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Comparison of Different Methods for Optimization of PID Controller Gain Coefficients

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ABSTRACT

Proportional-Integral-Derivative (PID) controller is widely used in technical applications due to its robustness and ease of application. The gain values of a PID controller have a strong impact on performance criteria such as settling time, rise time, and overshoot. Systems that possess at least one of these criteria are considered strong control systems. Adjusting the parameters to obtain the best step response of closed loop control systems is a complex operation. While long known methods such as the Ziegler-Nichols (ZN) method were initially used to compute parameter values, today, metaheuristic algorithms are employed. This article focuses on the tuning of gain parameters of a PID controller using metaheuristic algorithms for the control of a system with a third-order transfer function. The proposed algorithms are Fuzzy Logic (FL), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO). The comparison results concluded that GA is the best algorithm for optimization.

Keywords: PID; PSO; GA; Fuzzy Logic (FL); Metaheuristic

PID Kontrolörün Kazanç Katsayılarının Optimizasyonu için Farklı Yöntemlerin Karşılaştırılması

ÖZ

Orantılı-İntegral-Türev (PID) denetleyici, sağlamlığı ve uygulama kolaylığı nedeniyle teknik uygulamalarda yaygın olarak kullanılmaktadır. Bir PID denetleyicinin kazanç değerleri, oturma zamanı, yükselme zamanı ve aşma gibi performans kriterleri üzerinde güçlü bir etkiye sahiptir. Bu kriterlerin en az değerine sahip sistemler, güçlü kontrol sistemleri olarak kabul edilir. Kapalı döngü kontrol sistemlerinin, en iyi basamak tepkisini elde etmek için parametrelerin ayarlanması karmaşık bir işlemdir. Parametre değerlerini hesaplamak için başlangıçta Ziegler-Nichols (ZN) yöntemi gibi uzun zamandır bilinen yöntemler kullanılırken, günümüzde metasezgisel algoritmalar kullanılmaktadır. Bu makale, üçüncü dereceden transfer fonksiyonuna sahip bir sistemin kontrolü için metasezgisel algoritmalar kullanan bir PID kontrol cihazının kazanç parametrelerinin ayarlanmasına odaklanmaktadır. Önerilen algoritmalar, Bulanık Mantık (FL), Genetik Algoritma (GA) ve Parçacık Sürü Optimizasyonudur (PSO). Karşılaştırma sonuçları GA'nın optimizasyon için en iyi algoritma olduğu sonucuna varmıştır.

Anahtar Kelimeler: PID; PSO; GA; Bulanık Mantık (BM); Metasezgisel

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1. INTRODUCTION

PID controllers are widely used in technical applications due to its robustness and ease of applications [1]. The utilization of the PID algorithm does not guarantee the best control and even stability of the system if the gain values are not adequately tuned. Its proper functioning is not guaranteed; it can be significantly affected by dead times (the measured error may not arrive instantly or the control action may not be applied right away). The response of a control system can be defined in terms of the error, the degree to which the system exceeds a set point, and the amount of oscillation around any set value. However, a PID controller, relying solely on the measurable system variable rather than the underlying process information, is widely applicable and has a long history of successful use in a in many applications [2-6]. A PID controller has three gain coefficients to meet some system performance criteria. These are the proportional gain coefficient Kp, integral gain coefficient Ki, and derivative gain coefficient Kd. In some applications, only one or two of these parameters are used to achieve appropriate system control (PI, P, or PD). However, the absence of one of the control effects leads to errors in achieving the system's objective. Especially in nonlinear control systems, finding the optimal parameter values for the PID controller is a challenging task [7]. One commonly used method for parameter tuning is the Ziegler-Nichols (Z-N) method [8]. In many industrial systems, the Z-N method is not acceptable as it fails to sufficiently improve performance criteria such as overshoot, settling time, and rise time. The solution is to use metaheuristic solutions to optimize the step response of closed-loop control systems.

Optimizing the step response of control systems aims to minimize overshoot or reduce settling time and rise time. Metaheuristic algorithms are stochastic strategies that mimic the behavior of social and ecological systems, commonly used to optimize problems of applied sciences. These algorithms can be utilized to select the best combination of PID controller gain coefficients that yield the optimal transient response. In this study, Particle Swarm Optimization (PSO) algorithm, Genetic Algorithm (GA), and Fuzzy Logic (FL) rule-based PID controller parameter tuning methods were employed, and the results obtained were compared with each other.

