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A bacterial foraging optimization approach for tuning type-2 fuzzy logic controller

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Abstract: The type-1 fuzzy sets theory was proposed to handle uncertainty in control systems, but some cases showed some liabilities of type-1 fuzzy sets when faced with unpredictable disturbance and uncertainties. Therefore, type-2 fuzzy sets were introduced and extended while providing more degrees of freedom in designing criteria. The most important specification of type-2 fuzzy sets is the interval between a superior membership function and an inferior membership function, which is called the footprint of uncertainty. This paper presents a bacterial foraging optimization approach for optimizing the parameterized membership function. The above criterion is applied to an automatic voltage regulator system and results are presented and compared with the previous method.

Key words: Type-2 fuzzy logic system, bacterial foraging optimization algorithm, automatic voltage regulator, membership function tuning, fuzzy logic controller

1. Introduction

The fuzzy logic theory was introduced by Zadeh to increase the ability of controllers to cope with the problem of uncertainty. The basic feature of fuzzy reasoning allows for handling of a variety of uncertainties [1]. In type-1, fuzzy uncertainty is presented by a number in a range of [0,1], which is interpreted as degree of membership function. Working with this model is more reasonable since it is too difficult to determine an exact value for uncertainty. Two models have been proposed for fuzzy logic controllers (FLCs). The first was introduced by Mamdani, which is known as the Mamdani model [2–4], and the second is known as the Takagi–Sugeno–Kang model, which was proposed by Takagi, Sugeno, and Kang [5]. Despite the fact that the type-1 FLC was proposed to tackle the uncertainty and minimize its effects, some researchers revealed that in some cases, there may be limitations in its ability, since the membership degree for each input is a crisp number. Thus, another kind of fuzzy approach was proposed to cope with the above problem. The new approach was proposed by Zadeh and was named type-2 fuzzy sets [1]. The main characteristic was that the membership functions (MFs) were themselves fuzzy, and therefore we can consider more degrees of freedom in designing the controller [1]. Since the type-2 fuzzy approach was proposed, many applications have been proposed in the literature [6–9]. A type-2 fuzzy proportional controller was proposed in [10]. Type-2 fuzzy sets were applied in decision-making problems [11–13] and also in communication and networks [14–16]. Mohammadi et al. proposed an evolutionary technique for tuning type-2 fuzzy logic controllers [17]. In another work, a type-2 FLC was applied in optimizing antenna arrays used in radio mobile communications [18]. New centroid methods for type-2 fuzzy systems were discussed in [19,20]. Designing a type-2 FLC (T2FLC) depends on some factors, of which the most important is

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selecting the appropriate rule set with suitable MFs. Some iterative and heuristic approaches have been proposed for altering MFs to achieve appropriate performance [21–23]. In this paper, it is considered that the MFs are initially constructed based on experience. Each MF has some variables and so we have an optimization problem. Mohammadi et al. proposed an extended discrete action reinforcement learning automata (EDARLA) as a new method for optimizing MFs, and their results outperformed other previous methods, the genetic algorithm (GA) and discrete action reinforcement learning automata (DARLA) [17]. We proposed an optimizing method based on the foraging strategy of a special kind of bacterium. The results prove that our method outperforms other previous approaches.

This paper is organized in 6 sections. Section 1 was assigned to introduction. Section 2 contains a brief introductory explanation of the type-2 fuzzy logic system (T2FLS). The bacterial foraging optimization algorithm (BFOA) is the subject of Section 3. The automatic voltage regulator (AVR) is introduced in Section 4. The basic part of Section 5 is the presentation of the simulation and results, as well as comparison with EDARLA. Finally, Section 6 is the conclusion of our work.

