HNUE JOURNAL OF SCIENCE DOI: 10.18173/2354-1059.2019-0044
Natural Sciences, 2019, Volume 64, Issue 6, pp. 161-172
This paper is available online at http://stdb.hnue.edu.vn

TUNING PID CONTROLLER BASES ON CHEMICAL REACTION OPTIMIZATION ALGORITHM

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Abstract. Chemical Reaction Optimization (CRO) algorithm plays an important role to determine optimal parameters of PID controller in which the model of DC motor is used as a plant. Tuning PID controller using the traditional Ziegler-Nichols (ZN) method usually produces large overshoot and Integral time absolute error, Integral absolute error and Integral square error performance indices. Therefore, recently researchers have applied random search approaches such as Genetic algorithm (GA), Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO) to find optimal parameters for PID controller. Among modern heuristic algorithms, CRO was introduced in 2010, it combined advantage features of both GA and Simulated Annealing (SA) to find global minimum in search space. In this paper, we describe the application of CRO algorithm to search optimal parameters for PID controller because CRO combines both features of local and global searching techniques to increase the chance of finding global solution. The comparison of tuning PID controller by CRO and traditional Ziegler-Nichols method is also presented. The simulated results show the advantages of tuning PID using CRO compared to traditional methods in terms of performance indices and transient responses.

***Keywords*:** Tuning PID, CRO algorithm, Ziegler-Nichols method, performance index, optimization.

1. Introduction

Proportional Integral and Derivative (PID) controllers have been used in industrial control applications for a long time. This is due to its simplicity, low-cost design and robust performance in a wide range of operating conditions. According to a survey in 1998, nearly 90% of the controllers used in industries are PID controllers [1]. By adding a derivative term into Proportional Integral (PI) controller, it improves the stability of control loop. The combined effect of Proportional and Derivative (D) controllers introduces a predictive capability in the controller since D term is able to react to foreseeable future control errors. The proportional term works as a fast acting correction

Received May 30, 2019. Revised June 21, 2019. Accepted June 28, 2019.
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which will produce a change in the output as quickly as the error arises. The integral action takes a period of finite time to act but has the capability to make the steady zero state error. Unfortunately, tuning the PID of controllers is tedious and it might be difficult to tune the PID gains properly due to the nonlinearity and the high complexity of the system [2]. Therefore, besides the traditional tuning methods, we need heuristic methods for tuning parameters of controller. Recently, random search algorithms are widely chosen to solve nonlinear optimization problems. The categories of these algorithms do not require differentiable and continuous objective functions. Some random search algorithms are used for tuning PID controller such as GA [3-5], PSO [2, 6-9] and GWO [10].

Among random search optimization algorithms, the CRO combines advantage features of both GA and SA random search algorithms [11]. It was proposed by Albert Y. S. Lam and Victor O. K. Li in 2010. This algorithm is successfully applied to maximize expectation clustering [12] and solve many problems such as Quadratic assignment problem, Resource-constrained project scheduling problem, Channel assignment problem in wireless mesh networks, Population Transition Problem in peer-to-peer live streaming, Cognitive radio spectrum allocation problem, Grid scheduling problem, Standard continuous benchmark functions, Stock portfolio selection problem, Artificial neural network training problem and so on [11]. CRO is a modern meta-heuristic algorithm for optimization problem. It simulates the nature of chemical reaction. When chemical reaction is in balance state, the produced substances are stable and have minimal energy. In other words, chemical reaction converts unstable substances to stable ones. In chemical point of view, the chemical reaction begins with some molecules which have large energy reacting with each other through a sequence of elementary reactions [11]. Finally, they are transformed to the molecules with minimal energy for existence. This nature is implemented in the CRO algorithm for solving optimization problems. In this paper, we use the CRO algorithm to find global optimization for parameters of PID controller and compare results with the traditional Ziegler-Nichols tuning method with respect to integral performance indices.

2. Content

2.1. PID controller

Proportional Integral Derivative (PID) controller is widely used in industry and practice. PID is often used in close loop control system presented in Figure 1.