The subsequent sections of the article are planned as follows: The method of the study is explained in Chapter 2. Section 3 provides information about the simulations conducted after the description of optimization algorithms. In Section 4, the results are presented.

2. MATERIAL AND METHODS

We can define the control problem as shown in Figure 1. The gain coefficients (Kp, Ki, Kd) of the PID controller are desired to be optimized for the best control performance. The output of the PID controller is calculated based on the time-varying error as shown in Equation 1.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

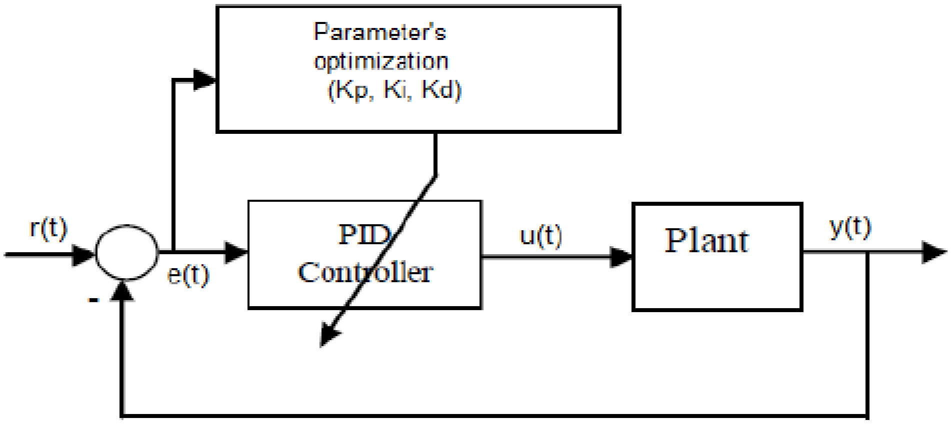


Figure 1: Structure of PID controller parameter optimization.

Performance indices are used as quantitative measures to evaluate the system performance of a PID controller. This technique is commonly used to design an "optimal system" and adjust a set of PID parameters to meet the required specifications. For a system controlled by PID, there are typically four performance indices that indicate the system performance: ISE, IAE, ITAE, and ITSE. They are defined as follows:

$$ISE = \int_0^\infty e^2(t)dt \quad (2)$$

$$ITAE = \int_0^\infty t|e(t)|dt \quad (3)$$

$$IAE = \int_0^\infty |e(t)|dt \quad (4)$$

$$ITSE = \int_0^\infty te^2(t)dt \quad (5)$$

Here, t represents time, and e(t) is the difference between the setpoint and the controlled variable. ISE is used in this article to define the performance for different parameters.

The transfer function of the system to be controlled is a third-order system as given in Eq.6

$$G(s) = \frac{s+2}{s^3+2s^2+3s+5} \tag{6}$$

3. OPTIMIZATION METHODS

3.1 Optimization with Particle Swarm Optimization (PSO) Algorithm (PSO-PID)

PSO is an optimization algorithm based on evolutionary computation techniques. The basic PSO algorithm was developed from swarm research such as fish schools and bird swarms [9]. After its initial introduction in 1995 [10], the original PSO was modified in 1998 to improve its performance.

The PSO algorithm is initialized with random particles and then iteratively updates generations to search for the optimal solution. Each particle represents the proportional, integral, and derivative gains of the PID controller. In each iteration, each particle is updated with two important values: pbest and gbest. pbest represents the best-known position of the particle, while gbest represents the best-known position of the swarm. Each particle updates its positions (x) and velocities (v) based on the following equations 7 and 8 according to the best two values:

$$v_{t+1} = wv_1 + c_1 r_1 (p_t - x_t) + c_2 r_2 (G_t - x_t) \tag{7}$$

$$x_{t+1} = x_t + v_{t+1} \tag{8}$$

The model created in Matlab/Simulink for the simulations of the optimization of PID controller gain coefficients using the PSO algorithm is shown in Figure 2.

