$

$$J = ISE = \int_0^t e^2(t)\, dt \tag{22}$$

$$J = ITAE = \int_0^t t\, |e(t)|\, dt \tag{23}$$

The size of the population and the number of iterations are set the same for all heuristic approaches. Furthermore, the G_0 and α parameters of the GSA approach are taken as 200 and 20, respectively. The obtained optimal values of the PID controller parameters and the response of the AVR system at the end of the simulation process are represented in Table 2. The transfer functions of the AVR system for ABC, PSO, and differential evolutionary (DE) algorithm are shown in Eqs. (24), (25), and (26), respectively. The transfer function of the system adjusted by the GSA approach is shown in Eq. (27).

Table 2. Optimized PID parameters and transient response parameters.

K_g	T_g	Type of controller	K_p	K_i	K_d	Max. overshoots	Settling times (5% band)	Rise times	Peak times
1.0	1.0	ABC-PID [24]	1.6524	0.4083	0.3654	1.250	0.920	0.156	0.36
		PSO-PID [24]	1.7774	0.3827	0.3184	1.300	1.000	0.161	0.38
		DE-PID [24]	1.9499	0.4430	0.3427	1.330	0.952	0.152	0.36
		GSA-PID	1.4379	1.2208	0.7363	1.240	0.597	0.107	0.24

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.03654s^3 + 3.819s^2 + 16.56s + 4.083}{0.0004s^5 + 0.0454s^4 + 0.555s^3 + 5.164s^2 + 17.52s + 4.083} \tag{24}$$

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.03184s^3 + 3.362s^2 + 17.81s + 3.827}{0.0004s^5 + 0.0454s^4 + 0.555s^3 + 4.694s^2 + 18.77s + 3.827} \tag{25}$$

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.03427s^3 + 3.622s^2 + 19.54s + 4.43}{0.0004s^5 + 0.0454s^4 + 0.555s^3 + 4.937s^2 + 20.05s + 4.43} \tag{26}$$

$$\frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.07363s^3 + 7.507s^2 + 14.5s + 12.21}{0.0004s^5 + 0.0454s^4 + 0.555s^3 + 8.873s^2 + 15.38s + 12.21} \tag{27}$$

It is clear from Table 2 that the GSA algorithm has better performance for percent overshoots than the ABC, PSO, and DE algorithms by 0.8065%, 4.8387%, and 7.2580% respectively. When the GSA algorithm is examined in terms of peak time, it provides 50% better results than the ABC and DE algorithms, and 58.3333% better than the PSO algorithm. For settling time, the proposed algorithm has better results by 54.1038% than the ABC algorithm, by 59.4639% than the DE algorithm, and by 67.5041% than PSO algorithm. It appears that the rise time of the GSA algorithm has the best result as 50.4672%, 42.056%, 45.7943% better than the PSO, DE, and ABC heuristic methods, respectively. The results obtained by changing the voltage curve at the end of the simulation of the GSA are presented comparatively for ABC, PSO, and DE [24] in Figures 6 and 7, showing settling times for each, which is within 5% bandwidth.

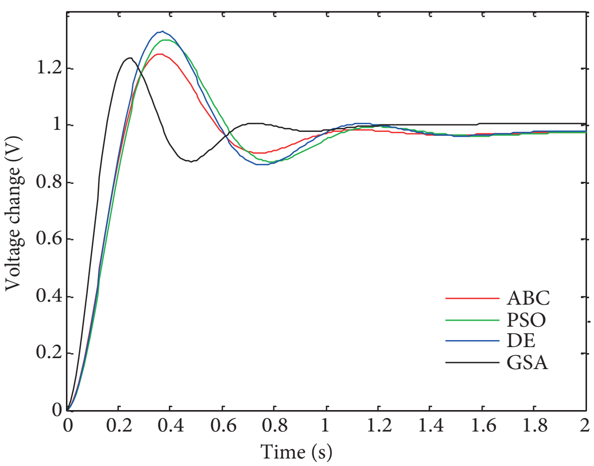

Figure 6. Voltage changing curves of the GSA, ABC, PSO, and DE algorithms.