PID controller combines the features of three P, I and D controllers. The P element instantaneously adjusts proportional control variable to the error signal. This is quite logical and it may be compared to the natural reaction of a process operator. The larger the error signal is, the larger the proportional control variable should be adjusted. One drawback of the P term is any change in the operating conditions which will result into an offset, which is a steady state deviation of controlled variable from the set points. To overcome this drawback, the I term is added to form a PI controller. Meanwhile, the D term is added to the PI controller to form a PID controller because this element considers change rate of the error. Therefore, using the derivative element in controller allows the control variable to anticipate and counteract the cause of the error signal

before it can take significant values. In PID controller, the control variable is related to the error signal by equation (1).

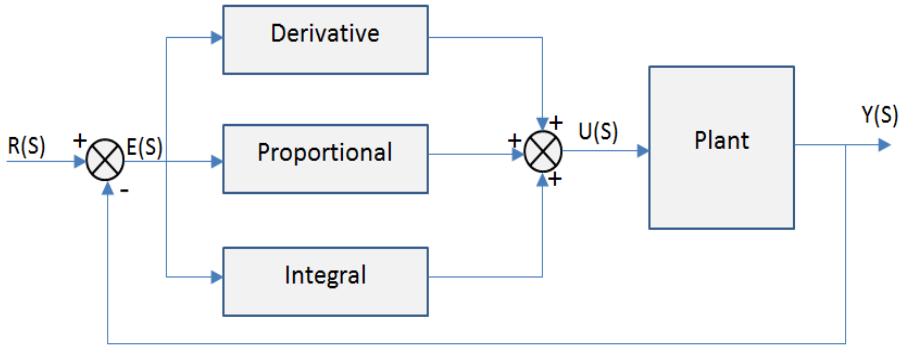

Figure 1. Block diagram of close loop control system with PID controller

$$u(t) = K_P \times e(t) + K_I \times \int_0^t e(\tau) \times d\tau + K_D \times \frac{de(t)}{dt} \quad (1)$$

This expression is often written in other form.

$$u(t) = K_P \times \left(e(t) + \frac{K_I}{K_P} \times \int_0^t e(\tau) \times d(\tau) + \frac{K_D}{K_P} \times \frac{de(t)}{dt}\right) = K_P \times \left(e(t) + \frac{1}{T_I} \times \int_0^t e(\tau) \times d(\tau) + T_D \times \frac{de(t)}{dt}\right) \quad (2)$$

Where $T_I = \frac{K_P}{K_I}$ is referred as the integral time constant or reset time of controller.

$T_D = \frac{K_D}{K_P}$ is derivative time constant.

The transfer function of PID controller can be written as the following form:

$$C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D \times s = K_P \times \left(1 + \frac{1}{T_I \times s} + T_D \times s\right) = K_P \times \frac{1 + T_I \times s + T_I \times T_D \times s^2}{T_I \times s} \quad (3)$$

where K_P, K_I, K_D are proportional gain, integral gain and derivative gain respectively.

By tuning these three parameters, the controller can provide control action which is designed for specific process requirements. There are some traditional methods to determine K_P, K_I, K_D such as Ziegler - Nichols, CHR modification of the Ziegler - Nichols settings, Cohen-Coon controller settings, Lambda Tuning Technique, Haalman Controller Settings. In addition, there are some optimization methods widely used for tuning controller. In these methods, the controller parameters are determined with a view to minimizing the given integral performance criteria such as integral of the absolute error (IAE), integral of the square error [13] listed as below:

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

$$ISE = \int_0^{+\infty} e(t)^2 dt \quad (5)$$

$$ITAE = \int_0^{+\infty} t|e(t)| dt \quad (6)$$

$$ITSE = \int_0^{+\infty} te(t)^2 dt \quad (7)$$

In case of PID controller, error signal *e(t)* is function of K_P, K_I, K_D. We can choose one of integrals above as objective function for the modern heuristic random search algorithms.

