

## Optimization Techniques in PID Controller on a Nonlinear Electro-Hydraulic Actuator System

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### ABSTRACT

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The controller is an important component in the nonlinear control system, especially for the system that needs accuracy in position tracking. Electro-Hydraulic Actuator (EHA) system is a popular nonlinear system that is used by researchers. Proportional-Integral-Derivative (PID) controller is the most popular controller that is normally used in the industry. This is mainly because of its simplicity in the design process. However, there are three constants that need to be assigned in the PID controller, often we called this as the parameters selection process or the PID tuning process. In this paper, a comparison study for the selection process of the PID parameters process will be conducted among Ziegler-Nichols tuning method, conventional Particle Swarm Optimization (PSO) technique and Priority-based Fitness Particle Swarm Optimization (PFPSO) technique. PFPSO is one of the improved versions of the conventional PSO technique. The simulation study will be conducted on a nonlinear Electro-Hydraulic Actuator (EHA) system. A simple robustness test on the PID controller will be evaluated in terms of actuator internal leakage. Results showed that the PID performed better when its controller's parameters are selected using PFPSO technique rather than the Ziegler-Nichols method and conventional PSO technique.

#### Keywords:

Electro-Hydraulic Actuator System,  
Ziegler-Nichols Tuning Method, Particle  
Swarm Optimization

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## 1. Introduction

Controllers are designed and used in a feedback control system to improve system response or to achieve desired and prescribed response. The first application feedback controller used in the industrial process is agreed to be James Watt's Flyball governor. It was developed in 1769 to control the speed of a steam engine [1]. Until 1922, a Russian-American engineer Nicholas Minorsky developed a controller, which is now called Proportional-Integral-Derivative (PID) controller. He had developed PID controller based on his observation on the helmsmen steering ships and found out that they acted not only on the current error itself, but also on the past error and the current rate of

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change of the error [2,3]. There are three constants which are called controller parameters that need to be selected or assigned in PID controller:  $K_p$  is the proportional gain;  $K_i$  is the integral gain and  $K_D$  is the derivative gain. All these three gains are responsible for three different actions which occur simultaneously in PID controller: proportional action, integral action, and derivative action.

However, the parameters selection process for these three values is often a topic of interest among researchers. There are a lot of methods which had been developed or invented by researchers across the years. The best known and widely used is Ziegler-Nichols (ZN) tuning method. It was developed by Ziegler and Nichols in 1942 [4].

In recent years, the parameters selection techniques have shifted to optimization techniques. Many optimization techniques had been developed and proposed by researchers in different system over the last decades, such as neural network optimization [5-7], Evolutionary Algorithm [8], Particle Swarm Optimization (PSO) [8,9], Genetic Algorithm (GA) [10-12], Differential Evolution (DE) Algorithm [13]. A suitable optimization technique will yield the optimal parameters in each scheme for it to render the maximum output or the desired output based on the input fed to the respective system.

In this paper, the Ziegler-Nichols (ZN) tuning method, Particle Swarm Optimization (PSO) and improved version of Particle Swarm Optimization (PSO) in [14] will be employed to optimize PID controller parameters. An output performance comparison study will be done on these three techniques and then a simple robustness test will be evaluated.

The paper will continue by following sections: section 2 will describe the methodology, including the non-linear EHA system and PID controller design. The parameters selection process using different optimization techniques will be discussed in section 3 and section 4 will discuss the output performance of the controller after optimized by three different techniques. Finally, conclusions are drawn in section 5.

## 2. Methodology

### 2.1 PID Controller Design

PID controller is the most popular controller used in industry and often used as a benchmark by researchers. Figure 1 illustrates the PID controller structure. The top path is called the proportional path, the output of the proportional path is the multiplication of the error ( $e$ ) and the proportional gain,  $K_p$ . The second path is the integral path. The output of this path is the multiplication of the integral of the error ( $e$ ) and the integral gain,  $K_i$ . Note that the integral of the error is the area under the curve of the graph of error ( $e$ ) versus time. Finally, the third path is the derivative path. The error ( $e$ ) is first differentiated to get the rate of change of the error and then multiply it with derivative gain,  $K_D$ . All the output of these three paths is then added together using a summing block to become a total PID controller action and produce a control signal ( $u$ ) to a plant or system.

