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Original Article

Design and Implementation of PID Controller for the Cooling Tower's pH Regulation Based on Particle Swarm Optimization PSO Algorithm

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Abstract
The PH regulation of cooling tower plant in southern fertilizers company (SCF) in Iraq is important for industry pipes protection and process continuity. According to the Mitsubishi standard, the PH of cooling water must be around (7.1 to 7.8). The deviation in PH parameter affects the pipes, such as corrosion and scale. Acidic water causes pipes to corrode, and alkaline water causes pipes to scale. The sulfuric acid solution is used for PH neutralization. The problem is that the sulfuric acid is pumped manually in the cooling tower plant every two or three hours for PH regulation. The manual operation of the sulfuric acid pump makes deviations in the PH parameter. It is very difficult to control the PH manually. To solve this problem, a PID controller for PH regulation was used. The reason for using the PID controller is that the PH response is irregular through the neutralization process. The methodology is to calculate the transfer function of the PH loop using the system identification toolbox of MATLAB, to design and implement a PID controller, to optimize the PID controller response using particle swarm optimization PSO algorithm, and to make a comparison among several tuning methods such as Ziegler Nichols (ZN) tuning method, MATLAB tuner method, and PSO algorithm tuning method. The results showed that the PSO-based PID controller tuning gives a better overshoot, less rise time, and an endurable settling time than the other tuning methods. Hence, the PH response became according to the target range. The experimental results showed that the PH regulation improved using the PSO-based PID controller tuning.

Keywords
PH Regulation, PSO Algorithm, PID Controller, Cooling Tower, MATLAB, System Identification.

I. INTRODUCTION

Cooling towers are heat rejection devices used to transfer waste heat to the atmosphere through the cooling of a water stream [1]. Cooling towers are used to increase productivity and efficiency in industrial machinery. The formation of Corrosion and humid grass inhibits the heat transfer system thus affecting the efficiency level of the cooling tower. Without proper water treatment, corrosion and scaling occurs in the pipes and basin which results in poor heat transfer and renders the cooling tower inefficient [2]. Corrosion is one of the most severe threats in today's industrial and marine environment because it can swiftly degrade metals through oxidation and reduction of chemical and electrochemical processes [3]. The emergence of corrosion, moss, and crustal precipitation can inhibit heat transfer so that it can disrupt the level of thermal effectiveness of the cooling tower. Not only does it reduce thermal effectiveness, but it can also damage the cooling tower [4]. When water vaporizes from the cooling tower, these solids remain; causing the cooling water body to become more concentrated which may then produce scale deposition heat transfer surfaces. The hardness and silica ions are the knotty scale forming species in cooling tower water [5]. So, the PH

Fig. 1. PH sensor

Fig. 2. PH transmitter

regulation in cooling towers is a very important job. Controlling of PH in neutral region is an important process as small change in input gives the huge change in output [6]. System identification toolbox of MTALAB is used to find the transfer function of PH loop [7]. The PID controller parameters are traditionally tuned through the Zeigler-Nichols method [8]. In this paper, design and implementation of PID controller for the cooling tower's pH regulation based on Particle Swarm Optimization PSO algorithm is proposed.

II. PH Loop Devices of Cooling Tower

The PH loop consists of the devices below:

A. PH Sensor

The PH sensor is installed in the process. It converts the PH of cooling water to an electric signal. It is connected to the PH transmitter. Fig. 1 shows the PH sensor.

B. PH Transmitter

The PH transmitter takes the electric signal from the PH sensor and displays it on its screen. The PH reading appears on the transmitter screen. Fig. 2 shows the PH transmitter.

C. Sulfuric Acid Pump

The water coming from the process and entering the cooling tower is alkaline. That means the PH is high. The sulfuric acid pump is used to pump the sulfuric acid solution to the cooling tower to reduce the PH of the cooling water. The sulfuric acid pump is operated manually and irregularly by operators. Fig. 3 shows the sulfuric acid solution pump.