2.2. CRO algorithm

CRO is a modern meta-heuristic algorithm for optimization problem. It simulates the loosely couple of chemical reacts with optimization [11]. A chemical reacting system consists of the chemical substances and its environs. Each chemical material has potential and kinetic energies and energy of the environs are presented by central energy buffer [11]. The chemical reactions are divided into two types: endothermic which needs of supplied heat from environs to initialize the reaction process and exothermic which releases heat of chemical substances to the surroundings. To implement two types of chemical reactions, in the CRO, it needs to assign the initial buffer size: positive value means endothermic reaction and zero value means exothermic reaction. When the chemical reaction reaches balance state, all chemical substances are stable and have minimal potential energy. The CRO captures that phenomenon by converting potential energy to kinetic energy and by gradually releasing the energy of chemical molecules to the environs. The CRO bases on four kinds of elementary reaction which are on-wall ineffective collision, decomposition, inter-molecular ineffective collision, and synthesis. Two ineffective collisions perform a local search and the rest perform a global search. Therefore, the CRO mixtures two types of searching to make effectively a search of the global minimum in a solution space. The CRO combines advantage features of both SA and GA. The energy conservation requirement gives similar effects of the Metropolis Algorithm used in SA while the decomposition and synthesis operations share the similarities with the crossover and mutation operations of GA. When the number of molecules is small, the CRO is more likely to the SA. When some crossover and mutation operators are implemented in decomposition and synthesis, the CRO is more likely the GA [11]. The CRO simulates each solution for a problem given by a molecule. Each molecule has some essential properties such as the molecular structure (ω) which is presented for a solution of the given problem, potential energy (*PE*) which is an objective function value that corresponds to the given solution presented by ω, kinetic energy (*KE*), number of hit (*NumHit*) which counts the number of collision that the molecule has been taken. When the molecule undertakes a collision with a wall of container or other molecules, one of elementary reactions will happen and it may make a change in the molecular structure (change solution). Other attributes of the molecule include a minimum structure (*MinStruct*) which stores a molecular structure that has minimum objective function value, a minimum potential energy (*PE)* value which can be obtained when the molecule reaches to its minimum structure. The last property of molecule is the minimum hit number (*MinHit*) that is the number of hit molecules achieving the *MinStruct.* There are four elementary reactions implemented in CRO including [11]:

- On-wall ineffective collision: This reaction happens when a molecule collides with the wall of container. This reaction changes the structure of molecule from ω to ω' (neighborhood of ω) so that it leads to some changes of energy. In addition, a portion of the transformed molecule's kinetic energy is released to central energy buffer (*buffer*). Let *KElossRate* denotes a parameter of the CRO and its value is in the range of 0 to 1,

and k is a random number generated from the range of *KElossRate* to 1. The kinetic energy of transformed molecule can be calculated by the equation (8) below:

$$KE_{\omega'} = (PE_{\omega} + KE_{\omega} - PE_{\omega'}) \times k \tag{8}$$

where $PE_{\omega'} = f(\omega')$ with f is objective function. Remaining energy is released to *buffer* to be determined as $(PE_{\omega} + KE_{\omega} - PE_{\omega'}) \times (1 - k)$ and the condition of energy conservation holds:

$$PE_{\omega} + KE_{\omega} \geq PE_{\omega'} \tag{9}$$

- Decomposition: This elementary reaction takes place when the molecule hits a wall of container and then it is broken into several parts (In this case, for the simplicity, we consider that it is broken into 2 parts). It means that we change the solution with two new ones. In other words, the decomposition reaction permits the system to search in other region of the solution space after performing all local searches by taking *On-wall ineffective collision.* To be satisfied the condition of energy conservation, the inequality (10) must be held:

$$PE_{\omega} + KE_{\omega} + \alpha_1 \times \alpha_2 \times buffer \geq PE_{\omega_1'} + PE_{\omega_2'} \tag{10}$$

where: α_1, α_2 are random numbers generated from the range of 0 to 1 and ω_1', ω_2' are produced from ω.

If the inequality (10) is held, then we can replace the existing molecule with ω by two new ones with $the\ \omega_1'\ and\ \omega_2'$ respectively and their kinetic energy can be determined by the following (11) – (13) formulas:

$$E_{rem} = (PE_{\omega} + KE_{\omega} + \alpha_1 \times \alpha_2 \times buffer) - (PE_{\omega_1'} + PE_{\omega_2'}) \tag{11}$$

$$KE_{\omega_1'} = E_{rem} \times \alpha_3 \tag{12}$$

$$KE_{\omega_2'} = E_{rem} \times (1 - \alpha_3) \tag{13}$$

where α_3 is random number generated from the range of 0 to 1.
And the *buffer* is assigned to a new value by:

$$buffer = buffer - \alpha_1 \times \alpha_2 \times buffer = (1 - \alpha_1 \times \alpha_2) \times buffer \tag{14}$$

- Inter-molecular ineffective collision: This reaction happens when two molecules collide with each other produced two new ones. The conservation energy can be expressed by (15)

$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} \geq PE_{\omega_1'} + PE_{\omega_2'} \tag{15}$$