2. Type-2 fuzzy logic system

The concept of the type-2 fuzzy set was introduced by Zadeh in 1975 as an extension of the type-1 set [1]. It is characterized by fuzzy membership grades. An interval type-2 fuzzy set $A\tilde{}$ in X is defined as:

$$\tilde{A} = \int_{x\in X}\int_{u\in J_x\subseteq[0,1]} 1/(x,u) = \int_{x\in X} \left[\int_{u\in J_x\subseteq[0,1]} 1/u \right] \Big/ x, \tag{1}$$

where x is the primary variable and u is the secondary variable. X is the domain of x and J_x is the domain of u. The uncertainty can be described by a region named the footprint of uncertainty, which can be represented in terms of an upper and lower MF. The membership degree of each element in a type-2 fuzzy set is a fuzzy set $[l;r]$, where l and r are membership degrees on the lower and upper MFs. Figure 1 shows the T2FLC MF. A T2FLS includes 5 major parts. The schematic block diagram of the T2FLS is shown in Figure 2. It works almost like the T1FLS, except that in the output and before defuzzification, it is necessary to reduce the type-2 fuzzy sets to type-1 fuzzy sets [24].

The fuzzifier gives a mapping of the crisp point, x, into a fuzzy set, $\tilde{A}$. In a T2FLS, the inference engine combines rules and maps from the input type-2 fuzzy sets to the output type-2 fuzzy sets. Since the outputs of the inference engine are type-2 fuzzy sets, they should be type-reduced before the defuzzifier can be used to produce a crisp output. As was mentioned before, this is the basic difference between T1FLSs and T2FLSs. Additional details about type-2 fuzzy sets are available in [24,25].

3. Bacterial foraging optimization algorithm

The BFOA was proposed by Passino and includes 3 major operators: chemotaxis, reproduction, and elimination-dispersal [26].

3.1. Chemotaxis

The behavior of the bacteria toward the nutrient sources is interpreted as chemotaxis. The bacterium tries to find nutrient-rich areas and stay away from toxic environments. An E. coli bacterium moves in 2 different ways: tumble and swim. Tumble is a unit walk in a random direction and is always continued by another tumble or a

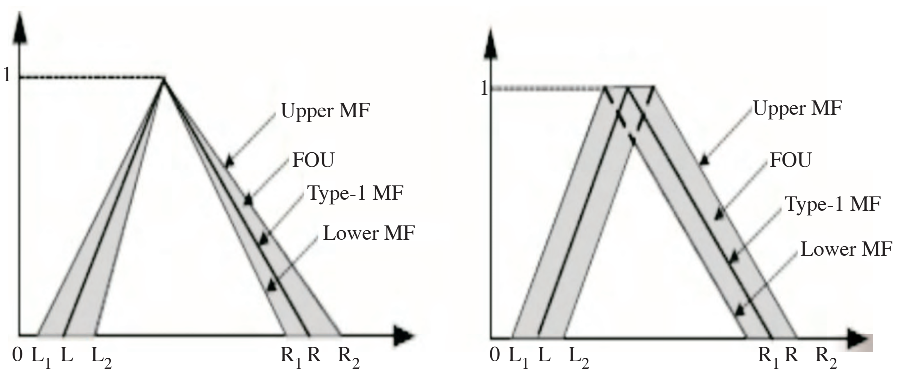

Figure 1. T2FLC MFs: A) type-2 fuzzy set evolved by blurring the width of a triangular type-1 fuzzy set; B) type-2 fuzzy set evolved by blurring the apex of a triangular type-1 fuzzy set.

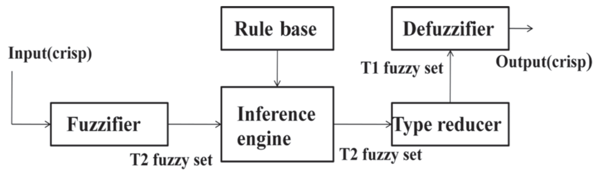

Figure 2. Schematic block diagram of T2FLS.

swim. If a random direction results in a better position, it will be followed by swim, or else another tumble will be taken. In fact, swim is a unit walk in a previous random direction. In each tumble unit, the walk position of the bacterium is updated based on Eq. (2):

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\phi(j), \tag{2}$$

where i is the index of the bacterium, and $\theta^i(j,k,l)$ is the position of the ith bacterium in the jth step of chemotaxis, the kth stage of reproduction, and the lth stage of elimination-dispersal. C is the step size of the chemotaxis operation, which determines the height of each random step. The cost function of the ith bacterium is determined based on its position and is represented by $J(i,j,k,l)$. $J_{\min}$ is represented by the minimum fitness value. In the swim stage, if at $\theta^i(j+1,k,l)$ the cost function becomes better than at $\theta^i(j,k,l)$, another step will be taken in the same direction. This sequence will continue until N_s steps are taken in swim. N_s is the upper band for the number of steps in swim.