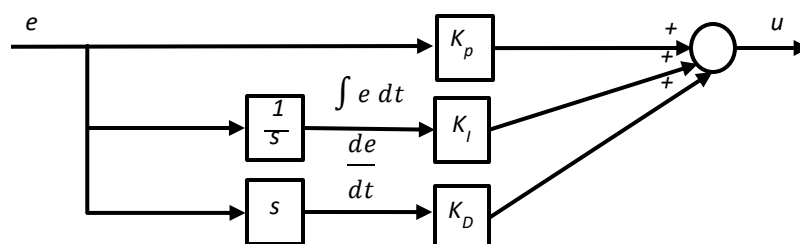


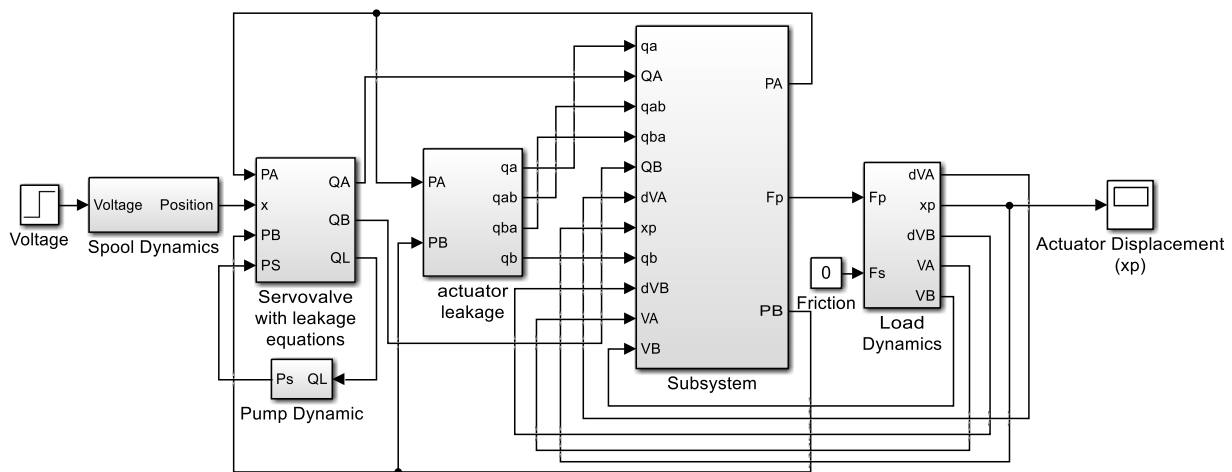
Fig. 1. PID controller structure

The overall PID control function can be expressed mathematically as in Eq. (1).

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

### 2.2 Electro-Hydraulic Actuator (EHA) System

Electro-hydraulic actuator (EHA) system is a type of non-linear system due to its disturbance and uncertainties. The established nonlinear EHA model in [15] be utilized in this paper as it has includes some of the disturbances and uncertainties characteristics like leakage, pump, and load dynamics equations. Figure 2 shows the structure EHA model used in this paper. The EHA system dynamic parameters are listed in Table 1.



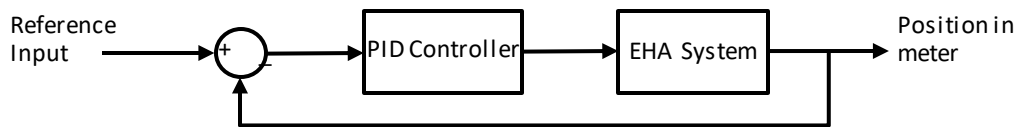
**Fig. 2.** The structure of the EHA model

