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PID BASED ON ARTIFICIAL BEE COLONY ALGORITHM CONTROLLED AVR SYSTEM

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Abstract. *In a synchronous generator, the electrometrical coupling between the rotor and the rest of the system causes it to behave in a manner similar to a damper system. We consider the problem of enhancing the stability of PID based on artificial bee colony algorithm controlled automatic voltage regulator in this article. Firstly, the generated strategy of initial value based on Logistic mapping and best-so-far selection were integrated into original artificial bee colony algorithm. Then parameters of PID were self-adjusted by using the proposed ABC algorithm, so as to realize self-tuning of automatic voltage regulator. The simulation results show that the proposed method can exhibit desired response of PID controlled AVR system.*

Keywords: Artificial bee colony, Automatic voltage regulator, Chaotic, PID controller, Synchronous generator

1. **Introduction.** A proportional-integral-derivative (PID) controller is a generic control loop feedback mechanism, and its calculation involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted by P, I, and D. It is widely used in process control, motor drives, flight control and instrumentation [1-4]. The reason of this acceptability is its simple structure which can be easily understood and implemented. Unfortunately, it has been quite difficult to tune properly the gains of PID controllers because many plants are often burdened with problems such as high order, time delays, and nonlinearities. To solve this problem, plenty of researchers have proposed intellectual optimization algorithms to self-tune the parameters of PID controllers, e.g., an optimization algorithm of differential evolution (DE) in [5], genetic algorithm (GA) in [6], and particle swarm optimization (PSO) in [7,8] were employed to search PID controller parameters. Though the above search methods have successfully solved the tuning of PID controllers, they have their own disadvantages. The premature convergence of DE and GA degrades their performance and reduces their search capability. However, how to select suitable inertia weight factor of PSO has been a challenging technique. The artificial bee colony (ABC) algorithm introduced by Karaboga [9] is an approach that has been used to find an optimal solution in numerical optimization problems. This algorithm is inspired by the behavior of honey bees when seeking a quality food source. Due to ABC's simple concept, robust mechanism and easy implementation yet effectiveness, it has become popular in evolutionary

optimization community. Both self-organization and labor division are clearly exemplified in ABC algorithm. The framework of ABC algorithm balances the effect of diversification and intensification effectively when searching the whole search space, which means the exploration of the whole search space and the exploitation of the promising area in the search space are well organized. The performance of ABC algorithm has been compared with other optimization methods such as DE, GA, and PSO. The comparisons were made based on various numerical benchmark functions, which consist of unimodal and multimodal distributions. The comparison results showed that ABC can produce a more optimal solution and thus is more effective than the other methods in several optimization problems [10,11]. The automatic voltage regulator (AVR) is to hold the terminal voltage magnitude of synchronous generator at a specified level [12]. In a synchronous generator, the electrometrical coupling between the rotor and the rest of the system causes it to behave in a manner similar to a damper system, which exhibits a spring mass oscillatory behavior. This paper introduces a PID based on ABC to controlled AVR system. The ABC algorithm is applied to the AVR system in order to optimize the control parameters of the PID controller of AVR system. The aim of this work is to reduce the oscillatory behvior of an AVR.

The rest of the paper is documented in the following headings. AVR system is formulated in Section 2. In Section 3.1, we introduce PID controlled AVR system. Section 3.2 proposes a PID based on artificial bee colony algorithm to controlled AVR system. Finally, the performance of the proposed method is numerically evaluated in Section 4 while Section 5 is devoted for the concluding remarks.

2. **Description of an AVR Model.** The real model of AVR system is shown in Figure 1. Figure 2 shows its transfer function model. An AVR system consists of five basic components, i.e., amplifier, exciter, generator, sensor, and comparator.

The transfer function of an amplifier model is given by

$$\frac{u_{\mathrm{a}}(s)}{e(s)} = \frac{K_{\mathrm{a}}}{1 + sT_{\mathrm{a}}} \tag{1}$$

where K_{a} and T_{a} represent the gain and time constant of amplifier, respectively.