The above discussion is specified to the single bacterium. Each bacterium has repellant and attractant effects on the others. To consider these effects, Eq. (3) is added to the cost function [26,27]:

$$\begin{aligned} J_{cc}(\theta, P(j,k,l)) &= \sum_{i=1}^{S} J_{cc}^i(\theta, \theta^i(j,k,l)) = \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-W_{attract}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right)\right] \\ &\quad + \sum_{i=1}^{S} h_{repellant}\exp\left(-W_{repellant}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right). \end{aligned} \tag{3}$$

Now we have:

$$J = J(i,j,k,l) + J_{cc}(\theta, P), \tag{4}$$

where $\theta^i = [\theta_1, ..., \theta_p]^T$ is the position of the bacterium in a D-dimensional space, θ_m^i is the mth component of the ith bacterium, S is the number of bacteria (population size), $d_{attract}$ is the depth of the attractant released by the cell, $W_{attract}$ is a measure of the width of the attractant signal, $h_{repellant}$ is the height of the repellant effect, and $W_{repellant}$ is the measure of the width of the repellant. The number of steps that should be taken in chemotaxis is specified by N_s

3.2. Reproduction

The basic idea of this operation is that nature tends to eliminate animals with poor foraging strategies and keep those that have better ones. In this operation, the whole population is sorted based on fitness. Eq. (5) shows how the fitness functions are sorted. Half of the population, which has the worse cost function, is eliminated. Each of the remaining members, which have better fitness, is reproduced to 2 children bacteria to keep the population size. N_{re} is the number of reproduction steps that should be taken [26,27].

$$J_{health}^i = \sum_{j}^{N_c+1} J(i,j,k,l) \tag{5}$$

3.3. Elimination and dispersal

To increase the ability of bacteria for global searching and to prevent them from becoming involved in local optimums, some of the bacteria are randomly eliminated and some of them are dispersed. N_{el} is the number of elimination and dispersal steps that should be taken.