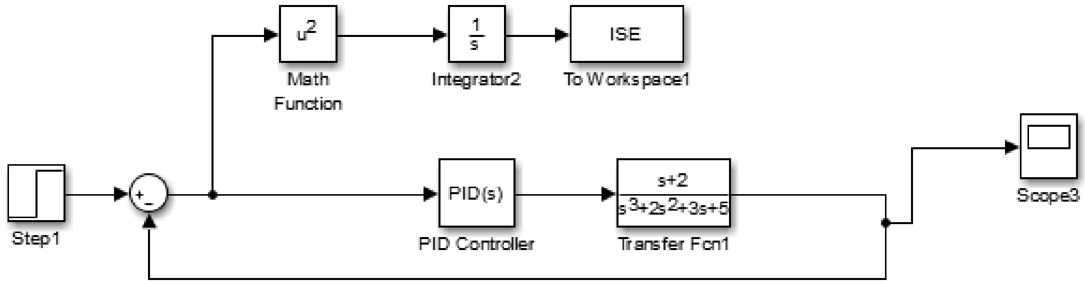


Figure 2: Control system Simulink model for PSO optimization

The parameters for the PSO algorithm were selected as shown in Table 1. The variation of the fitness index with respect to iterations can be seen in Figure 3. The best fitness index value was calculated as ISE = 2.2247.

Table 1: PSO parameters

Parameters	**Value**
Max. itearation	50
Swarm population	60
$c_1 = c_2$	2
w_{max}	0.9
w_{min}	0.4
Fitness index	ISE

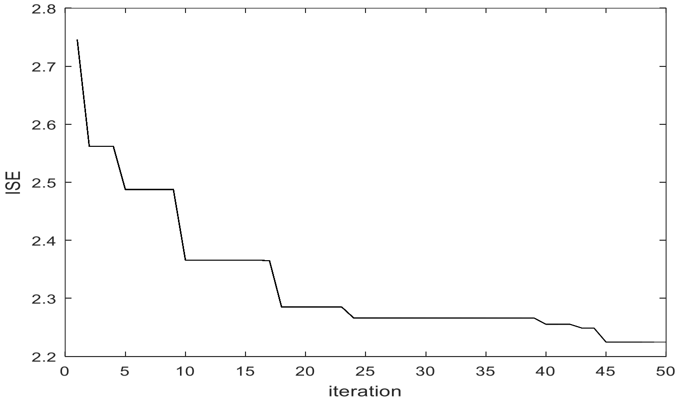


Figure 3: The best fitness values

Based on the fitness value in Figure 3, the PID controller gain parameters are determined as follows: Kp = 23.866, Ki = 32.034, and Kd = 8.590.

3.2 Optimization with Genetic Algorithm (GA) (GA-PID)

Genetic Algorithm (GA) is a metaheuristic approach inspired by the natural selection process and belongs to the class of evolutionary algorithms (EA). Genetic algorithms can generate high-quality solutions inspired by biological processes such as mutation, crossover, and selection. Therefore, it is used in many optimization and search problems [11-14].

Genetic Algorithm is an optimization method inspired by natural selection and genetics. The algorithm starts with a randomly initialized population of potential solutions in the search space. Individuals are represented by design variables or their encoded form (chromosome). Some solutions from the initial population are used to generate a new population using genetic operators (crossover, mutation, etc.). This is motivated by the hope that the new population will be better than the previous one. Solutions to be used for creating new solutions are randomly selected based on their values (represented by an objective function specific to the problem at hand, to be minimized or maximized): the better the individual, the higher its chances of survival and reproduction until a convergence criterion is met (typically a fixed number of generations or a target value reached by the objective function). Some advantages of genetic algorithms are listed below [15]:

- Global search capability: Genetic algorithms can explore a wide range of solutions and are not easily trapped in local optima.
- Robustness: Genetic algorithms can handle complex, non-linear, and multimodal optimization problems.
- Population-based approach: By maintaining a population of solutions, genetic algorithms provide diversity and allow for better exploration of the search space.
- Adaptability: Genetic algorithms can adapt to changing environments or problem conditions by updating the population through selection and evolution.
- Parallelization: Genetic algorithms can be parallelized, allowing for faster computation by evaluating multiple solutions simultaneously.