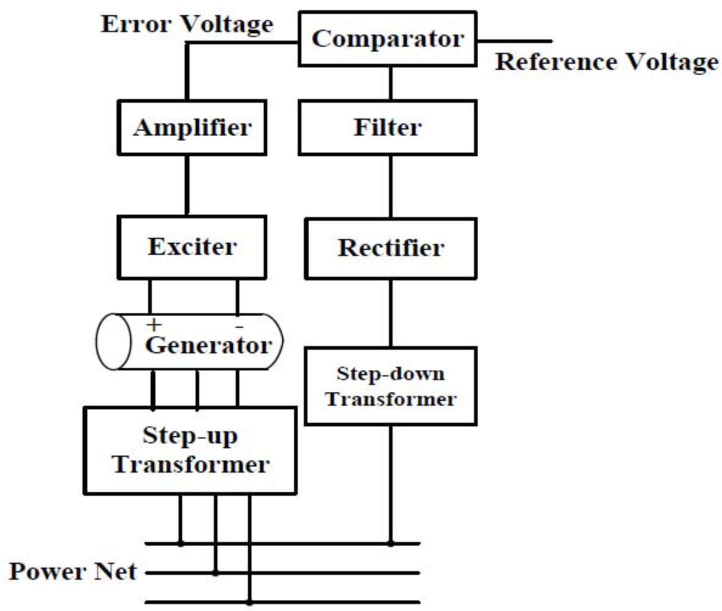


FIGURE 1. Real model of AVR

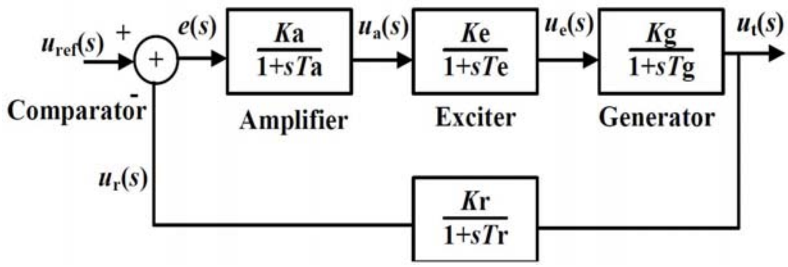


FIGURE 2. Transfer function model of AVR

The transfer function of a exciter model may be represented by a gain K_e and single time constant T_e and is given by

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

The transfer function relating the generator terminal voltage to its field voltage can be represented by a gain K_g and single time constant T_g and is given by

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

The sensor circuit, which rectifies, filters, and reduces the terminal voltage, is modeled by the following simple first-order transfer function

$$\frac{u_r(s)}{u_t(s)} = \frac{K_r}{1 + sT_r} \tag{4}$$

The output $e(t)$ of the comparator can be described as

$$e(t) = u_{ref}(t) - u_r(t) \tag{5}$$

where $u_{ref}(t)$ and $u_r(t)$ are the reference voltage and the ourput of sensor model, respectively.

The transfer function of the entire AVR system can be represented as (6).

$$\frac{u_t(s)}{u_{ref}(s)} = (K_aK_eK_g)(1 + sT_r) \Big/ [(1 + sT_a)(1 + sT_e)(1 + sT_g)(1 + sT_r) + (K_aK_eK_gK_r)] \tag{6}$$

where, the parameters limit is listed in Table 1 [13].

TABLE 1. Parameters limit of AVR

components	parameter limits	
amplifier	$10 \le K_a \le 40$	$0.02 \le T_a \le 0.1$ (second)
exciter	$1 \le K_e \le 10$	$0.4 \le T_e \le 1$ (second)
sensor	$K_r = 1$	$0.001 \le T_r \le 0.06$ (second)
generator	$0.7 \le K_g \le 1$	$1 \le T_g \le 2$ (second)

In order to make it easier to analyze, the reference voltage adopted the unitary step function, i.e., $u_{ref}(t) = 1(V)$, $t \in [0, T]$. In the case with $K_g = 1$, $T_g = 1$, $K_a = 10$, $T_a = 0.1$, $K_e = 1$, $T_e = 0.4$ and $T_r = 0.01$, the transfer function has two real poles $(-12.4892, -99.9712)$ and two complex poles $(-0.5198 - 4.6642j, -0.5198 + 4.6642j)$. Figure 3 shows the output response of AVR system. Although the transfer function is stable, it presets oscillatory behavior.