**Table 1**

EHA system parameters

| Symbol    | Description                           | Value                                  |
|-----------|---------------------------------------|--|
| $R_c$     | Servo-valve coil resistance           | 100 $\Omega$                           |
| $L_c$     | Servo-valve coil inductance           | 0.59 H                                 |
| $I_{sat}$ | Torque motor saturation current       | 0.02 A                                 |
| $\xi$     | Servo-valve damping ratio             | 0.48                                   |
| $\omega$  | Servo-valve natural frequency         | 543 rad/s                              |
| $K$       | Servo-valve gain                      | $2.38 \times 10^{-5} m^{5/2}/kg^{1/2}$ |
| $\beta$   | Hydraulic fluid bulk modulus          | $1.4 \times 10^9 N/m^2$                |
| $P_s$     | Pump pressure                         | $2.1 \times 10^7 Pa$                   |
| $P_r$     | Return pressure                       | 0 Pa                                   |
| $K_s$     | Spring stiffness                      | 10 Nm                                  |
| $X_s$     | Total actuator displacement           | 0.1 m                                  |
| $A_p$     | Piston area                           | $645 \times 10^{-6} m^2$               |
| $M_p$     | Total mass                            | 9 kg                                   |
| $B_s$     | Damping coefficient                   | 2000 Ns/m                              |
| $K_{Lin}$ | Actuator internal leakage coefficient | $1 \times 10^{-12}$                    |

Figure 3 illustrates the block diagram of the EHA system with PID controller optimized by using different parameters selection techniques as discussed earlier.



**Fig. 3.** The block diagram of EHA system with PID controller

### 3. Parameters Selection Processes

#### 3.1 Ziegler-Nichols (ZN) Tuning Method

Ziegler-Nichols tuning method is probably the best known and most widely used methods. It was developed by John G. Ziegler and Nathaniel B. Nichols in the 1940s [4]. The Ziegler-Nichols method will first get the ultimate gain,  $K_u$  and ultimate period,  $P_u$  with the P-only controller by the trial-and-error method and then use these two values to get  $K_p$ ,  $K_i$ , and  $K_d$  values. First, set the  $K_i$  and  $K_d$  values in Figure 3 to zero and left only  $K_p$  value. Increase  $K_p$  value until the EHA system oscillation continuously (marginally stable).  $K_u$  is referring to the value of  $K_p$  when the EHA system is marginally stable and  $P_u$  is the period of the non-decaying oscillations at this point of marginal stability. The value of  $K_p$ ,  $K_i$ , and  $K_d$  values can be calculated using the formula in Table 2.

**Table 2**

Ziegler-Nichols method to get PID controller parameters

| Controller | $K_p$       | $K_i$           | $K_d$           |
|------------|-------------|-----------------|-----------------|
| PID        | $0.6 * K_u$ | $2 * K_u / P_u$ | $K_u * P_u / 8$ |

#### 3.2 Conventional Particle Swarm Optimization (PSO) Technique

Particle Swarm Optimization (PSO) is introduced by James Kennedy and Russell Eberhart in 1995. It was developed from the swarm intelligence and based on fish and bird flock movement behavior to find the food.

A number of particles that are moving around the searching space are used on the basic principle of the PSO algorithm to look for the best solution. Each particle will keep track of its coordinate in the fitness equation that has achieved by that particular particle. This value is known as personal best,  $P_{BEST}$ . Another value called global best,  $G_{BEST}$  is tracked by the PSO. Each particle can be shown by its current position and velocity as shown in Eq. (2) and Eq. (3).

$$x^{i+1} = x^i + v^{i+1} \quad (2)$$

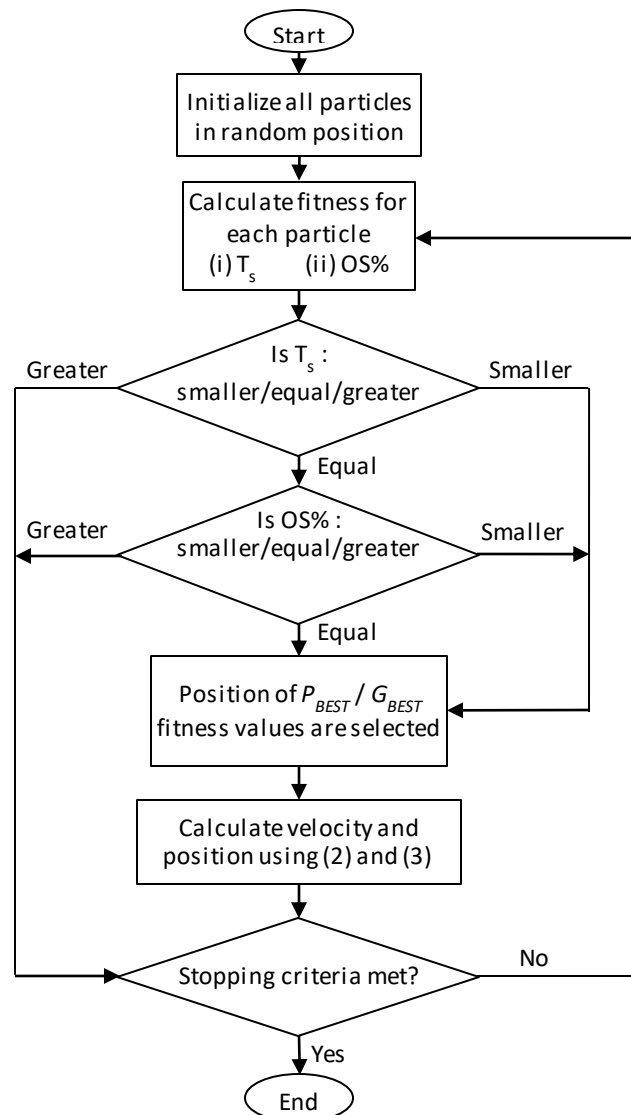
$$v^{i+1} = \omega v^i + c_1 r_1 (P_{BEST} - x^i) + c_2 r_2 (G_{BEST} - x^i) \quad (3)$$

