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Optimal PID Control of pH Neutralization Plant

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***Abstract*—pH control plays an important role in a wide range of industrial applications for waste management. The high non–linearity in pH neutralization processes and the uncertainty of the plant dynamics are key challenges that cannot be effectively addressed using PID controllers tuned with conventional methods. Some of the available and quite often tuning methods used for designing PID controllers are Cohen–Coon, Ziegler–Nichols (ZN), and Tyreus–Luyben. To address these problems, particle swarm optimization (PSO) is employed to tune the PID controller for a pH neutralization plant. The PSO algorithm is one of the most powerful methods for resolving non–smooth global optimization problems. In this paper, the mathematical model of pH process is developed taking into consideration of the overall plant's dynamics. The PSO based PID controller is then implemented and evaluated by comparing its performance with that of ZN–PID.**

***Keywords*—Neutralization, PID Controller, Ziegler–Nichols (ZN), Particle swarm optimization (PSO)**

I. INTRODUCTION

In chemical and petrochemical industries where tons of toxic products are pumped into the environment due to contaminated chemical waste, pH is an important variable. The majority of wastes produced are alkaline in nature [1, 2]. This trend has negative effects on the environment, especially on the marine life [3, 4], where the waste water is released. The problem is also having serious effects on agricultural products produced using such water. Therefore, it is essential to treat those chemical wastes to an acceptable pH level, i.e., ideally 7. The pH neutralization process plant is used to neutralize the chemical waste product which may arise as a result of some manufacturing processes before releasing it to the environment. This is mainly to protect environment by making the discharged water safe for marine life and agricultural applications, and by avoiding damage to infrastructure due to corrosion.

The control of pH neutralization process is highly challenging. This is because the process is characterized by high nonlinearities and changing process dynamics which are usually difficult to model. These factors degrade the performance of the system. Therefore, many researchers are trying to introduce and implement robust control methodologies for modeling and control of pH processes.

Over the last decades, various control strategies were developed for adequate performance of pH neutralization process mainly due to the high nonlinearities, time varying characteristics, sensitivity around the equilibrium and for the adequate performance of set–point tracking, disturbance rejection [5], robustness [6], fault diagnosis [7], steady state and transient response [8] and changeable problems [9].

In process control industries, PID controllers are the mostly used owing to their simple design and tuning [8]. The most important and crucial task while designing the controller is proper tuning of its parameters. To dates, Ziegler–Nichols (ZN) tuning is the most widely accepted method for determining the parameters of PID controllers. However, ZN–PID's are found to be satisfactory for first–order processes with small dead–time even in the presence of load disturbances, but under set–point change and long dead–time, it fails to keep the process within acceptable limit [10]. To overcome this, PSO based adaptive PID controller is designed by using the excellent optimization power of PSO [11, 12]. Ant colony optimization [13] and dynamic set–point weighing methods were also used to improve the performance of plant in [14]. However, it has been reported that for nonlinear pH neutralization process the use of classical PID controller is inappropriate because of the nonlinearities involved [15]. Among the available optimization algorithms, PSO algorithm can be easily implemented, has very few parameters to adjust and has been successfully applied in wide range of optimizations. Hence, in this study, an attempt will be made to develop PSO based PID controller towards achieving optimum performance. Here, PSO is used to obtain the best set of PID controller parameters with respect to a given closed loop performance index. The developed PSO–PID controller performance is compared with ZN–PID method in terms of set–tracking and in the presence of disturbances.

In this paper, PID controller is selected because of its commonality in process industries. The PSO algorithm used for tuning the controller has the advantages of being intelligent, simplicity in calculations like no overlapping and mutation calculations, fitness function can be non–differentiable, applicable to larger dimension problems and easy to implement.

The remaining part of the paper is structured as follows: The proposed methodology is presented in Section II. The simulation results for the proposed methodology are discussed in Section III. Lastly, in Section IV, a conclusion is drawn.