If the inequality (15) is satisfied then two old molecules are replaced by two new ones and their kinetic energy can be calculated as follows:

$$E_{rem} = \left(PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2}\right) - (PE_{\omega_1'} + PE_{\omega_2'}) \tag{16}$$

$$KE_{\omega_1'} = E_{rem} \times \alpha_4 \tag{17}$$

$$KE_{\omega_2'} = E_{rem} \times (1 - \alpha_4) \tag{18}$$

- ***Synthesis:*** This reaction takes place when two molecules hit each other and fuse together to result only one molecule. The conversation energy can be shown by (19):

$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} \geq PE_{\omega'} \quad (19)$$

If the inequality (19) is satisfied, then two old molecules are replaced by a new one and the new molecule's kinetic energy can be calculated as the following:

$$KE_{\omega'} = \left(PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2}\right) - PE_{\omega'} \quad (20)$$

The CRO algorithm has three steps. The first step is initialization. In this step, we initialize parameters of algorithm including: *PopSize* that is the number of molecules in which each molecule structure represents for a solution of the given problem; *KelosssRate* and *MoleColl* which is the parameter that decides whether it is a mono-molecular collision or an inter-molecular collision. If we generate a random number in range of 0 to 1 that is greater than *MoleColl*, then a mono-molecular collision takes place. Otherwise, an inter-molecular collision happens; the *buffer* is initial energy of environs; *InitialKE* is initial kinetic energy of each molecule; δ and θ are parameters related to decomposition and synthesis reactions. If the inequality (21) is met, then decomposition reaction takes place and if the inequality (22) is satisfied then synthesis reaction happens.

$$NumHit - MinHit > \delta \quad (21)$$

$$KE \leq \theta \quad (22)$$

The next step of the algorithm is iteration. In this step, we make a sequence of sub steps. Firstly, we generate a random number *c* that belongs to the range of 0 to 1 then we check the condition: if it is greater than *MoleColl* or the system has only one molecule so we have a mono-molecular collision. Otherwise, we have an inter-molecular collision. In the case of a mono-molecular collision, we choose randomly one molecule from the system and check the condition (21) on it. If it meets the given condition, we perform a decomposing reaction. Otherwise, we perform an on-wall ineffective collision. For an inter-molecular collision, we also randomly choose two molecules from the system then check the condition (22) on each molecule. If both molecules are satisfied by the condition (22) then we perform a synthesis reaction on them. Otherwise, we perform an inter-molecular ineffective collision reaction. After performing an elementary reaction, we check whether the conversation energy condition is met or not. If it does not meet the condition then the change is canceled. Next, we check objective function value of any new solutions. If it is better than the best-solution before, then we update the new best-solution. Finally, we check the stopping criterion. If it is satisfied then we move to the final step. Otherwise, we will start a new iteration.

In the final step, we find the best solution for the given problem and its objective function value.

In summary, the CRO algorithm can be expressed by flowchart as Figure 2.