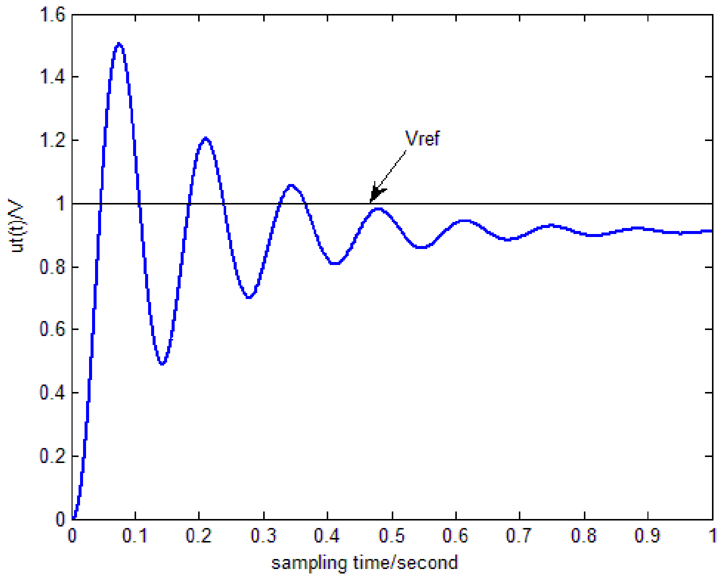


FIGURE 3. Output response of AVR system without PID controller

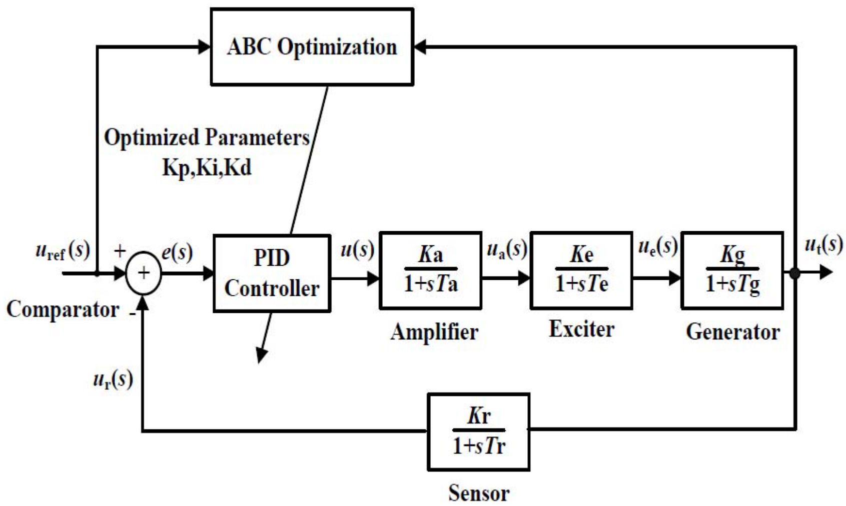


FIGURE 4. Block diagram of PID based on ABC controlled AVR system

3. **PID Based on ABC Algorithm Controlled AVR System.** To eliminate or reduce the oscillatory behavior and improve dynamic response performance, we applied PID based on artificial bee colony algorithm controlled AVR system, and its block diagram is shown in Figure 4.

3.1. **PID controlled AVR system.** The transfer function of PID controlled AVR system can be written by (7).

$$\frac{u_t(s)}{u_{\mathrm{Vref}}(s)} = (s^2K_d + sK_p + K_i)(K_aK_eK_g)(1 + sT_r)\Big/[s(1 + sT_a)(1 + sT_e)(1 + sT_g)(1 + sT_r) + (K_aK_eK_gK_r)(s^2K_d + sK_p + K_i)] \tag{7}$$

where, the transfer function of PID controller can be described as (8).

$$\frac{u(s)}{e(s)} = K_{\mathrm{p}} + \frac{K_{\mathrm{i}}}{s} + K_{\mathrm{d}}s \tag{8}$$

where K_{p}, K_{i}, and K_{d} represent the proportional, the integral and derivative values, respectively. From (7) and (8), we knew that the derivative controller of PID adds a finite zero to (6) and improves the transient response. The integral controller adds a pole at the origin, thus increasing system type by one and reducing the steady-state error due to a step function to zero. Thus, the PID controller with optimal parameters can be used to improve the dynamic response as well as reduce the steady-state error. We can get optimal value of PID controller parameters through the minimization of nonlinear multimodal performance criteria in (9)-(12), but it requires multidimensional solution search which makes the operation much more complicated. In next section, artificial bee colony algorithm is applied to determine the optimal value of PID controller.

$$ITAE = \int_0^t t\,|V_{\mathrm{ref}} - u_t(t)|dt \tag{9}$$

$$IAE = \int_0^t |V_{\mathrm{ref}} - u_t(t)|dt \tag{10}$$

$$ITSE = \int_0^t t[V_{\mathrm{ref}} - u_t(t)]^2 dt \tag{11}$$

$$ISE = \int_0^t [V_{\mathrm{ref}} - u_t(t)]^2 dt \tag{12}$$

3.2. **PID based on ABC algorithm controlled AVR system.** ABC is an algorithm that simulates the foraging behavior of a bee colony, and is used to solve the multidimensional optimization problems. A honey bee swarm consists of three kinds of bee: employed bee, onlooker bee and scout bees [10]. In ABC algorithm, the position of a food source represents a possible solution to the optimization problem and the nectar amount of a food source corresponds to the object function of the associated solution. On onlooker bee calculation phase, new candidate solutions depend on the probability of the old solution, and the probability is related to the objective function value. Although ABC was used in finding the best solution from all feasible solutions, it converges slowly at the last stages of the search process. Therefore, we rewrote update equation of the new candidate solution as (13). Figure 5(a) and Figure 5(b) show the optimization mechanism of our ideal and original ABC algorithm, respectively. In Figure 5, the line with arrow and dotted line with an arrow represent one time and multi-times iteration.