where

- $x^{i+1}$  = position of particle at iteration k
- $v^{i+1}$  = velocity of particle at iteration k
- $\omega$  = inertia weight factor
- $r_1, r_2$  = random numbers between 0 and 1
- $c_1, c_2$  = acceleration coefficients

### 3.3 Priority-based Fitness Particle Swarm Optimization (PFPSO) Technique

PFPSO technique is a combination of Priority-based Fitness Scheme and conventional Particle Swarm Optimization (PSO) technique. It was developed by Jaafar in 2012 and apply it to a nonlinear double-pendulum crane system [5]. The  $P_{BEST}$  and  $G_{BEST}$  values in this PFPSO technique are updated according to the priority: settling time ( $T_s$ ) and overshoot percentage (OS%). Figure 4 shows the flowchart of the Priority-based Fitness Particle Swarm Optimization (PFPSO) technique in optimizing the PID parameters.



**Fig. 4.** The flowchart of PFPSO technique in optimizing PID parameters

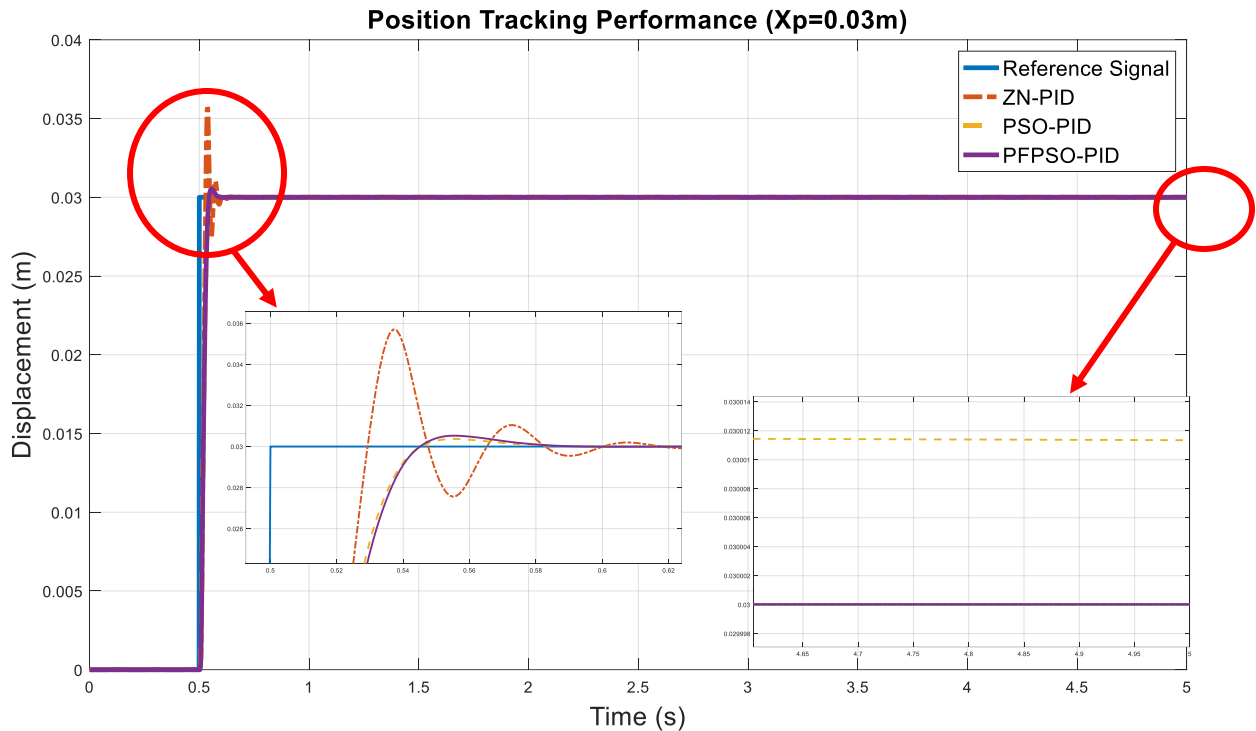