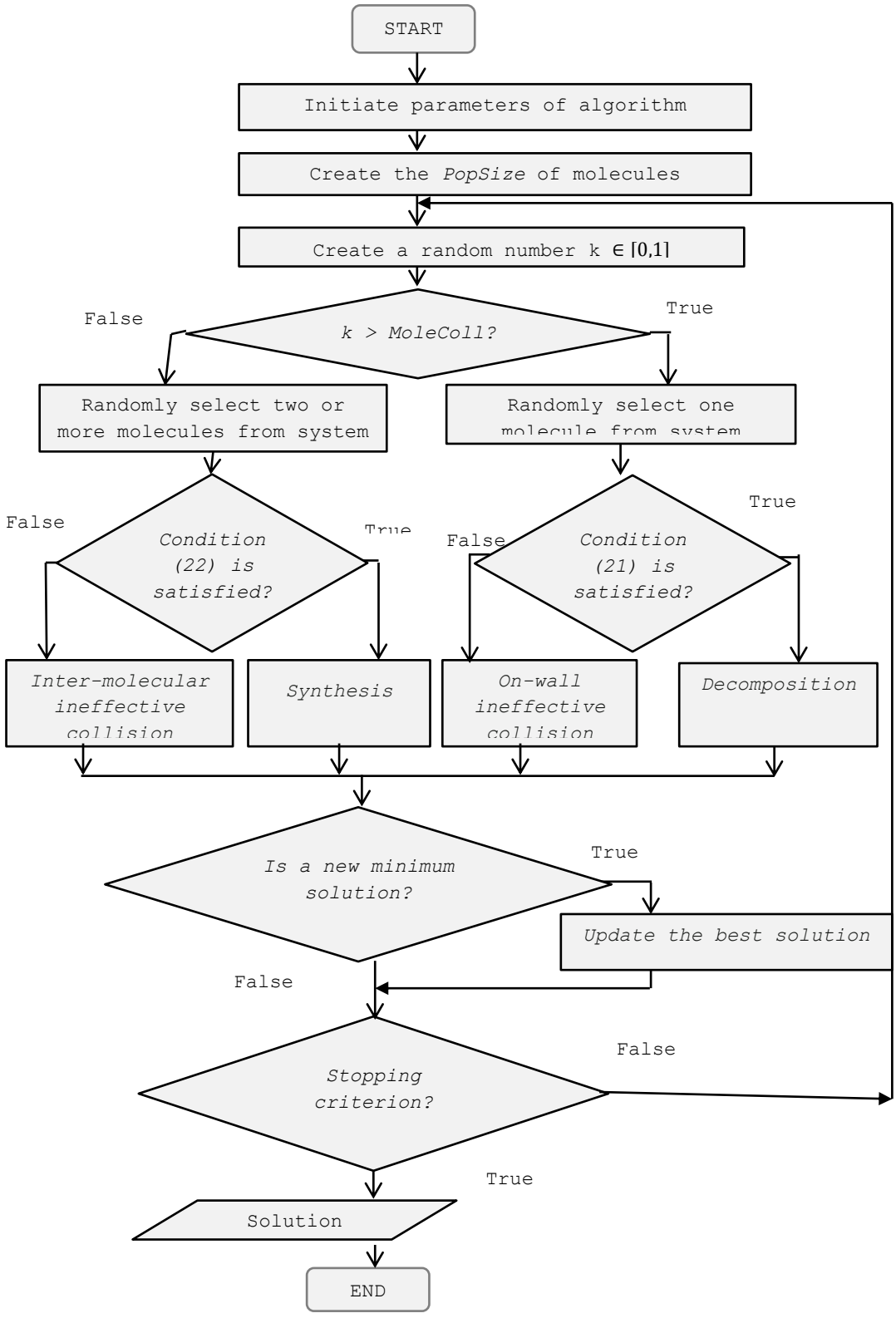

Figure 2. Flowchart of CRO algorithm

2.3. Tuning PID controller

In this article, we use the oldest traditional Ziegler Nichols (ZN) method for tuning PID controller and our proposed method using the CRO algorithm to find optimal parameters of PID controller in order to minimize integral performance indices. ZN method was proposed by John Ziegler and Nathaniel Nichols in 1942 and is still a simply and fairly effective PID tuning method. Ziegler and Nathaniel Nichols proposed two methods for tuning PID controller. The first method is applied for a process model in the type of First order system with transport lag. It has a step response as shown in Figure 3 [14].

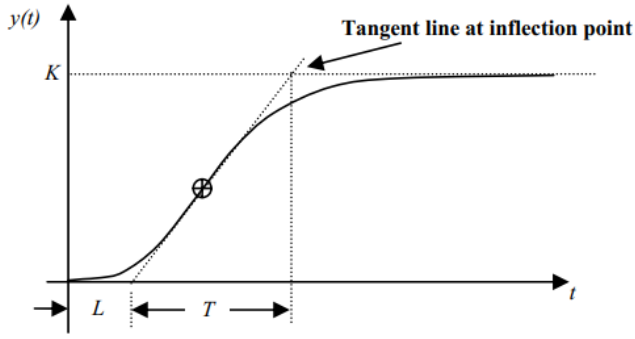

Figure 3. Step response of plant for first ZN method

From this response, we can estimate a delay time L, a constant time T and a state value K. Then K_P, K_I and K_D parameters of the PID controller can be calculated by equations (23) - (25) as follows:

$$K_P = 1.2 \times \frac{T}{L} \tag{23}$$

$$K_I = 0.5 \times \frac{K_P}{L} = 0.6 \times \frac{T}{L^2} \tag{24}$$

$$K_D = 0.5 \times L \times K_P = 0.6 \times T \tag{25}$$

The second ZN method for tuning PID controller can be expressed in the following steps:

- Decrease integral and derivative gains to zero value (to disable the integral and derivative effects)

- Increase proportional gain from zero value to ultimate value K_u at which oscillations occur with period T_u.