Fig. 3. Sulfuric acid pump

III. PH Loop of Cooling Tower Modeling

To design the controller for PH loop, the transfer function of the loop must be obtained. There are two methods for system modeling physical and data-driven methods. For complex systems, the associated physical equations and dynamics are sometimes difficult to be constructed using domain knowledge-based derivations. On the contrary, data-driven-based modeling can skip this challenge providing the associated input/output data are available [9]. Meng Chen proposed a data-driven speed control method which uses the least square method to identify the precise mathematical model of the system based on the input and output data of the controlled system in real-time [10]. A data-driven approach is used to

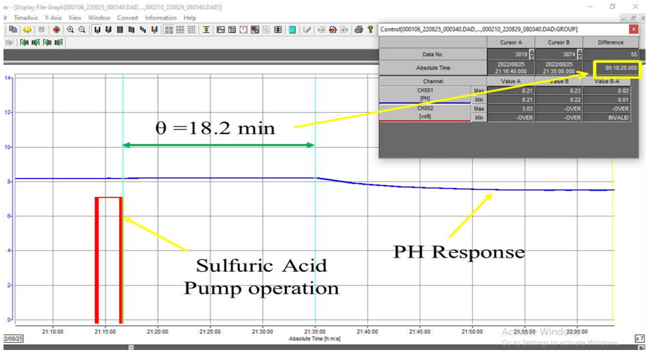

Fig. 4. Delay time calculation

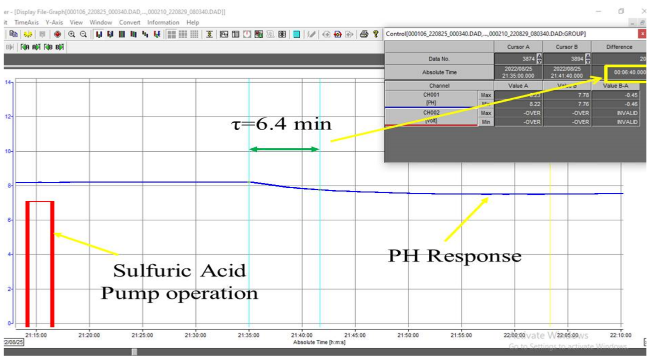

Fig. 5. Time constant calculation

describe the whole system relying only on experimental data. The modeling process followed is the classical one used for System Identification [11]. The pH regulation system has the characteristics of non-linearity and time lag, which makes it difficult for the traditional controller to achieve accurate pH control. The mathematical model of the PH regulation system can be described using first-order system transfer function plus a delay time [12]. Equation (1) refers to the first-order system transfer function plus a delay time (FOPDT).

$$G(s) = \frac{ke^{-\theta s}}{\tau s + 1} \tag{1}$$

Where k is the gain coefficient, θ is the delay time, and τ is the time constant.

The input-output data was measured locally by installing a Yokogawa recorder type DX1000. Fig. 4, 5, and 6 show the calculation of FOPDT system variables that is shown in Table 1. The drawings of the PH response were opened using the Yokogawa data viewer program.

From Table I, the transfer function of the PH loop is as equation (2).

$$G_{original}(s) = \frac{0.0953e^{-18.2s}}{6.4s + 1} \tag{2}$$

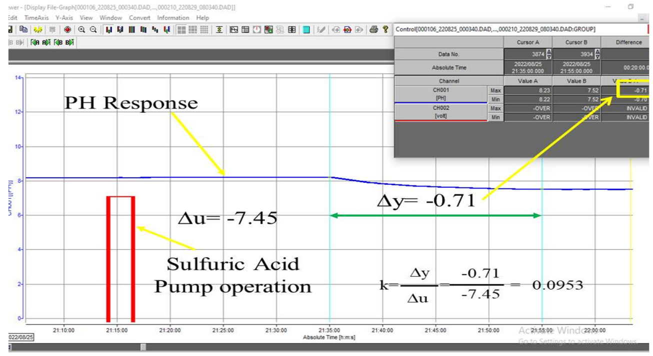

Fig. 6. Gain coefficient calculation

TABLE I.
FOPDT VARIABLES VALUES

Variable	Description	Value	Unit
k	Gain coefficient	0.0953	—-
θ	Delay time	18.2	min
τ	Time constant	6.40	min

Where $G_{original}(s)$ is the original function

IV. PID CONTROLLER

PID is a linear controller, which is currently the most widely used control strategy in actual engineering. The PID control method is simple and practical [13]. Generally, the PID controller is used as feedback controller in process industries. In spite of dynamic characteristics of process plant, the PID controller provides excellent control performance. It has three basic nodes i.e. Proportional, Integral and Derivative mode. To design a PID controller, three main parameters are to be determined like Proportional gain (Kp), Integral gain (Ki) and Derivative gain (Kd). The PID controller output can be obtained by using equation (3). Where u (t) represents the control signal and e (t) represents the error signal [14].

$$u(t) = K_p.e(t) + K_i \int_0^t e(t).dt + k_d.\frac{de(t)}{dt} \tag{3}$$

V. PID CONTROLLER TUNING

Three tuning methods were used to tune the PID controller, which are Ziegler Nichols, MATLAB Tuner, and Particle swarm optimization PSO methods.