$$\boldsymbol{\theta}_{\mathrm{OB}}(l,d) = \begin{cases} \boldsymbol{\theta}_{\mathrm{best}}(d) + \varphi_{ld}[\boldsymbol{\theta}(l,d) - \boldsymbol{\theta}(r_1,d)] & p_l \geq \overline{p} \\ \boldsymbol{\theta}(r_1,d) + \varphi_{ld}[\boldsymbol{\theta}(l,d) - \boldsymbol{\theta}(r_2,d)] & p_l < \overline{p} \end{cases} \tag{13}$$

where $l = 1, 2, \wedge, N_{\mathrm{S}}$, N_{S} is the number of onlooker bee. $\boldsymbol{\theta}_{\mathrm{OB}}$ is a new solution on onlooker phase. $\boldsymbol{\theta}_{\mathrm{best}}$ is the best-so-far solution. $d = 1, 2, \wedge, D$, D is the dimension of solution. r_1 and r_2 are randomly chosen in $[1\ N_{\mathrm{F}}]$, N_{F} is the number of candidate solution, $N_{\mathrm{F}} = N_{\mathrm{S}}$ in this article. Here, $r_1 \neq i$ and $r_2 \neq r_1 \neq i$. φ_{ld} is randomly selected from $[-1\ 1]$. $\overline{p} = \frac{\sum_{l=1}^{N_{\mathrm{s}}} p_l}{N_{\mathrm{s}}} = \frac{1}{N_{\mathrm{s}}}$, and p_l is calculated by (14).

$$p_l = \frac{F(l)}{\sum\limits_{l=1}^{N_{\mathrm{s}}} F(l)} \qquad l = 1, 2, \wedge, N_{\mathrm{S}} \tag{14}$$

where $F(l)$ is the fitness function of the l-th candidate solution.

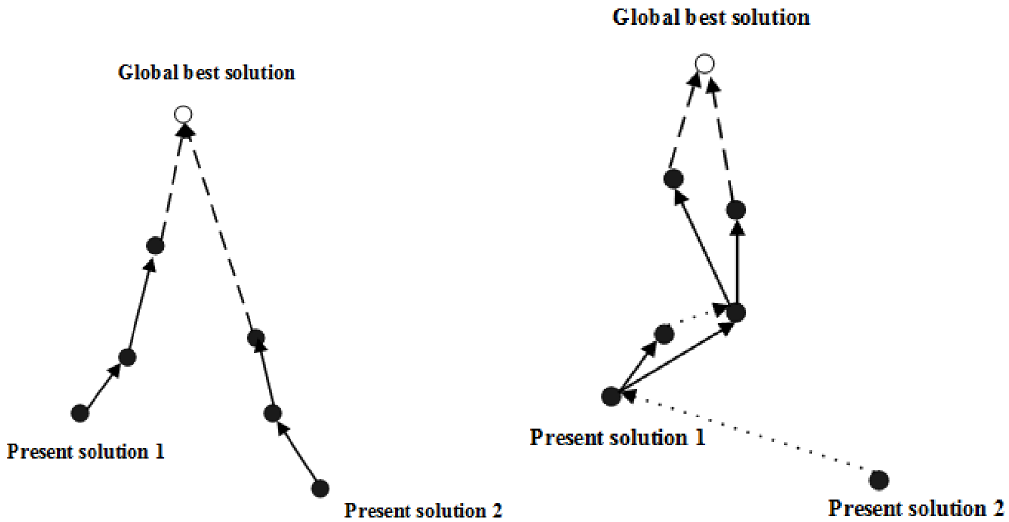
The new candidate solutions on employed bee and scout bee phase can be obtained by (15) and (16), respectively.

$$\boldsymbol{\theta}_{\mathrm{EB}}(l,d) = \boldsymbol{\theta}(l,d) + \varphi_{\mathrm{ld}}[\boldsymbol{\theta}(l,d) - \boldsymbol{\theta}(r_1,d)] \tag{15}$$

where r_1 is randomly chosen in $[1\ N_{\mathrm{F}}]$, $r_1 \neq l$.

$$\boldsymbol{\theta}_{\mathrm{SB}}(l,d) = \boldsymbol{\theta}_{\mathrm{best}}(d) + \varphi_{\mathrm{ld}}[\boldsymbol{\theta}(l,d) - \boldsymbol{\theta}(r_2,d)] \tag{16}$$

where r_2 is randomly chosen in $[1\ N_{\mathrm{F}}]$, $r_2 \neq l$.