From the estimated K_u and T_u, we can calculate parameters of PID controller as follows:

$$K_P = 0.6 \times K_u \tag{26}$$

$$K_I = 2 \times \frac{K_p}{T_u} = 1.2 \times \frac{K_u}{T_u} \tag{27}$$

$$K_D = \frac{K_p T_u}{8} = 0.6 \times \frac{K_u T_u}{8} \tag{28}$$

To apply the CRO algorithm for finding optimizational parameters of PID controller, we can choose one of the integral performance indexes listed in the equations (4) - (7) as the objective function. In our case, we choose the integral of time absolute error (ITAE) as the objective function. We encode K_P, K_I and K_D parameters as a molecule structure (solution) and then we run the CRO algorithm to search global

minimum of ITAE. When the stopping criterion is satisfied, we obtain the optimal parameters of PID controller.

2.4. Experiment

To test our proposed method, we consider the model of DC motor which is described in Figure 4.

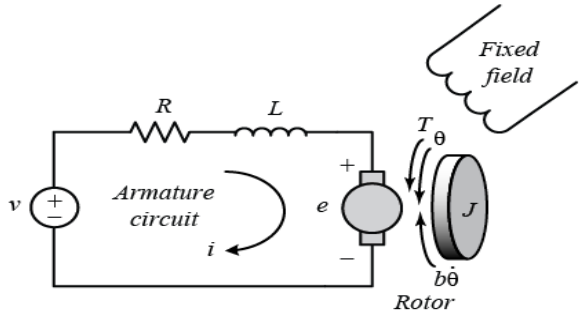

Figure 4. Diagram of DC motor

And model can be expressed by the system equations (29) as below:

$$\begin{cases} J \times \frac{d^2\theta(t)}{dt^2} + b \times \frac{d\theta(t)}{dt} = K \times i(t) \\ L \times \frac{di(t)}{dt} + R \times i(t) = V - K \times \frac{d\theta(t)}{dt} \end{cases} \quad (29)$$

Substitute $\omega(t) = \frac{d\theta(t)}{dt}$ which is angular velocity of the motor to system equations (29), we obtain

$$\begin{cases} J \times \frac{d\omega(t)}{dt} + b \times \omega(t) = K \times i(t) \\ L \times \frac{di(t)}{dt} + R \times i(t) = V - K \times \omega(t) \end{cases} \quad (30)$$

where:

J is the moment of inertia of the rotor: 0.01 kg.N^2

b is the motor viscous friction constant: 0.1 N.m.s

K_e is the electromotive force constant: 0.01 V/rad/s

K_t is the motor torque constant: 0.01 N.m/A

R is the electric resistance: 1 Ω

L is the electric inductance: 0.5 H

$K = K_e = K_t$

We perform the Laplace transform on both two sides of the system equations (30). Finally, we obtain a transfer function of the system as the following:

$$P(s) = \frac{\omega(s)}{V(s)} = \frac{K}{(J.s+b)(L.s+R)+K^2} \quad (31)$$

We apply PID controller to the system so that we can get the best step-response presented in Figure 5.

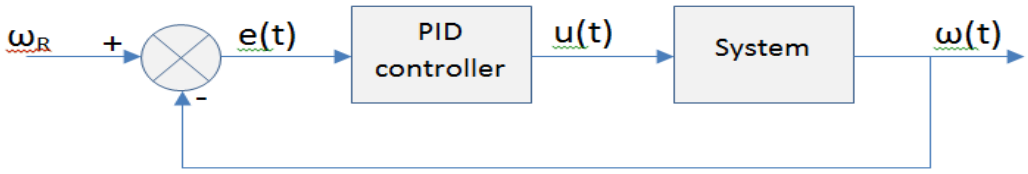

Figure 5. Schema of system with PID controller

We use the second ZN method and our proposed method to specify K_P, K_I and K_D parameters of PID controller for the model and we obtain results that are described in Table 1. The results show that all integral performance criteria such as ITAE, IAE, ITSE and ISE are smaller so that all performance indices of the CRO algorithm are better than the ones in the traditional method. To compare performance of the traditional method and our proposed method, we use a unit step change of rotor speed. Figures 6 and 7 show some unit step responses of the system with PID controller tuned by the traditional method and the CRO method.