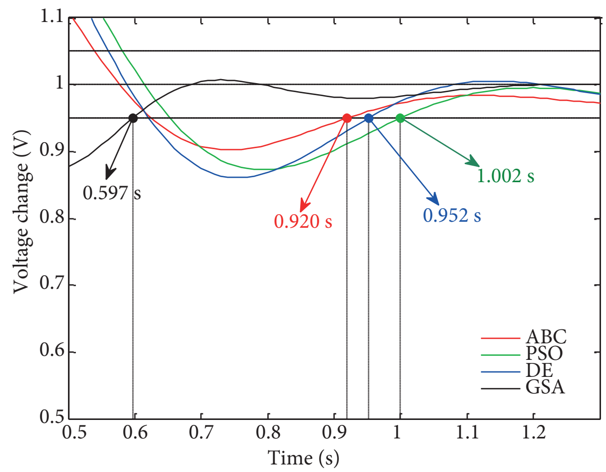

Figure 7. Zoom of the voltage changing curves for the settling times of heuristic algorithms.

In this section of the study, the performance criterion in the time domain was used to tune the parameters of the controller as an objective function for the results in Table 3. The obtained optimal gain values of the PID controller by the GSA approach for different values of the weighting factor are given in Table 3.

Table 3. Comparison between the results from the GSA and ABC approaches (GSA results are in bold).

β	Type of controller	K_p	K_i	K_d	Max. overshoots (%)	Settling times (5% band)	Rise times
0.5	**GSA-PID**	**0.6976**	**0.6027**	**0.3376**	**1.46**	**0.838**	**0.214**
	ABC-PID	0.7320	0.2827	0.2191	2.55	1.31	0.278
1	**GSA-PID**	**0.6068**	**0.4465**	**0.1897**	**2.04**	**0.447**	**0.325**
	ABC-PID	0.6806	0.2183	0.1381	6.63	2	0.34
1.5	**GSA-PID**	**0.6587**	**0.7626**	**0.4088**	**3.16**	**0.814**	**0.186**
	ABC-PID	0.6705	0.9679	0.3479	5.15	1.76	0.209

In Table 3, it is seen that the performance analysis results obtained from the proposed GSA-PID approach are compared with the results obtained from the ABC-PID approach. The bound values of the PID controller parameters are chosen in between [0,1]. The results of the comparison demonstrate that the designed PID controller by the proposed approach has less settling time, rise time, and overshoot than the ABC-PID controller. Figure 8 shows the behaviors of the AVR system with tuned gains by GSA and ABC for different weighting factors. The transient response of the system has been effectively improved by the proposed approach and a comparison of the responses of the heuristic approaches is shown in Figure 8.

When the gains of the AVR system are fixed, all time constants of the AVR system are changed in the range of +25%– +100% to evaluate the performance and robustness of the heuristic optimization algorithm. The obtained results of the proposed approach are shown in Figure 9 and Table 4.

Moreover, to demonstrate the efficiency of the GSA approach, different performance indexes such as IAE, ISE, ITAE, and ITSE are used as objective functions. These performance indexes are utilized under various operating conditions. The obtained simulation results of the proposed GSA heuristic algorithm are shown in Table 5 and comparison of the performance indexes is shown in Figures 10–13. From Table 5, it appears that the ITAE performance index has better performance for percent overshoots and when settling times are investigated; the best results belong to the ITSE and IAE performance indexes under 0.7–0.8 and 0.9–1.0 operating conditions, respectively. The ISE performance index has better performance for rise times and peak times than other performance indexes under different operating conditions.