(a) ABC algorithm (b) Proposed ABC algorithm

FIGURE 5. Optimization mechanism of different ABC

Similar with other optimization algorithms, population initialization is also a crucial task in ABC because it can affect the convergence speed and the quality of the final solution. If no information about the solution is available, then random initialization is the most commonly used method to generate candidate solutions. Owing to the randomness and sensitivity dependence on the initial conditions of chaotic maps, chaotic maps have been used to initialize the population so that the search space information can be extracted to increase the population diversity, and then accelerate convergence speed [14]. So we propose a novel initialization approach which employs opposition-based learning method and Logistic map of chaotic systems to generate initial population, and it can be described by (17) and (18).

$$\theta(l,d) = \theta_{\min}(d) + c_{\mathrm{G}}(l,d)[\theta_{\max}(d) - \theta_{\min}(d)] \quad l = 1, 2, \wedge, N_{\mathrm{F}}/2 \tag{17}$$

$$\theta(l,d) = [\theta_{\min}(d) + \theta_{\max}(d)] - \theta(l - N_{\mathrm{F}}/2, d) \quad l = N_{\mathrm{F}}/2+1, N_{\mathrm{F}}/2+2, \wedge, N_{\mathrm{F}} \tag{18}$$

where $c_{\mathrm{G}}(l,d)$ is the Logistic map operator. $\theta_{\max}(d)$ and $\theta_{\min}(d)$ are maximum and minimum of candidate solution d-th dimension, respectively.

In this article, ABC algorithm was employed to search optimal PID controller parameters in Figure 4. For clarity, the pseudo-code of proposed method is presented in Table 2.

Table 2. Realized steps of PID based on the proposed ABC algorithm controlled AVR system

Initialize: set maximum number of iteration $k_{\max}$, k_{limit}, N_{F}, N_{S}, D; generate initial $\theta(l,d)$ by (17) and (18), $l = 1, 2, \wedge, N_{\text{F}}$, $d = 1, 2, \wedge, D$. Choose one as goal function from ITAE, TAE, ITSE and ISE.

while (iteration <= $k_{\max}$)

Employed Bee Phase

for $l = 1$ to N_{S}
- $\boldsymbol{\theta}_{\text{EB}}(l) = \boldsymbol{\theta}(l)$;
- Randomly select the dimension of the solution, d;
- Calculate $\boldsymbol{\theta}_{\text{EB}}(l,d)$ by (15);
- Calculate goal function value $F_{\text{EB}}(l)$ of $\boldsymbol{\theta}_{\text{EB}}(l)$;
- if $F_{\text{EB}}(l) < F(l), \boldsymbol{\theta}(l) = \boldsymbol{\theta}_{\text{EB}}(l), k_{\text{count}}(l) = 0$; else, $k_{\text{count}}(l) = k_{\text{count}}(l) + 1$;

end

Select the best-so-far solution $\boldsymbol{\theta}_{\text{best}}$ from $\boldsymbol{\theta}$, and calculate p_l by (14);

Onlooker Bee Phase

for $l = 1$ to N_{S}
- Calculate new $\boldsymbol{\theta}_{\text{OB}}(l)$ by (13);
- Calculate goal function value $F_{\text{OB}}(l)$ of $\boldsymbol{\theta}_{\text{OB}}(l)$;
- if $F_{\text{OB}}(l) < F(l), \boldsymbol{\theta}(l) = \boldsymbol{\theta}_{\text{OB}}(l), k_{\text{count}}(l) = 0$; else, $k_{\text{count}}(l) = k_{\text{count}}(l) + 1$;

end

Scout Bee Phase

for $l = 1$ to N_{F}
- if $k_{\text{count}}(l) \geq k_{\text{limit}}$
- Calculate new $\boldsymbol{\theta}_{\text{SB}}(l)$ by (16);
- Calculate goal function $F_{\text{SB}}(l)$ of $\boldsymbol{\theta}_{\text{SB}}(l)$;
- if $F_{\text{SB}}(l) < F(l), \boldsymbol{\theta}(l) = \boldsymbol{\theta}_{\text{SB}}(l), k_{\text{count}}(l) = 0$;

end

iteration + 1;

end

Select the best final solution $\boldsymbol{\theta}_{\text{best}}$ from $\boldsymbol{\theta}$, i.e., $\boldsymbol{\theta}$ is optimal of K_{p}, K_{d} and K_{i}.