A. $G_{original}(s)$ tuning

As shown in equation (2), The Original transfer function $G_{original}(s)$ was tuned in two methods as below:

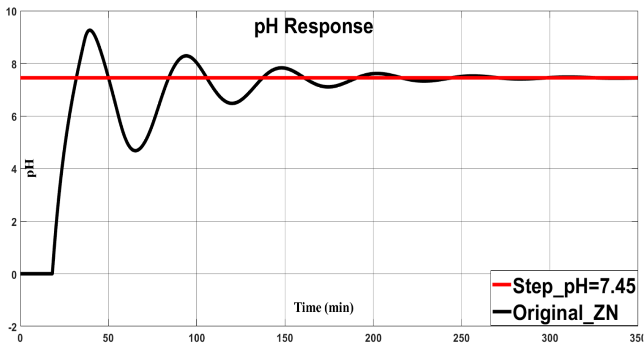

Fig. 7. Step response

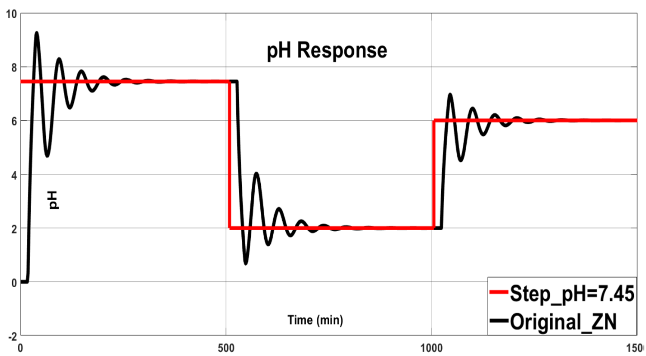

Fig. 8. Multi step response

1) *Ziegler Nichols ZN*

In this logic, the controller is set as a proportional controller, and then the process is near the specific operating point of marginal stability. The 'Kp' value will increase till the output shows oscillations that are studied. The value of 'Kp' corresponding to this is called critical gain 'Kcr'. The period of the oscillation 'Pcr' is called the critical period. The PID parameters are then calculated using Table II [15].

Fig. 7 shows the step response of the original function using ZN tuning. Fig. 8 shows the Multi-Step Response of the original function using ZN tuning.

2) *MATLAB Tuner*

The MATLAB Tuner method was used to improve the response of the original function. Fig. 9 shows the step response original function using MATLAB Tuner. Fig. 10 shows the Multi-Step Response of the original function using MATLAB Tuner.

B. *Pade Approximation*

As shown in Fig. 9 and Fig. 10, the original function has a delay time also the performance of the response is not good. The delay time affects control. To solve this problem, the Pade approximation method was used to approximate the original function ($G_{original}$). The FOPDT model of PH is approximated

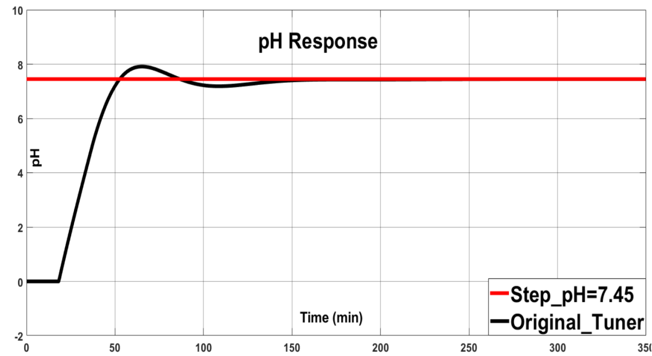

Fig. 9. Step response $G_{original}$

TABLE II.
ZIEGLER NICHOLS CLOSE LOOP PID PARAMETERS

Variable	Relation	Value
Kcr	From drawing	13.8114947
Pcr	From drawing	47.009
Kp	0.6*Kcr	8.28689682
Ti	0.5*Pcr	23.5045
Td	0.125*Pcr	5.876125
Ki	Kp/Ti	0.352566395
Kd	Kp*Td	48.69484158

as a polynomial model using Pade approximation and hence control system is designed for it [16]. The first-order pade approximation is:

$$e^{-\theta s} = \frac{1-\frac{\theta}{2}s}{1+\frac{\theta}{2}s} \tag{4}$$

Where θ is the delay time.