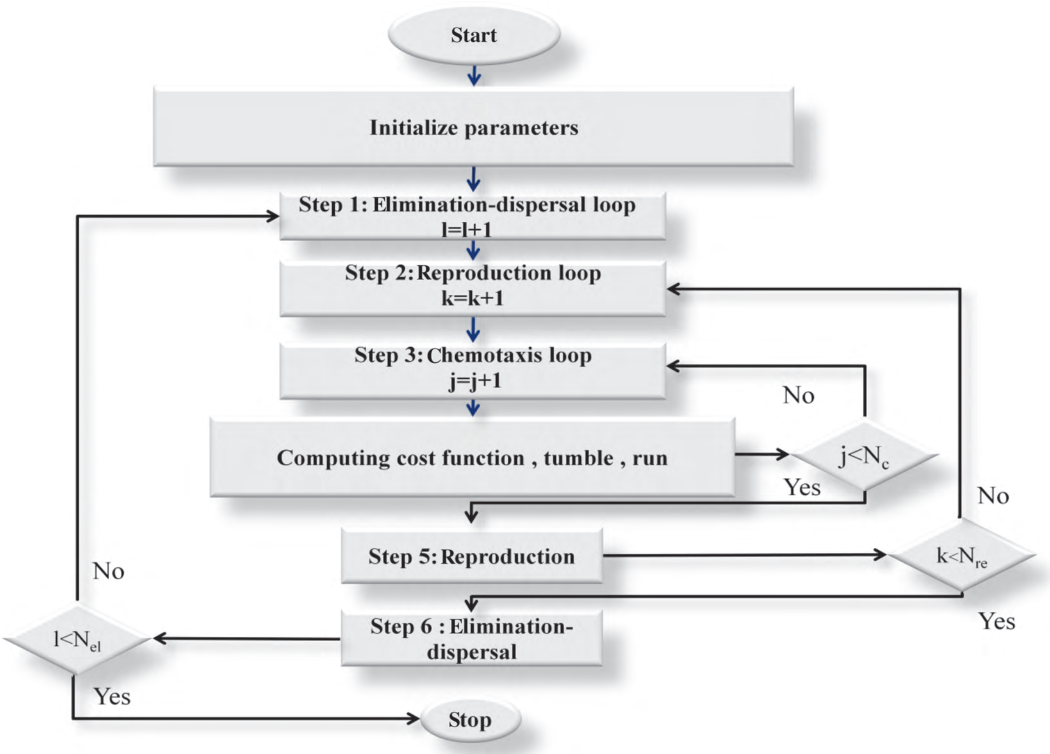

Figure 3. BFOA flowchart.

Some of the algorithm parameters should be initialized before the algorithm starts. These parameters are N_c, N_{re}, N_{el}, C, $d_{attract}$, $w_{attract}$, $w_{repllant}$, and $h_{repllant}$.

The flowchart of the algorithm is presented in Figure 3. It should be noticed that 3 of the above operators are formed with 3 nested loops, in which the chemotaxis frequency is greater than the reproduction frequency and the reproduction frequency is greater than the elimination and dispersal frequencies [26,27].

4. Automatic voltage regulator

The block diagram of an AVR system is represented in Figure 4. The objective is keeping a synchronous generator voltage in a specific range. Hence, the performance and stability of the AVR system seriously affects the security of the power system. In this paper, it is desired that the output track the input step.

To consider uncertainty in our study, the additive band-limited noise is added in the feedback loop. Other parameters of the AVR system are represented in Table 1. The parameters are set based on [28,29]. The output response of the controller without the controller and noise are shown in Figure 5.

5. Simulation

5.1. Simulation criteria

In this work, a T2FLC with 2 inputs and 1 output is designed to improve the output response of an AVR system. The Gaussian MFs are selected for the inputs and outputs. The MFs' centers are the optimization variables. The 1st input represents the error and the 2nd represents the error derivation. The MFs are shown in Figures 6 and 7, which show the parameters that should be optimized.

For each input, we have 3 MFs, which are "negative", "zero", and "positive". The output is divided into 5 intervals, which are "negative ground" (NG), "negative" (N), "zero" (Z), "positive" (P), and "positive ground" (PG).

Table 1. AVR system settings.

Parameters	Value
k_A	10
τ_A	0.1
k_E	1
τ_E	0.4
k_G	1
τ_G	1
k_R	1
τ_R	0.01

5.2. Fitness function

We consider the following fitness function in the simulation:

$$\min_k J(K) = G_e \int_0^T e^2(t)dt + G_u \int_0^T u_c^2(t)dt + G_M M_P, \tag{6}$$

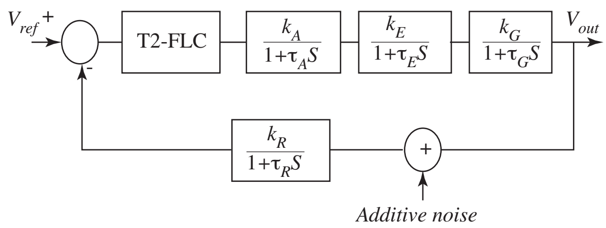

Figure 4. AVR block diagram.

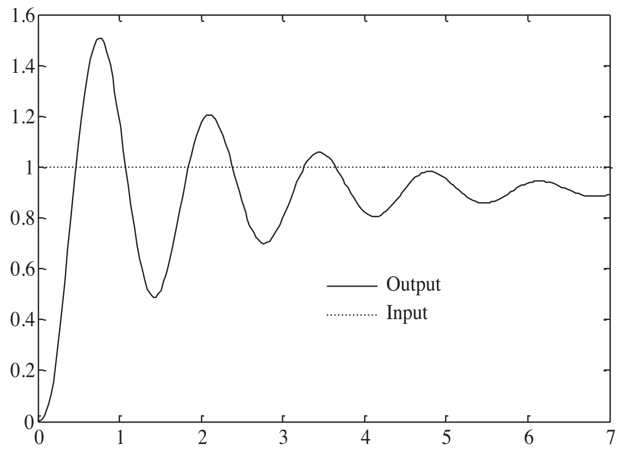

Figure 5. AVR output response without controller or noise.