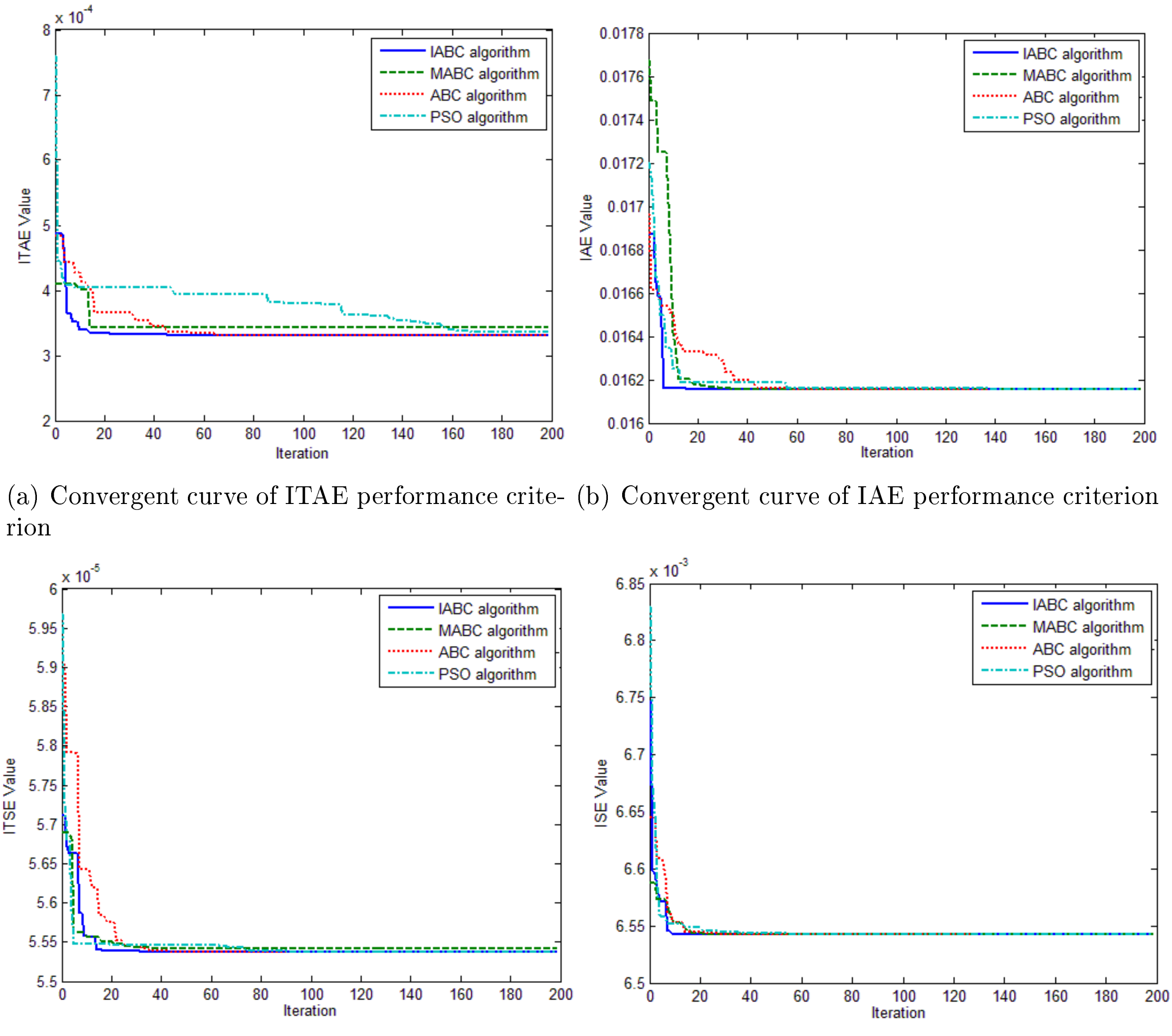
4. **Simulation Analsyis.** In this section, a serious simulation is provided to investigate the performance of the proposed ABC algorithm and the proposed AVR system in Section 3. The simulation experiment was performed on Matlab ver.2010b. The parameters of AVR system are used for simulation as follows: $K_{\text{a}} = 10$, $T_{\text{a}} = 0.1$, $K_{\text{e}} = 1$, $T_{\text{e}} = 0.4$, $K_{\text{r}} = 1$, $T_{\text{r}} = 0.01$.