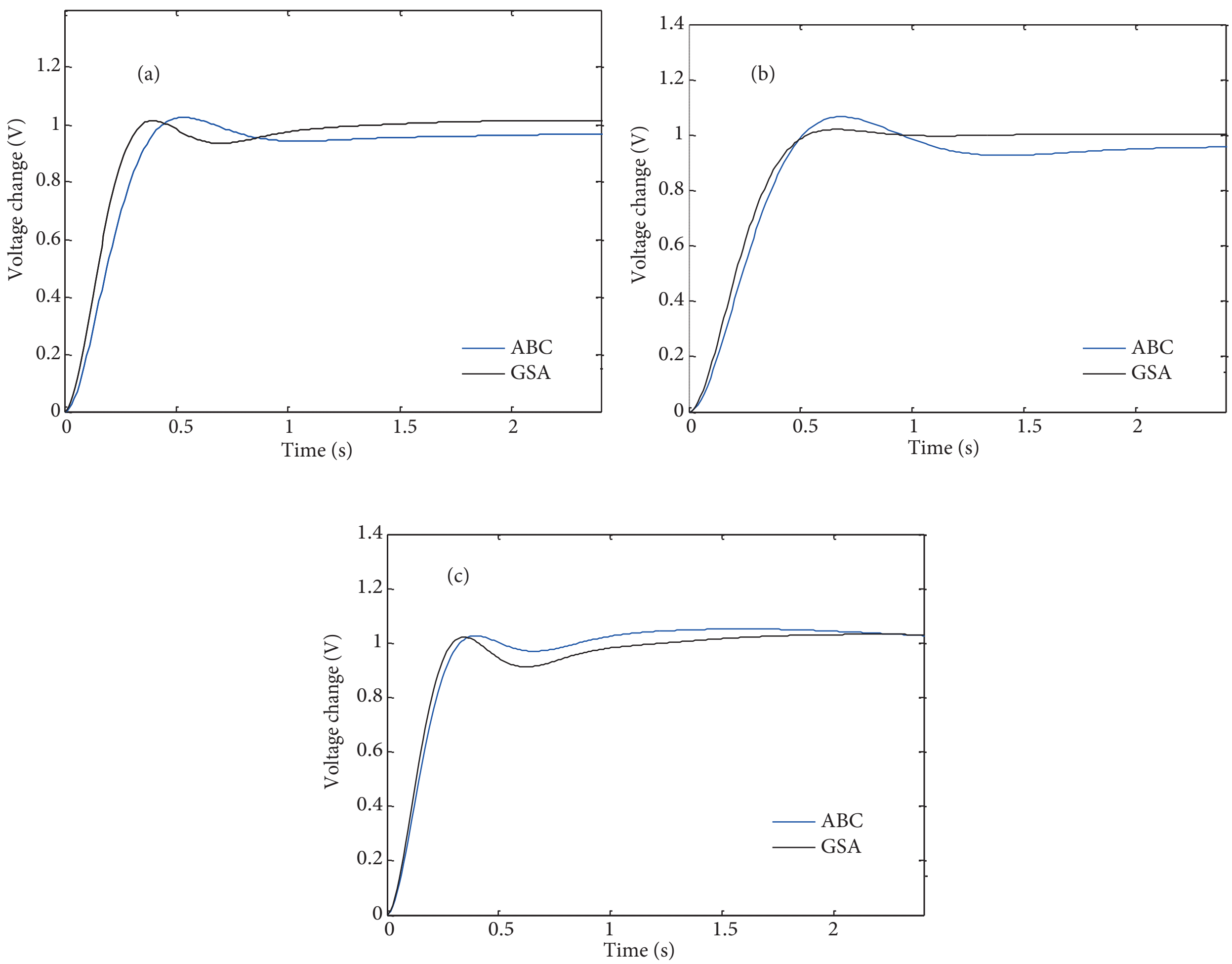

Figure 8. Voltage changing curves of the GSA and ABC: a) for $\beta = 0.5$; b) for $\beta = 1$; and c) for $\beta = 1.5$.

Table 4. Results of the GSA approach for entire time constants.