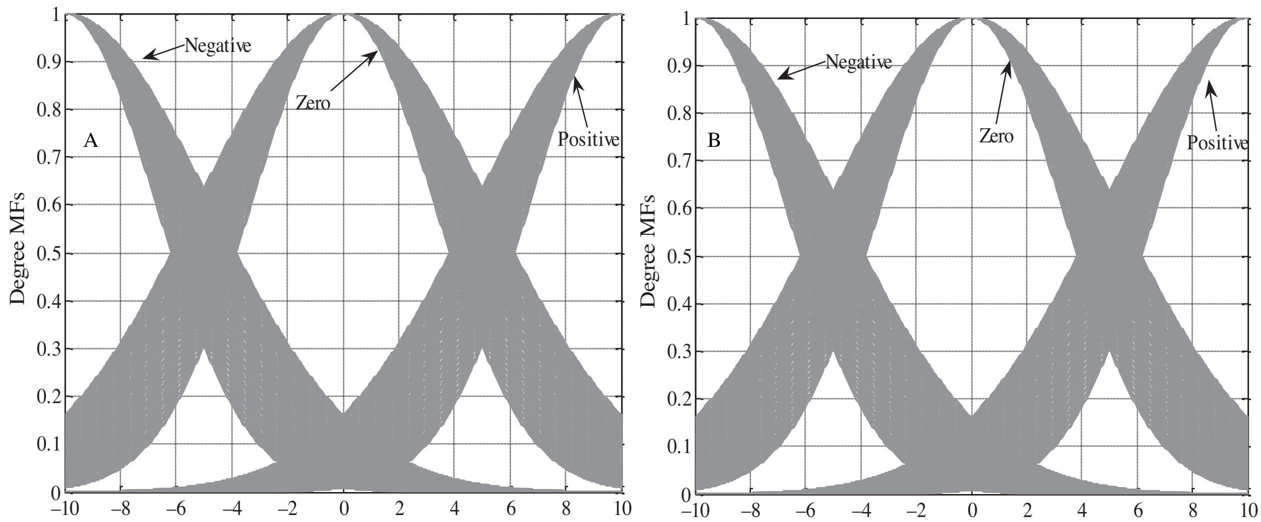

Figure 6. Input MFs: A) error; B) error derivation.

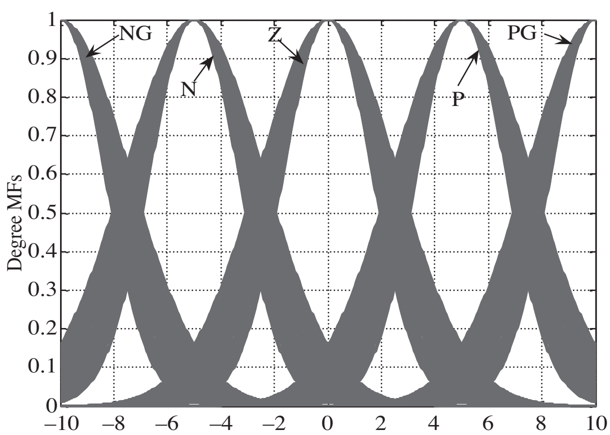

Figure 7. Output MFs.

where e(t) is the error, u(t) is the control signal, T is the running time, M_p is the overshoot, and G_e, G_u, and G_M are the weighted constants. In this paper, we consider $G_e = 1000$, $G_u = 1$, and $G_M = 10$ (notice that only G_u is different from its value in [17] and the others are the same as their values in [17]). More details about the fitness functions and simulation criteria are available in [17].

5.3. Simulation results

The simulation results are organized in 4 cases. In each case, tuning is performed in the presence of band-limited noise, with a special signal-to-noise ratio (SNR).

$$SNR(db) = 10\log_{10}(\frac{P_{signal}}{P_{noise}}) \tag{7}$$

In the first case, tuning is performed in the presence of additive noise with SNR = 40. The output responses in the presence of noise, with and without the controller, are shown in Figure 8. It is clear that the output response with the T2FLC has improved significantly. The output parameters for the T2FLC that was tuned by the BFOA are presented in Table 2.