4.1. **Performance of the proposed ABC algorithm for performance criteria.** To better measure the optimization performance of the proposed ABC algorithm (we denote it as IABC), we made a comparison with ABC in [9], MABC in [10] and PSO in [15]. The lower and upper bounds of the K_{p}, K_{i}, K_{d} are 0 and 3, respectively. The PSO parameters are used for simulation as (19) while the IABC, MABC and ABC parameters are used for simulation as (20). In this simulation, K_{g} and T_{g} are both chosen as 1. We performed 30 trials for all optimization algorithms with different random numbers to observe the variation in their evaluation values. Figure 6 shows the convergent curve of different optimization algorithms.

$$\begin{cases} k_{\max} = 200 \\ \text{particle population size} = 20 \\ \text{maximum inertia weight factor} = 0.9 \\ \text{minimum inertia weight factor} = 0.4 \\ \text{acceleration constant} = 0.9 \end{cases} \tag{19}$$

$$\begin{cases} k_{\max} = 200 \\ k_{\text{limit}} = 5 \\ N_{\text{F}} = 20 \end{cases} \tag{20}$$

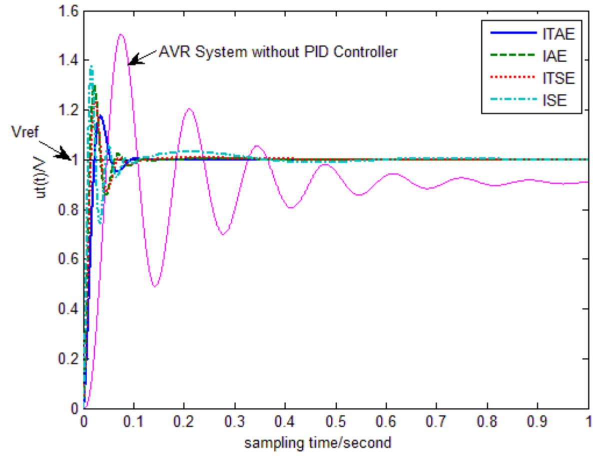
Figure 6 graphically presents the comparison in terms of convergence characteristics of four evolutionary processes in solving the four different performance criterions. In Figure 6, we compare the results using the same number of iterations. The results indicate IABC can converge to the optimal solution more quickly on almost all performance criterions when it is compared with the other algorithms. The results mean the proposed algorithm can give better solutions than other algorithms in all cases of PID controller parameters.



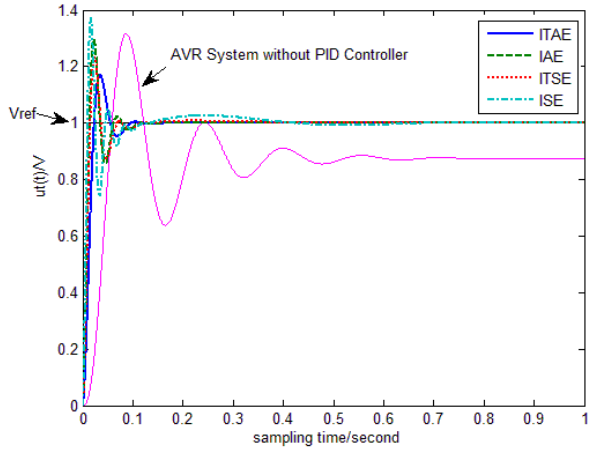
(a) Convergent curve of ITAE performance criterion (b) Convergent curve of IAE performance criterion

(c) Convergent curve of ITSE performance criterion (d) Convergent curve of ISE performance criterion

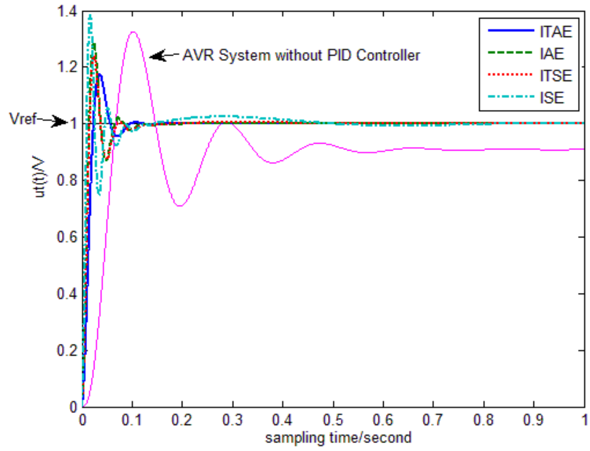
FIGURE 6. Convergent curve of different optimization algorithms



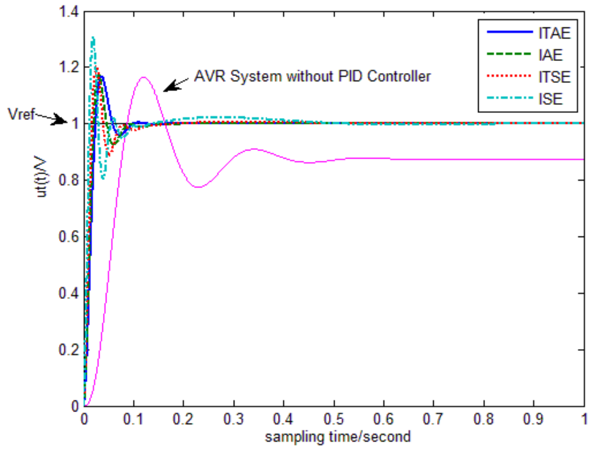
(a) AVR system of $K_g = 1$ and $T_g = 1$