The most important step in the application of a genetic algorithm is the selection of objective functions used to evaluate the fitness of each chromosome. Typically, there are four performance indices used as objective functions (Equations 2-5). Here, the Integral of Squared Error (ISE) is used as the performance index to minimize the error signal. Figure 4 summarizes the computation steps of the control law.

Below, the genetic algorithm is characterized with a total of 50 generations. The population crossover rate is 0.8, the population mutation rate is 0.08, and the number of individuals per population is equal to 30.

First, the optimization interface is opened in Matlab by typing "optimtool". Then, GA optimization is selected, and the parameter settings are determined as shown in Table 2. Finally, the GA optimization is started by clicking "Start". After optimizing fifty times, the obtained values for Kp, Ki, and Kd are 49.70, 49.93, and 49.99, respectively.

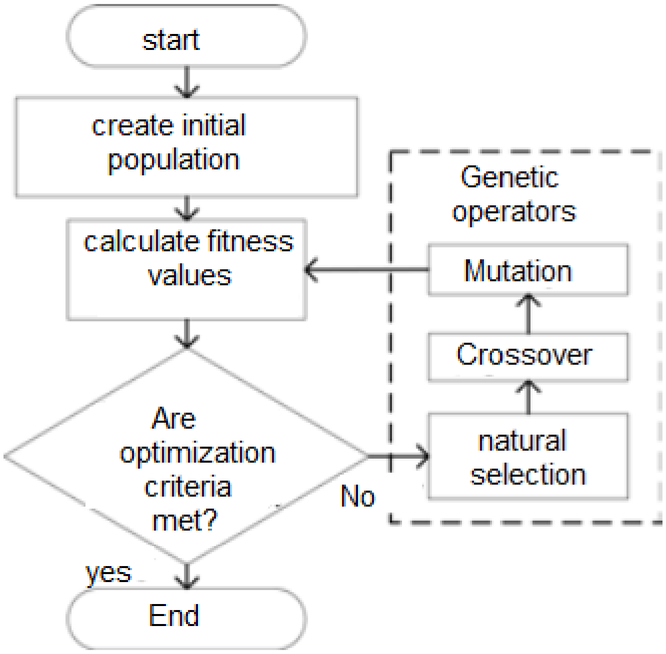


Figure 4: General structure of genetic algorithm

Table 2. GA Optimization Parameters

Parameters	**Value**
Max. itearation	50
Population type	30
Creation function	Uniform
Scaling function	Rank
Selection function	Tournoment
Mutation function	Adaptive feasible
Crosover function	Aritmetic
Plot function	Best fitness
Level of display	İterative

The obtained optimal performance criterion value through iterations is determined as ISE = 0.01547.

3.3 Optimization With Fuzzy Logic (FL-PID)

In this section, Fuzzy Logic Controller (FLC) will be used for the optimization of PID gains. The use of FLC brings adaptability to the controller and enhances its robustness. The Self-Tuning Fuzzy PID (STFPID) controller can be formulated as follows:

$$f'(t) = \left[K_p(t)e(t)\right] + \int_0^t [K_i\,(\tau)e(\tau)]d(\tau) + \frac{d[K_d(t)e(t)]}{dt}$$
$$= [k_p^0 + \Delta k_p(t)]e(t) + \int_0^t \left[k_i^0 + \Delta k_i(\tau)\right]e(\tau)d(\tau) + \frac{d\left[k_d^0 + \Delta k_d(t)\right]e(t)}{dt} \qquad (9)$$

Here, $K_p(t) = k_p^0 + \Delta k_p(t)$; $K_i(t) = k_i^0 + \Delta k_i(t)$; $K_d(t) = k_d^0 + \Delta k_d(t)$; are the control gains with some permissible variations.

k_p^0, k_i^0, k_d^0 : They are the time-invariant constant gain values of the PID controller. $\Delta k_p(t)$, $\Delta k_i(t), \Delta k_d(t)$ are the time-varying controller gains during the simulation period.

An Adaptive Fuzzy Logic Controller (FLC) is proposed here to generate Δkp(t), Δki(t), Δkd(t). FLC utilizes fuzzy linguistic variables NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big) to represent them. FLC has two inputs: the system error e(t) and the derivative of the error with respect to time. To generate the controller gains, FLC requires three outputs. Thus, as shown in Figure 5, FLC has two inputs and three outputs. The triangular (and zmf) membership functions for the inputs and outputs are shown in Figure 6. The range of the input membership functions is (-3 3), and the range of the outputs is (-0.3 0.3) for Kp, (-0.06 0.06) for Ki, and (-0.03 0.03) for Kd.