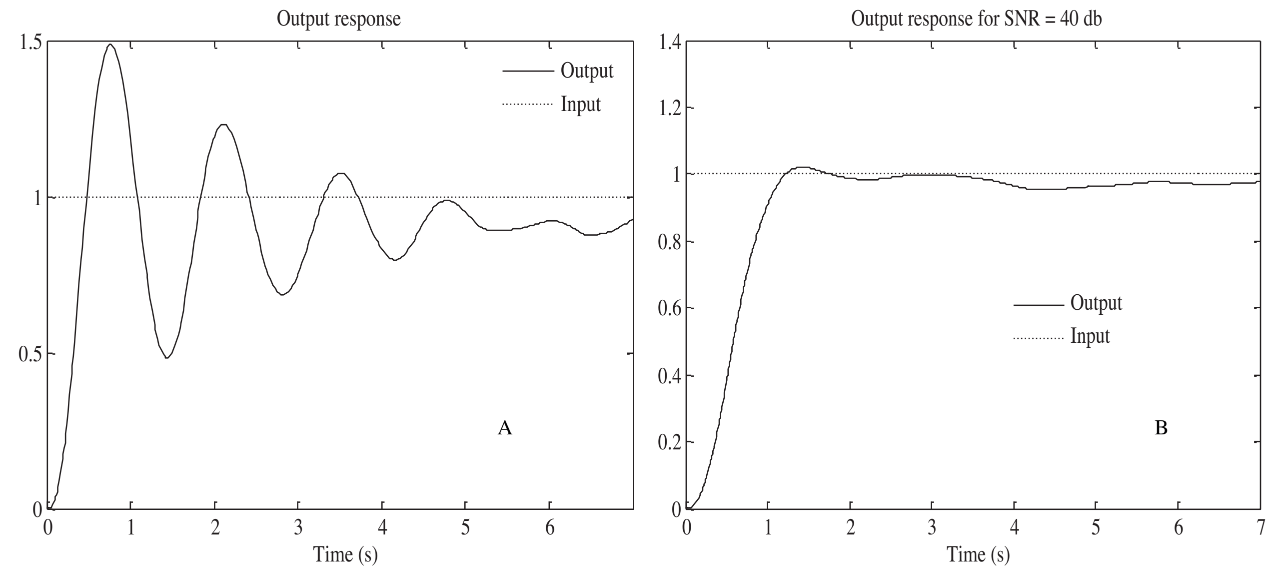

Figure 8. Output responses in presence of noise with SNR = 40 db: A) without controller; B) with controller.

In the second case, tuning is performed in the presence of additive noise with SNR = 30. The output results are shown in Figure 9. Steady state error, overshoot, and settling time were improved by the tuned T2FLC and the oscillations were damped effectively.

The results for the 3rd and 4th cases, in which SNR = 20 and SNR = 10, respectively, are presented in Figures 10 and 11, and it is clear that in both cases the controller is working properly in the presence of high-power noise.

The comparison between the BFOA results and the EDARLA is presented in Table 3. In Table 4, the values of the overshoot (OV), rise time (T_r), and settling time (T_s) for the 2 above methods are compared. The parameter settings for the BFOA are also shown in Table 5.

Table 2. MF parameters for optimizing.

	Term	Center
Input e	Negative	–Me
	Zero	0
	Positive	Me
Input de	Negative	–Mde
	Zero	0
	Positive	Mde
Output	NG	–Mo
	N	–Mo/2
	Z	0
	P	Mo/2
	PG	Mo