(b) AVR system of $K_g = 0.7$ and $T_g = 1$



(c) AVR system of $K_g = 1$ and $T_g = 2$



(d) AVR system of $K_g = 0.7$ and $T_g = 2$

FIGURE 7. The output response of different AVR systems

4.2. **Simulation and analysis of PID based on ABC controlled AVR system.** To verify the validity of PID based on ABC controlled AVR system, we also made a comparison between four PID controlled AVR systems with different K_g and T_g. K_g and T_g are as follows: $K_g = 1$ and $T_g = 1$, $K_g = 0.7$ and $T_g = 1$, $K_g = 1$ and $T_g = 2$, $K_g = 0.7$ and $T_g = 2$. Figure 7 shows the output response of different PID controlled AVR system by using performance criterion in (9)-(12). The dynamic tuning ability of different PID controlled systems is measured by following performance indexes: the overshoot $\delta_{\max}$, stead-state error (E_{ss}), rise time (t_r) and setting time (t_s). Ideally, their value should be equal to zero. However, above ideal situation is not available in the practical engineering. And the smaller they are, the better the dynamic response behavior of AVR system is. The comparison of tuning performance of different AVR systems is shown in Tables 3-6.

From the comparison results of Figure 7 and Tables 3-6, a disadvantage of the IAE and ISE criteria is that they may result in response with a relatively big overshoot and long settling time due to they weigh all errors uniformly over time. The ITAE and ITSE can overcome this drawback. Especially, ITAE performance criterion can ensure to have a desirable stability margin. It is clear from the results that all controllers could give good PID controller parameters in each simulation example, providing good terminal voltage step response of the AVR system. In other words, as revealed by the above comparison

TABLE 3. Performance comparison of AVR systems with $K_g = 1$ and $T_g = 1$

performance index	performance criterion			
	ITAE	IAE	ITSE	ISE
$\delta_{max}/\%$	17.4935	29.6098	23.5144	37.9433
E_{ss}	1.4423e-007	1.0745e-006	6.4356e-006	0.0016
t_s/s	0.0839	0.0975	0.0959	0.2896
t_r/s	0.0157	0.0097	0.0106	0.0069

TABLE 4. Performance comparison of AVR systems with $K_g = 0.7$ and $T_g = 1$

performance index	performance criterion			
	ITAE	IAE	ITSE	ISE
$\delta_{max}/\%$	17.0410	29.5992	23.5168	37.1816
E_{ss}	1.3601e-007	1.0834e-006	6.4424e-006	2.9951e-004
t_s/s	0.0847	0.0975	0.0959	0.3090
t_r/s	0.0159	0.0097	0.0106	0.0070

TABLE 5. Performance comparison of AVR systems with $K_g = 1$ and $T_g = 2$

performance index	performance criterion			
	ITAE	IAE	ITSE	ISE
$\delta_{max}/\%$	17.3735	28.5767	24.1141	38.0913
E_{ss}	5.5515e-007	2.4907e-005	1.7669e-005	0.0024
t_s/s	0.0852	0.1007	0.1046	0.3249
t_r/s	0.0161	0.0104	0.0109	0.0070

TABLE 6. Performance comparison of AVR systems with $K_g = 0.7$ and $T_g = 2$

performance index	performance criterion			
	ITAE	IAE	ITSE	ISE
$\delta_{max}/\%$	16.6891	17.4114	20.3367	30.7648
E_{ss}	3.2070e-007	3.5584e-005	1.1242e-005	8.8706e-004
t_s/s	0.0866	0.0799	0.1092	0.2986
t_r/s	0.0166	0.0141	0.0119	0.0084

results of simulation and analysis, the proposed method can reduce the oscillatory behavior of AVR system. Moreover, the proposed method can solve the searching and tuning problems of PID controller parameters easily.

5. **Conclusions.** In this paper, we have proposed an intelligent algorithm of artificial bee colony. An algorithm based on chaotic Logistic map is introduced to generate initial value of ABC optimization algorithm. Besides, the article demonstrates how to employ the proposed ABC algorithm to identify the PID parameters of an AVR system. Then many performance estimations schemes are performed to examine whether the proposed method has better performance than other conventional methods in solving the optimal PID controller parameters of AVR system. Through simulation experiments, the results validate good performance of the proposed AVR system.

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