The delay time of the original function is θ=18.2. Therefore, the equation (4) will be:

$$e^{-18.2s} = \frac{1-\frac{18.2}{2}s}{1+\frac{18.2}{2}s} \tag{5}$$

From equations (2) and (5), the approximated transfer function ($G_{approximated}$) will be:

$$G_{approximated}(s) = \frac{-0.8672s+0.0953}{58.24s^2+15.5s+1} \tag{6}$$

Fig. 11 shows the step response of approximated function ($G_{approximated}$) using MATLAB Tuner. Fig. 12 shows the Multi-Step Response of approximated ($G_{approximated}$) function using MATLAB Tuner.

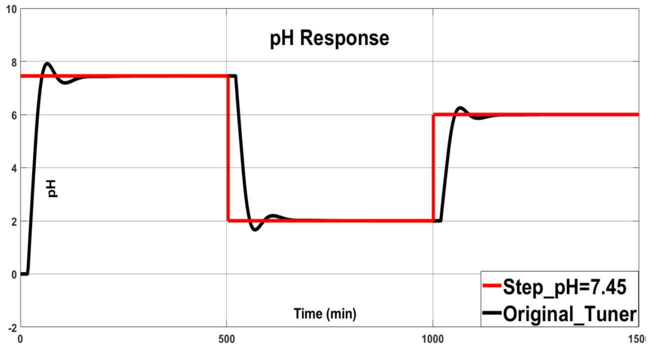

Fig. 10. Multi step response $G_{original}$

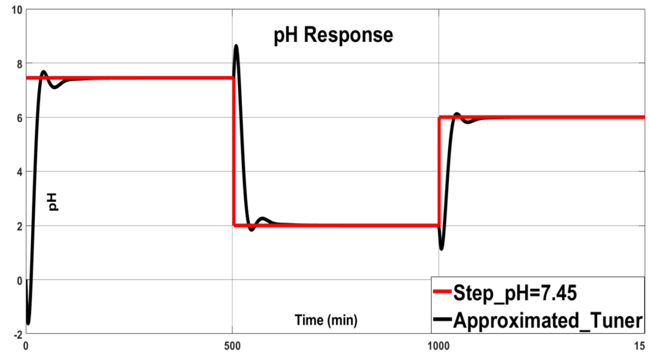

Fig. 12. Multi step response $G_{approximated}$

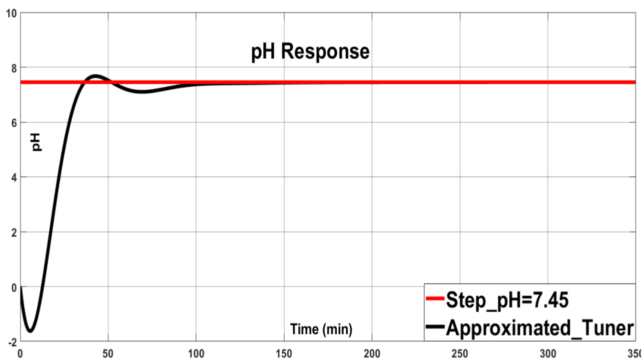

Fig. 11. Step response $G_{approximated}$

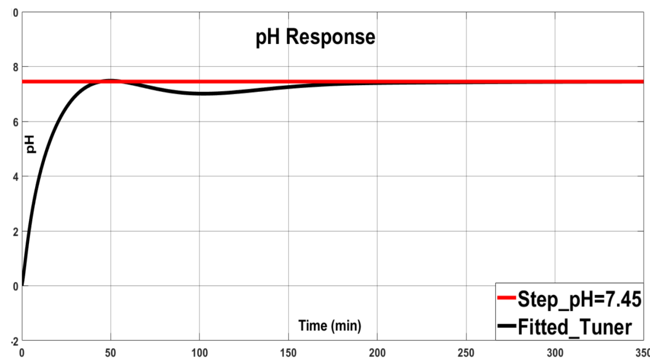

Fig. 13. Step response G_{fitted}

C. Fitted MATLAB tuner

As shown in Fig. 11 and Fig. 12, the approximated function $(G_{approximated})$ has a negative part and this problem affects the control. To solve this problem curve fitting was applied. The fitted transfer function (G_{fitted}) was calculated using the system identification toolbox of MATLAB. The fitted transfer function is as below:

$$G_{fitted}(s) = \frac{9.56e^{-5}s^2 + 2.32e^{-4}s + 7.3486e^{-6}}{s^3 + 1.17s^2 + 0.036s + 0.001122689} \quad (7)$$