## 4. Results and Discussion

The performance of the proposed PID controller parameters selection method was investigated via simulations in Simulink. Simulation results are compared among Ziegler-Nichols selected parameters (ZN-PID), conventional PSO technique selected parameters (PSO-PID) and PFPSO technique selected parameters (PFPSO-PID). Table 3 shows the PID selected parameters.

**Table 3**  
 PID selected parameters

| Controller | $K_P$    | $K_I$  | $K_D$  |
|------------|----------|--------|--------|
| ZN-PID     | 987      | 0.0150 | 0.0038 |
| PSO-PID    | 351.9716 | 7.3992 | 0.5068 |
| PFPSO-PID  | 317.3733 | 0.0215 | 0.0796 |

In order to evaluate the performance of the PID controller apply to a nonlinear EHA system, step reference input signal is fed into the system. Using the PID controller's parameters in Table 3, the simulation is executed and the output performance is shown in Figure 5.



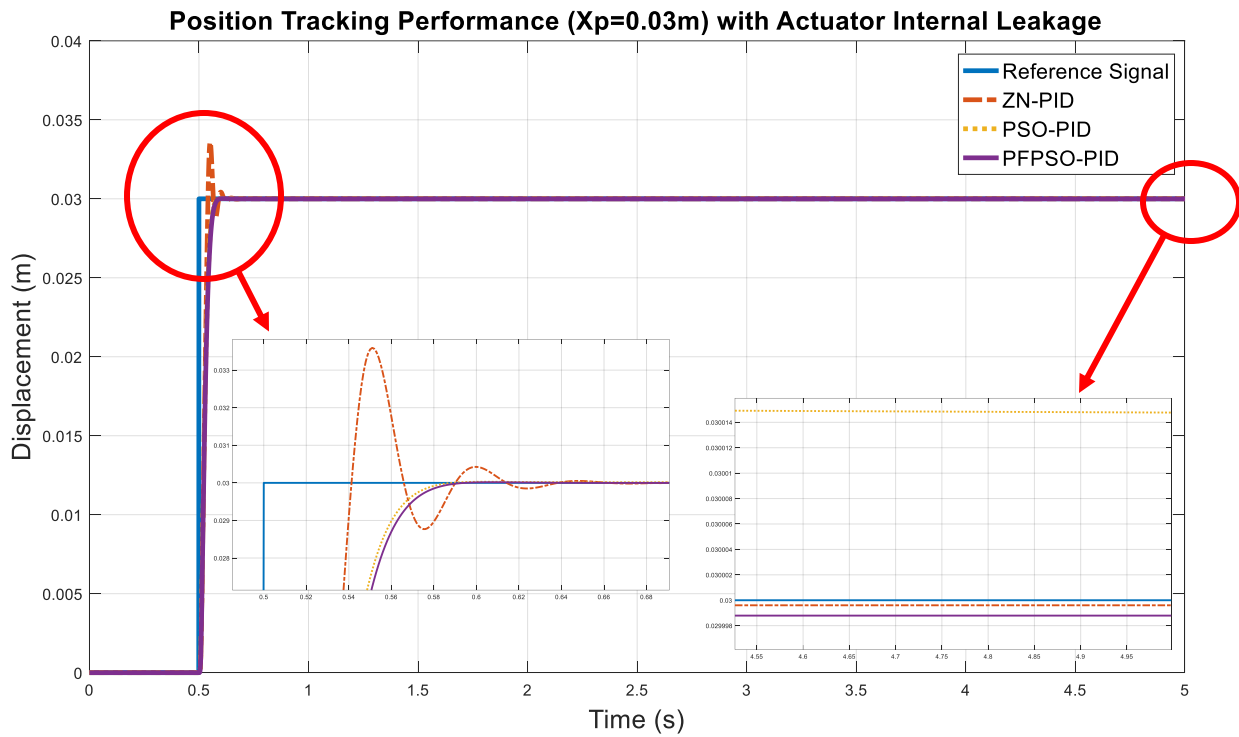
**Fig. 5.** The transient performance of step reference input