Time constants	K_p	K_i	K_d	Max. overshoots (%)	Settling times (5% band)	Rise times	Peak times
+25%	1.3331	0.9864	0.9833	23.4	0.731	0.1285	0.295
+50%	1.1866	1.0379	1.1466	21.5	0.876	0.1590	0.362
+75%	1.1885	0.9422	1.2683	20.7	1.032	0.1923	0.421
+100%	1.0157	1.0613	1.7766	23.4	1.09	0.1922	0.438

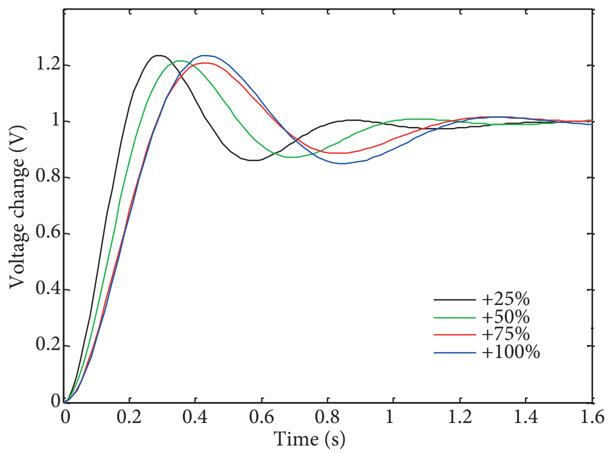

Figure 9. Voltage change curves ranging from +25% to +100% for entire time constants.

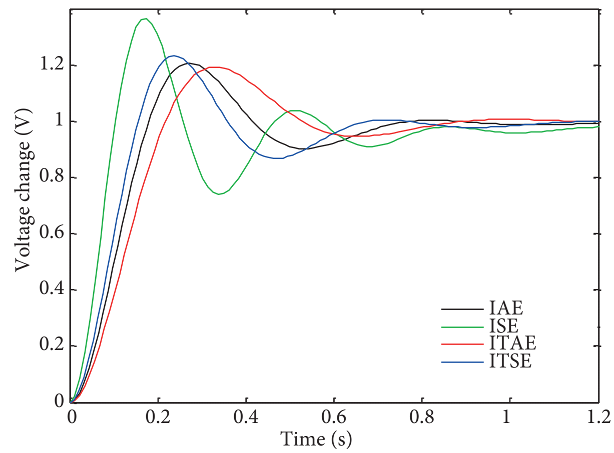

Figure 10. Comparison of performance indexes for $K_g = 0.7$.

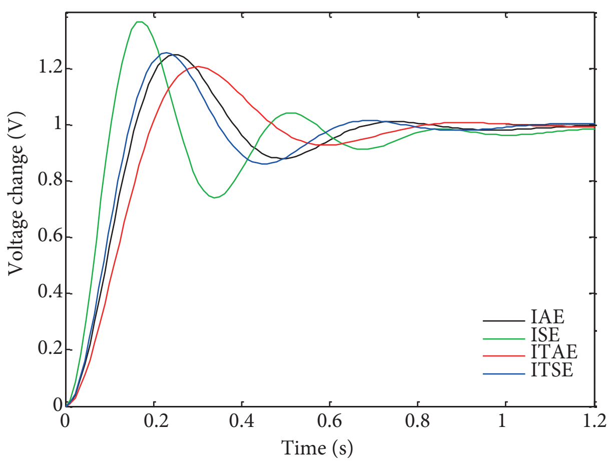

Figure 11. Comparison of performance indexes for $K_g = 0.8$.

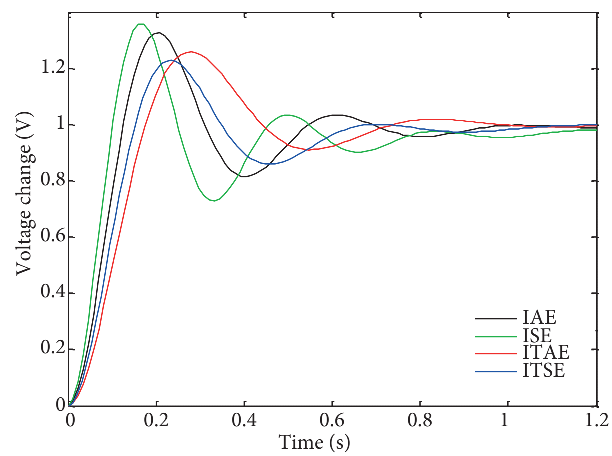

Figure 12. Comparison of performance indexes for $K_g = 0.9$.