Fig. 13 shows the step response of the fitted transfer function (G_{fitted}) using MATLAB Tuner. Fig. 14 shows the Multi-Step Response of the fitted transfer function (G_{fitted}) using MATLAB Tuner.

D. Fitted PSO

As shown in Fig. 13 and Fig. 14 The delay time was treated using Pade approximation and the negative part was treated using curve fitting but the performance of the fitted function response must be improved. This can be done using particle swarm optimization PSO algorithm tuning.

1) PSO Overview

The particle swarm optimization PSO algorithm developed by Kennedy and Eberhart is a swarm based evolutionary algorithm [17]. The algorithm is based on the movement of the birds in the flock according to the location of the bird closest to the food. Position and velocity update equations of the particles are used to model the movements of the flock. Equations of velocity and position are given below, respectively.

$$V_i^{k+1} = W^k V_i^k + c_1 r_1 (P_{Best}^k - X_i^k) + c_2 r_2 (G_{Best}^k - X_i^k) \quad (8)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (9)$$

Where k is the number of iteration, i, is the index of the particle, W is the inertia weight that directly affects velocity, c_1 and c_2 are the acceleration factors called cognition and social constants respectively, r_1 and r_2 are random numbers between 0 and 1. P_{Best} is the best local solution; G_{Best} is the best global solution, Vi and Xi are the velocity and position of particle i, respectively [18]. The particle swarm algorithm PSO is to find the optimal solution in the set area to minimize the value of the objective function. In this paper, integrated

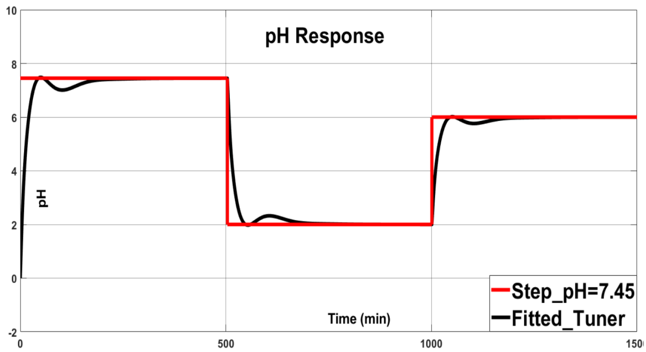

Fig. 14. Multi step response G_{fitted}

TABLE III.
PSO TUNING PARAMETERS

Parameter	Description	Value
m	number of variables	3
n	population size	100
wmax	max inertia weight	0.9
wmin	min inertia weight	0.4
c_1 and c_2	acceleration factors c_1 and c_2	2
r_1 and r_2	uniformly distributed random factors r_1 and r_2	1
LB	lower bounds of variables	-500
UB	upper bounds of variables	20000
maxiter	maximum number of iteration	1000
maxrun	maximum number of runs	1

time absolute error (ITAE) is selected as the objective function of the system [13].

$$ITAE = \int_0^\infty t|e(t)|.dt \tag{10}$$

The flowchart of the PSO algorithm is shown in Fig. 15 [19]. The PID controller tuning activity was done using PSO algorithm to find the best PID controller parameters K_p, K_i, and K_d. Table III shows the tuning parameters of the PSO algorithm.

Fig. 16 shows the block diagram of the PID-based PSO tuning. Fig. 17 shows the PSO convergence characteristic.

Fig. 18 and Fig. 19 show the fitted function G_{fitted} response based on PSO tuning.