The output performance analysis is recorded in Table 4. As observed, the ZN-PID yields extremely high overshoot with 19.03% of overshoot percentage. PSO-PID have the least overshoot which is only 1.23% of overshoot percentage and PFPSO-PID showed a 1.7622% of overshoot percentage. As discussed earlier, PFPSO-PID is done by considering the priority and this paper will focus on the priority in terms of settling time followed by the overshoot percentage. That is why the overshoot percentage of the PFPSO-PID is slightly higher than the PSO-PID. ZN-PID have a long settling time, which is 0.078s as compared to PSO-PID and PFPSO-PID which have almost the same settling time 0.04s and 0.041s respectively. ZN-PID shows great performance on the steady-state error with only  $0.2534 \times 10^{-6}$  m. The steady-state error for PSO-PID and PFPSO-PID are acceptable which have a value of 0.0378m and 0.0001m respectively.

**Table 4**  
 The output performance analysis for each parameter selection methods

| Controller | Overshoot Percentage (%) | Peak Time (s) | Settling Time (s) | Steady-state Error (m)  |
|------------|--------------------------|---------------|-------------------|-------------------------|
| ZN-PID     | 19.03                    | 0.537         | 0.078             | $0.2534 \times 10^{-6}$ |
| PSO-PID    | 1.2360                   | 0.555         | 0.040             | 0.0378                  |
| PFPSO-PID  | 1.7622                   | 0.555         | 0.041             | 0.0001                  |

Another similar simulation that includes the actuator internal leakage is done on the nonlinear EHA system to observe and record the robustness of the PID controller. Figure 6 shows the position tracking performance of the PID controller on the nonlinear EHA system where the same controller parameters in Table 3 is used and the actuator internal leakage is included.



**Fig. 6.** The output performance of the EHA system with actuator internal leakage

The output performance analysis is recorded in Table 5. From Figure 6, again the ZN-PID shows the obvious overshoot and 11.9765% of overshoot percentage is recorded. Both PSO-PID and PFPSO-PID shows only a small overshoot with 0.0974% and 0.0574% of overshoot percentage. The settling time for these three parameters selection techniques is below than 0.1s which is an acceptable value for this system. The steady-state error for the ZN-PID is recorded as  $1.3259 \times 10^{-5} \text{m}$  which is the least as compared to the other two techniques. The PSO-PID and the PFPSO-PID have the steady-state error of 0.0492m and 0.0040m respectively.

**Table 5**

The robustness test for PID controller for each parameter selection method

| Controller | Overshoot Percentage (%) | Peak Time (s) | Settling Time (s) | Steady-state Error (m)  |
|------------|--------------------------|---------------|-------------------|-------------------------|
| ZN-PID     | 11.9765                  | 0.551         | 0.084             | $1.3259 \times 10^{-5}$ |
| PSO-PID    | 0.0974                   | 0.605         | 0.065             | 0.0492                  |
| PFPSO-PID  | 0.0574                   | 0.607         | 0.068             | 0.0040                  |

## 5. Conclusions

Optimum parameters are needed for a PID controller to function more effectively in a system. In this paper, three parameters selection processes had been identified to select the PID controller's parameters which are ZN tuning method, conventional PSO technique, and PFPSO technique. These three processes are being investigated through MATLAB Simulink simulation and a comparison study had been made based on the output performance among these three selection processes. Results

showed that the PID controller is performed better when its controller parameters are selected by using PFPSSO technique rather than ZN tuning method and conventional PSO technique. A robust test in terms of actuator internal leakage is done on these three selection processes. The test results showed that the PFPSSO technique gives an outstanding performance among three selection processes.

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