In cases where the error is large, a larger value of Kp should be chosen to achieve a faster response. A smaller value of Kd can help avoid large instantaneous errors. A small value of Ki will assist in preventing overshoot.

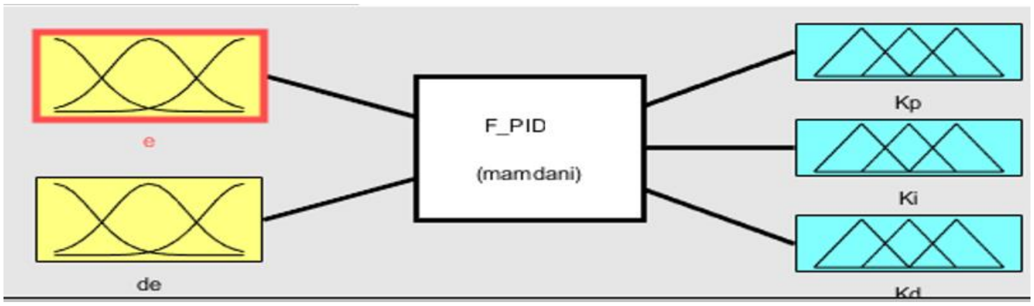
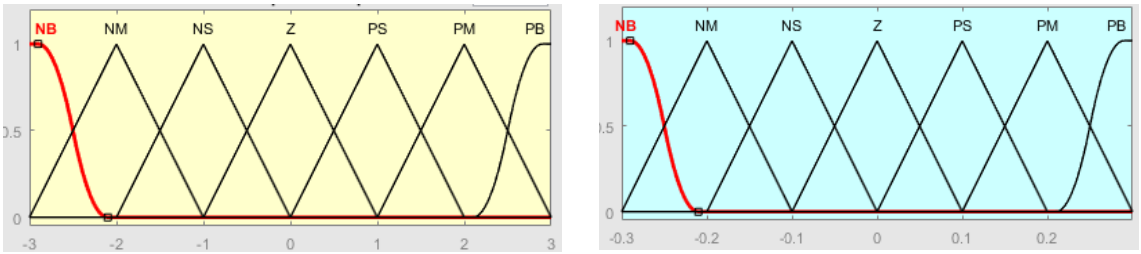


Figure 5: Fuzzy Logic model for tuning PID parameters (Matlab)



(a) (b)

Figure 6: a) Input membership functions (e, de) b) Output membership function (for Kp)

When the error is moderate, reducing Kp gain will help achieve a fast system response and minimize overshoot. A large Kd value will increase the speed of the system response, while Ki gain should be appropriate to reduce steady-state error. When the error is small, large values of Kp and Ki should be used to ensure the system has ideal static performance. Taking these considerations into account, fuzzy rules have been designed for Kp, Ki, and Kd as presented in Tables 3, 4, and 5 respectively.

Table 3: FLC Rule Base for calculate ΔKp(t)

e de	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

Table 4: FLC Rule Base for calculate ΔKi(t)

e de	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NM	NB	NB	NM	NS	NS	Z
NS	NS	NB	NM	NS	NS	Z	PS
Z	Z	NM	NM	NS	Z	PS	PM
PS	PS	NM	NS	Z	PS	PS	PM
PM	PM	Z	Z	PS	PS	PM	PB
PB	PB	Z	Z	PS	PM	PM	PB

Table 5: FLC Rule Base for calculate ΔKd(t)

e de	NB	NM	NS	Z	PS	PM	PB
NB	NB	PS	NS	NB	NB	NB	NM
NM	NM	PS	NS	NB	NM	NM	NS
NS	NS	Z	NS	NM	NM	NS	NS
Z	Z	Z	NS	NS	NS	NS	NS
PS	PS	Z	Z	Z	Z	Z	Z
PM	PM	PB	NS	PS	PS	PS	PS
PB	PB	PB	PM	PM	PM	PS	PS

The block structure of the STFPID (Self-Tuning Fuzzy PID) created in Matlab/Simulink is shown in Figure 7.