VI. RESULTS AND DISCUSSION

Table IV shows the PID controller tuning parameters (Kp, Ki, and Kd) based on three tuning methods. The best parameters that give the best response to the fitted function were found using the PSO algorithm tuning method. The PID controller parameters are Kp=20000, Ki=100.2575, and Kd=14345.3379. Table V shows the PID controller performance parameters. The best response was found using the PSO algorithm where the PID controller performance parameters are rise time=0.881s, settling time=1.7s, overshoot=0.103, peek time=1s, negative part=0, and delay time=0. The obtained results show that the best tuning method for PID controller is using the PSO algorithm.

TABLE IV.
PID TUNING PARAMETERS

Function	Tuning Method	Kp	Ki	Kd
Original	Ziegler Nichols	8.2868968	0.3526	48.6948
Original	MATLAB Tuner	4.009956	0.3172	-41.4847
Approximated	MATLAB Tuner	6.3718	0.4136	-16.4537
Fitted	MATLAB Tuner	268.534479	9.0686	1196.3479
Fitted	PSO Algorithm	20000	100.2575	14345.3379

TABLE V.
PID PERFORMANCE PARAMETERS

Function	Tuning Method	Rise Time(s)	Settling Time(s)	Overshoot (percentage)	Peek Time(s)	Negative Part	Delay Time(s)
Original	Ziegler Nichols	10.7	206	24.3	1.24	0	18.2
Original	MATLAB Tuner	25.3	130	6.2	1.06	0	18.2
Approximated	MATLAB Tuner	16.6	87.4	2.99	1.03	-1.623	6.838
Fitted	MATLAB Tuner	25.6	160	0.42	1	0	0
Fitted	PSO Algorithm	0.881	1.7	0.103	1	0	0

VII. CONCLUSION

This paper proposed the design and implementation of a PID controller for the PH loop of the cooling tower. Three methods were used to tune the PID controller. The transfer function of the PH loop is first order plus delay time FOPDT. The transfer function of the PH loop FOPDT was passed in three stages of conversion. The original transfer function $(G_{original})$ of the PH loop was calculated using the data-driven method. Yokogawa recorder was installed locally to record the input-output data. The $(G_{original})$ was tuned by two methods Ziegler Nichols and MATLAB Tuner. The problem with the $(G_{original})$ response is the delay time. The delay time causes problems with the control. This problem was solved using the pade approximation method. The approximated transfer function $(G_{approximated})$ has a negative part. The negative part of $(G_{approximated})$ effects during a control on the process. This problem was solved using curve fitting and system identification toolbox of MATLAB. The fitted transfer function (G_{fitted}) was tuned in MATLAB Tuner and PSO algorithm tuning methods. The results showed that the PID controller performance parameters were optimized using the PSO algorithm tuning method.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