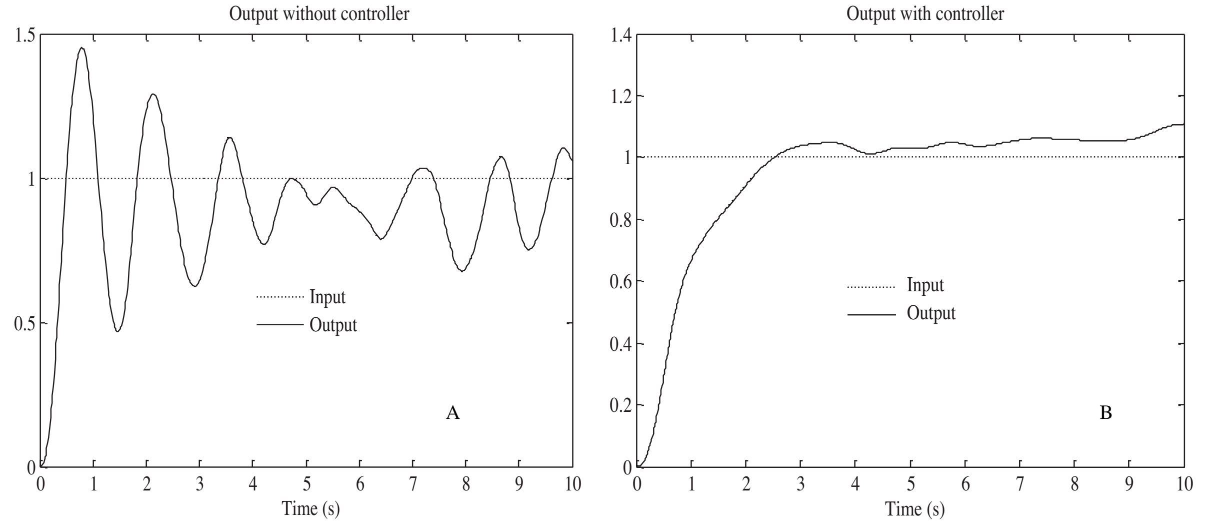

Figure 9. Output responses in presence of noise with SNR = 30 db: A) without controller; B) with controller.

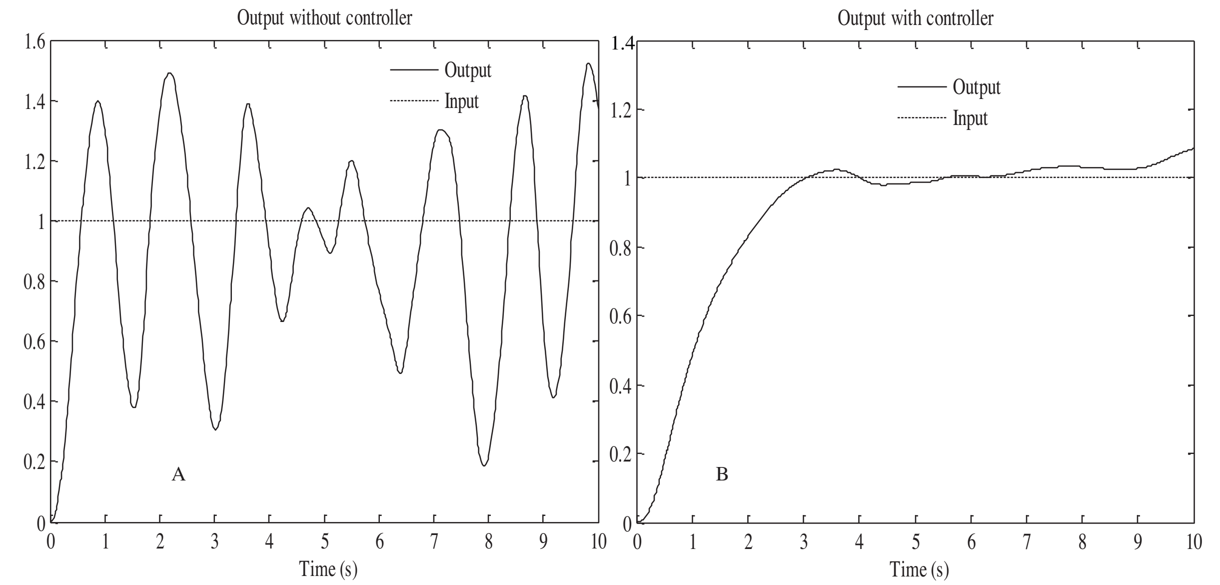

Figure 10. Output responses in presence of noise with SNR = 20 db: A) without controller; B) with controller.

Table 3. Comparison between the BFOA and EDARLA.