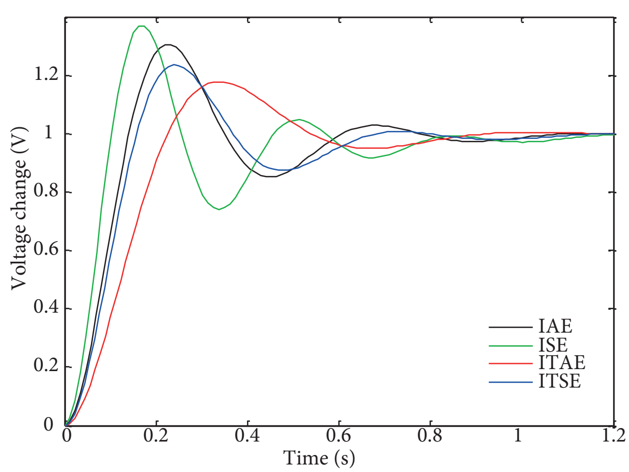

Figure 13. Comparison of performance indexes for $K_g = 1.0$.

Table 5. Results of the GSA approach for different performance indexes.

K_g	Objective functions	K_p	K_i	K_d	Max. overshoots (%)	Settling times (5% band)	Rise times	Peak times
0.7	IAE	2.0000	1.4668	0.8639	20.6	0.650	0.1219	0.272
	ISE	1.6889	2.0000	1.9785	36.4	0.769	**0.0702**	**0.175**
	ITAE	1.9656	1.3511	0.6335	**19.3**	0.699	0.1475	0.329
	ITSE	1.9398	1.7845	1.0851	23.1	**0.591**	0.1050	0.236
0.8	IAE	2.0000	1.4206	0.8825	24.9	0.608	0.1082	0.245
	ISE	1.4473	2.0000	1.7424	36.6	0.761	**0.0700**	**0.175**
	ITAE	1.8063	1.2567	0.6446	**20.5**	0.682	0.1338	0.302
	ITSE	1.8031	1.8250	1.0181	25.4	**0.567**	0.0995	0.230
0.9	IAE	2.0000	1.5909	1.1247	32.5	**0.512**	0.0849	0.208
	ISE	0.8296	2.0000	1.6192	35.8	0.757	**0.0685**	**0.160**
	ITAE	1.9334	1.3627	0.6536	25.9	0.649	0.1195	0.279
	ITSE	1.4250	1.4025	0.8732	**22.9**	0.585	0.1032	0.235
1.0	IAE	1.9105	1.3435	0.8359	30.4	**0.559**	0.0952	0.232
	ISE	1.1383	2.0000	1.4091	36.8	0.747	**0.0694**	**0.175**
	ITAE	1.3029	0.9045	0.4269	**17.8**	0.687	0.1530	0.336
	ITSE	1.4379	1.2208	0.7363	23.5	0.597	0.1070	0.239

5. Conclusion

The present paper focuses on the GSA based on Newton's law of gravity and mass interactions and is one of the recently improved heuristic algorithms for possible use for tuning the PID controller gains. The proposed method was applied to tune optimal gains of the controller in an AVR system. The robustness and performance of this method were tested under various operating conditions. The performance of the stochastic optimization method was compared with [24] and ABC. The robustness of the proposed approach was proven by changing the time constants in the range of +25%– +100% when various performance indexes were used as objective functions. The obtained simulation results showed that when the system parameters are changed, the proposed GSA approach can obtain higher quality solutions and can be successfully applied to optimize parameters of the PID controller of an AVR system. The obtained dynamic performance of the AVR system from the proposed approach was better than the other heuristic approaches. Additionally, the proposed heuristic method according to the results obtained from the GSA-PID approach is an influential search method for the optimal gain values of the PID controller. The optimized gains of the PID controller with the GSA approach can be used to improve system performance and to reinforce system stability.

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