Table 1. The comparison of performances of the traditional and CRO methods for tuning PID controller

Method	K_P	K_I	K_D	ITAE	IAE	ITSE	ISE
The traditional tuning method	15.00	75.00	0.80	5.5759	5.1906	1.9052	2.6326
The CRO tuning method	13.60	28.50	0.14	2.5061	3.5635	1.5307	2.5261

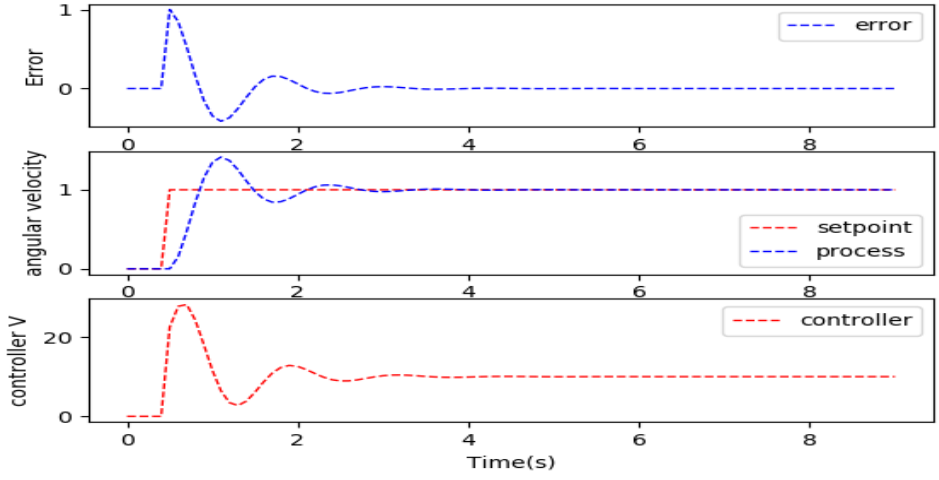

Figure 6. Unit step responses of the system with ZN tuning method

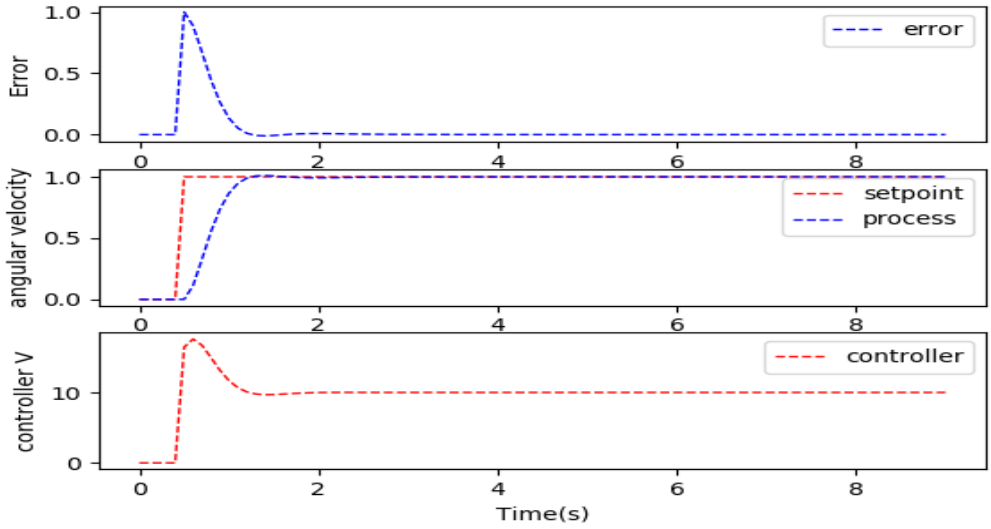

Figure 7. Unit step responses of the system with CRO tuning method

3. Conclusions

In this paper, we present the traditional rules and a meta-heuristic random search algorithm CRO for tuning PID controller. CRO combines advantage features of both GA and SA algorithms to find global optimal solution for given problem. To test performance of applying CRO algorithm for tuning PID controller, we perform simulation on the DC motor model. The simulated results show that our proposed method is better than the traditional rules with respect to performance integral indices. In the future, we will study how to solve multi-objective optimization problems using the CRO algorithm.

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