	BFOA				EDARLA			
SNR	Me	Mde	Mo	Jmin	Me	Mde	Mo	Jmin
40 dB	9.23	1.94	2.28	470.14	9.86	2.23	2.075	510.50
30 dB	12.63	9.26	7.408	684.39	12.43	9.19	7.36	695.26
20 dB	14.8	4.7	1	1.555×10^3	13.42	11.6	14.43	1.573×10^3
10 dB	17.21	5.56	0.91	1.0452×10^4	14.82	4.82	1.02	1.0508×10^4

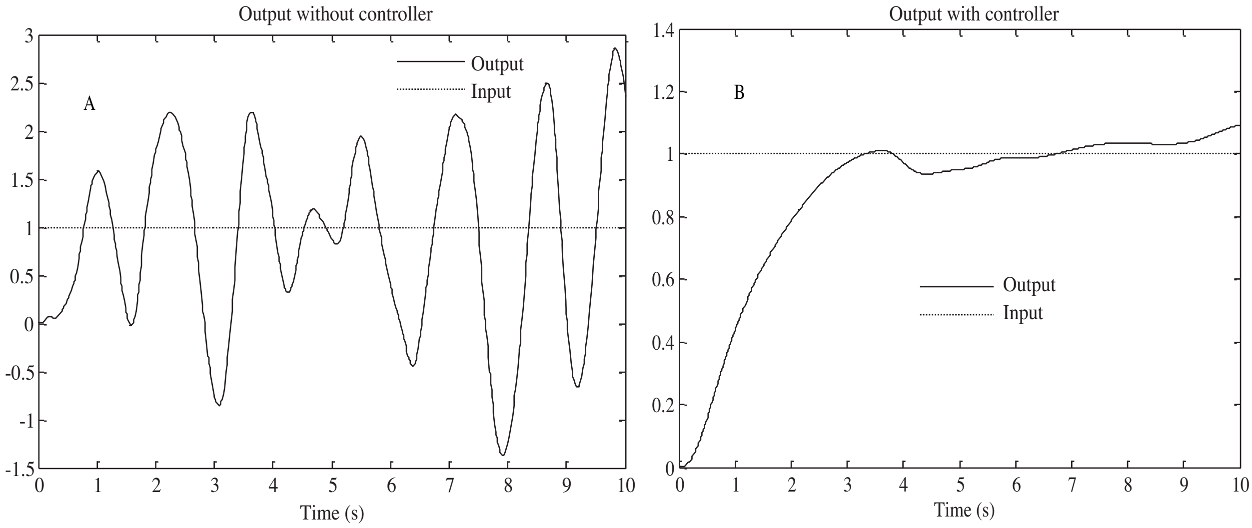

Figure 11. Output responses in presence of noise with SNR = 10 db: A) without controller; B) with controller.

Table 4. Comparison between the step response parameters.

	BFOA			EDARLA		
SNR	%OV	T_r (s)	T_s (s)	%OV	T_r (s)	T_s (s)
40 dB	2.1	0.71	1.52	3.23	0.98	1.63
30 dB	4.7	1.665	4	7.56	1.34	2.56
20 dB	3.4	1.92	3.9	11.43	1.98	3.05
10 dB	7.4	2.1	5.15	19.65	2.85	3.87

Table 5. BFOA parameter settings.

	BFOA parameters				
SNR	Nc	Nre	Nel	Step size	Population size
40 dB	25	2	1	0.01	30
30 dB	25	2	1	0.01	30
20 dB	30	2	1	0.005	30
10 dB	30	2	1	0.005	30

Table 3 shows that in all of the cases, the performance indexes were minimized more precisely than in the previous methods; thus, the BFOA outperforms previous methods. Table 4 also shows that in all cases, the overshoot of the system is reduced significantly and there is a tradeoff between the other parameters of the step responses. In 3 cases, the rise times are reduced and the settling times are acceptable.

6. Conclusion

In this paper, we have presented a new study of the type-2 controllers' design for an AVR system and proposed a bacterial foraging optimization approach for tuning the controller. The proposed controller was applied on an AVR system in the presence of noise. The simulations were taken for cases both with and without noise and the results verified the high performance of the hybrid controller. Four cases based on implementing band-limited white noise to the system were considered, and in all cases, the introduced performance index and overshoot were improved. Moreover, in 3 cases, the rise time was improved.

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