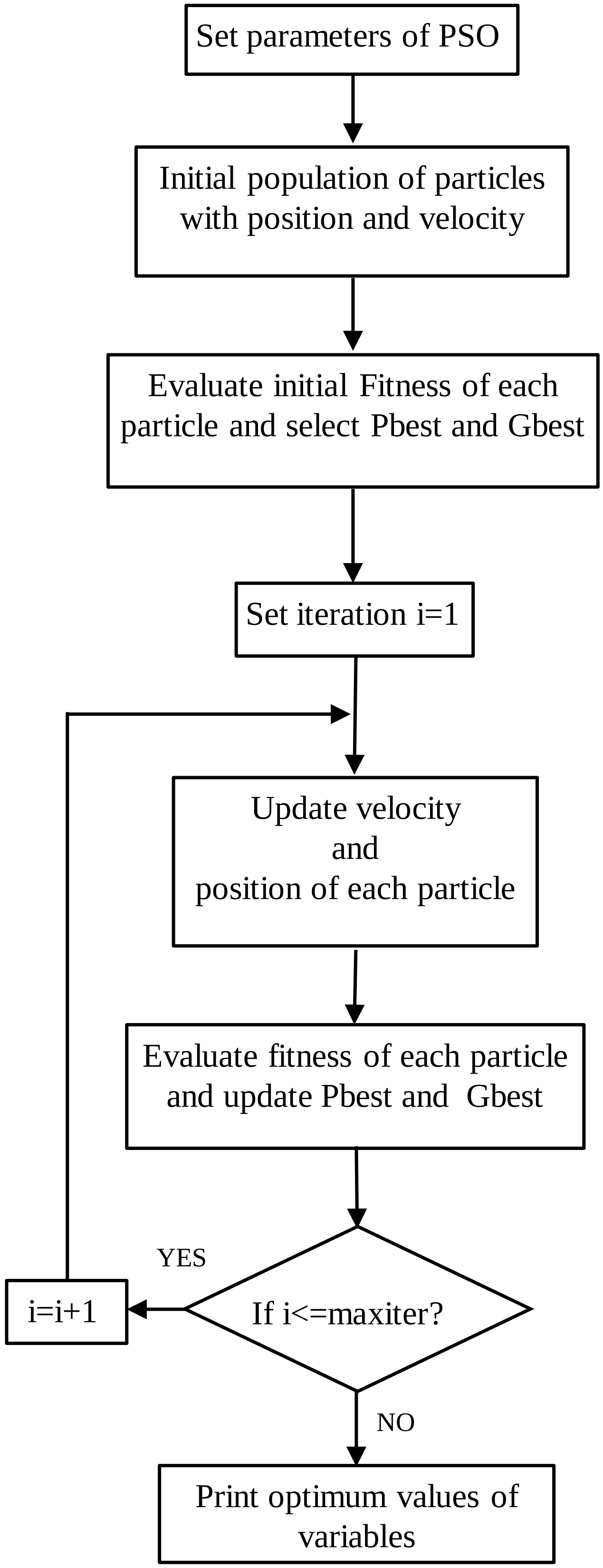

Fig. 15. The flowchart of PSO

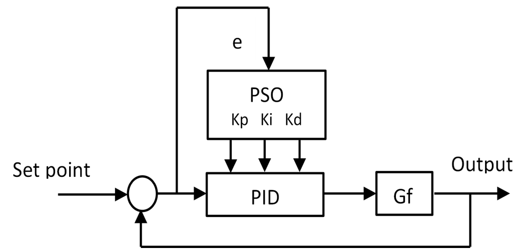

Fig. 16. Block diagram of the PID based PSO tuning

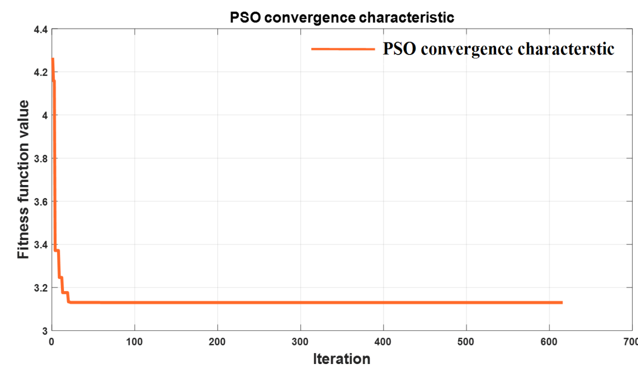

Fig. 17. PSO convergence characteristic

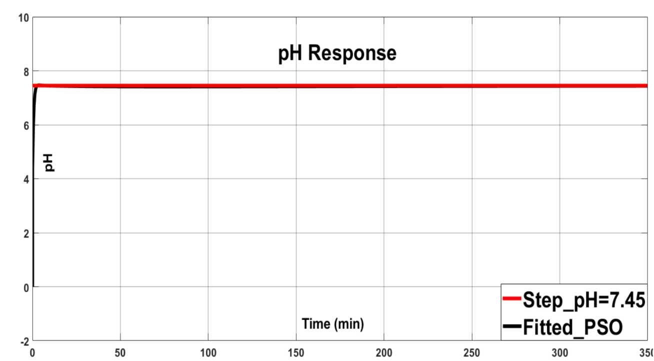

Fig. 18. Step response of G_{fitted}

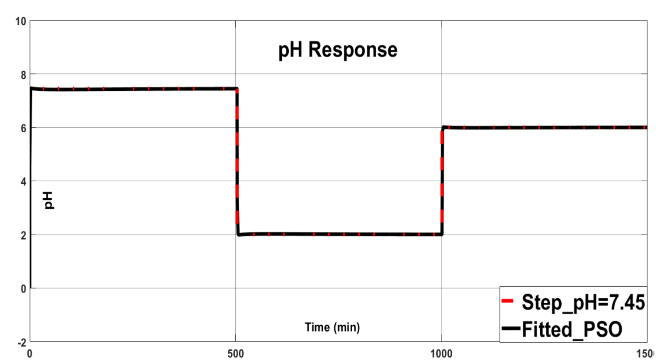

Fig. 19. Multi step response of G_{fitted}

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