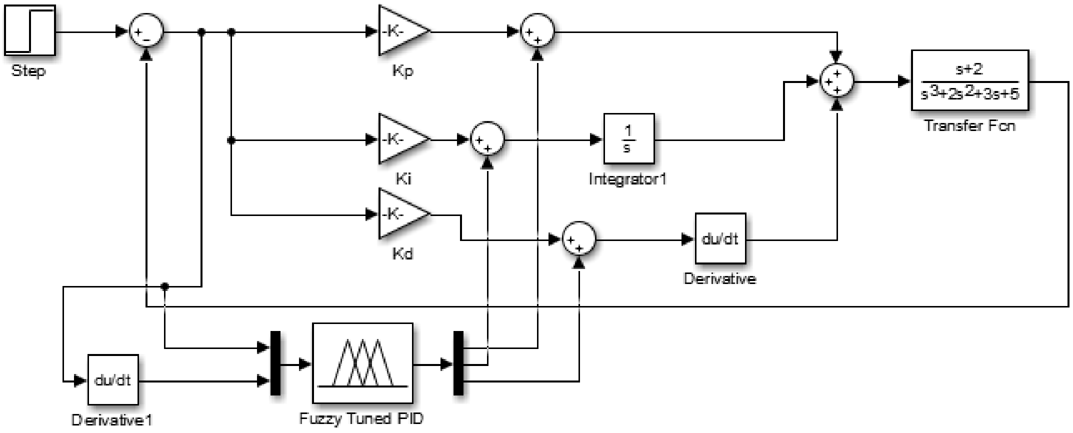


Figure 7: STFPID Matlab/Simulink Model

4. RESULTS

The simulation results of the examined three optimization algorithms for the controlled system's step response are shown in Figure 8. In terms of performance criteria such as rise time, overshoot, and settling time, the best control performance is achieved by the PID controller with gain parameters tuned by Genetic Algorithm (GA-PID). The second best controller in terms of performance achievements is the PID controller with gain parameters tuned by Particle Swarm Optimization algorithm (PSO-PID). The PID controller with gain parameters tuned by Fuzzy Logic rule base (FL-PID), as shown in Table 6, ranks third in performance evaluation. In future studies, simulations can be repeated with different performance indices (ITAE, IAE, ITSE) to further investigate the results.

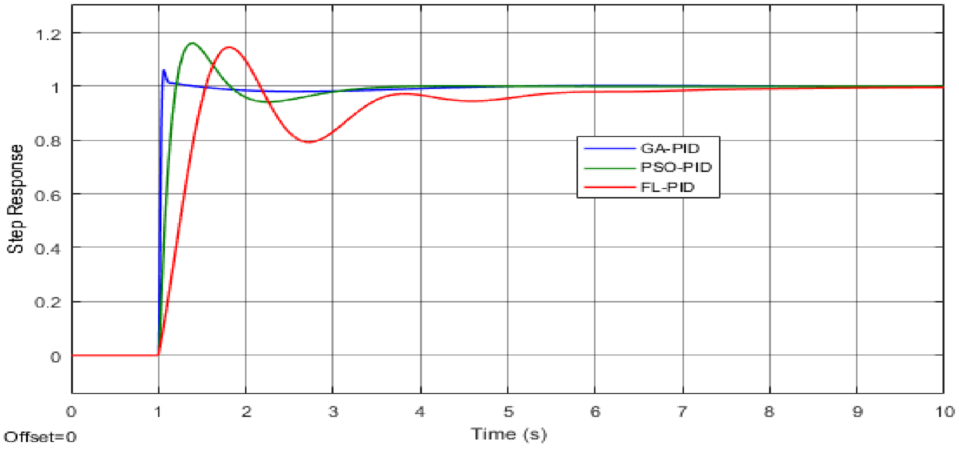


Figure 8: Step response of the system with proposed methods

Table 6: Obtained parameters

Optimization Algorithm	Kp	Ki	Kd	Overshoot (%)	Rise time (ms)	Setling time (s)	ISE
GA-PID	49.70	49.93	49.99	5.851	30.573	3.423	0.015
PSO-PID	23.86	32.03	8.59	15.698	143.364	4.295	2.224
FL-PID	0.98	0.45	1.25	18.452	463.972	8.195	18.245

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