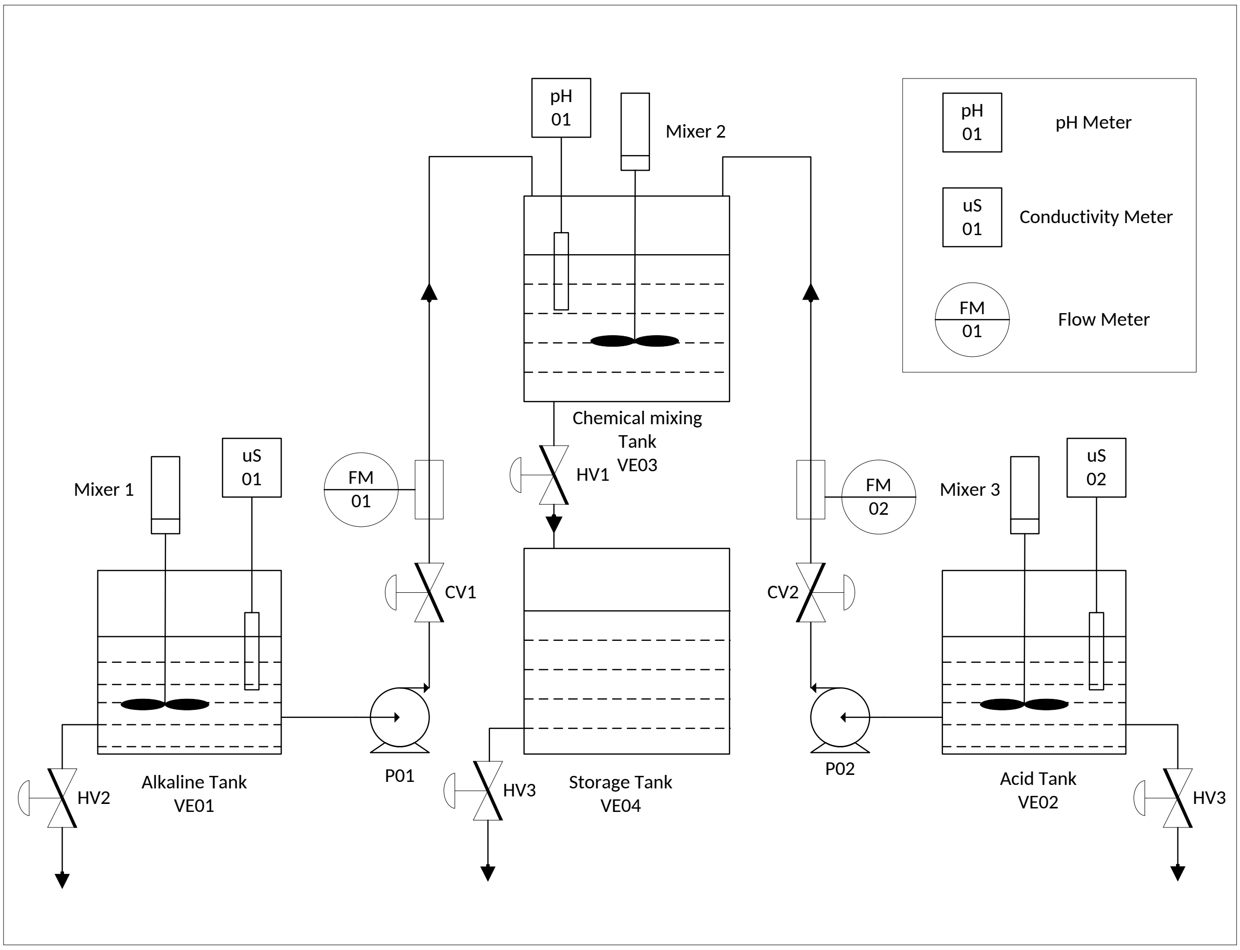

Fig. 1: Process and Instrumentation Diagram (P&ID) of the pH neutralization process plant.

II. Methodology

A. pH Neutralization Plant

The process and instrumentation diagram (P&ID) of pH neutralization plant is shown in Fig. 1. The plant consists of four main tanks: Alkaline tank (VE01), Acid tank (VE02), Chemical mixing tank (VE03) and Storage tank (VE04). In the figure, P01 and P02 are the pumps used to get the desired amount of alkaline and acid into the chemical mixing tank. FM01 and FM02 are the flow meters that indicate the flow rate of alkaline and acid streams respectively. Two control valves CV1 and CV2 are connected to the alkaline and acid alkaline pipelines respectively to control the flow of the acid and alkaline getting into the mixing tank. uS01 and uS02 are the conductivity meters used to monitor the concentrations of alkaline and acid respectively. Mixer 1, Mixer 2 and Mixer 3 contains a gear box motor, which keeps the solution in the tanks at the uniform state. The pH sensor pH01 measures the pH value of the mixed solution. The Hand valve HV1 is used to allow the flow of treated effluent from chemical mixing tank to storage tank. Similarly the hand valves HV2, HV3 and HV4 are used to drain out the tanks.

B. Fundamental Modeling of the pH Process

The Acid used in the chemical mixing tank is H_2SO_4 and alkaline used is $NaOH$. The reaction equation is

$$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O \tag{1}$$

The ionic equation is

$$2H^+ + 2OH^- \rightleftharpoons 2H_2O \tag{2}$$

Let:

- F_{Ac} is the flow rate of acid and F_{al} is the flow rate of alkaline $[ml/s]$.
- C_{Ac}, C_{Al} are the concentrations of acid and alkaline respectively $[mol/ml]$.
- V is the volume of the chemical mixing tank $[ml]$.
- V_o is the initial volume of the chemical mixing tank $[ml]$.
- C_o is the initial concentration of H^+ ions in the mixing tank $[mol/ml]$.

The volume of the mixing tank is determined by the following equation:

$$V = V_o + F_{Ac}t + F_{Al}t \tag{3}$$

where, t is time $[s]$.

TABLE I: RESULTANT pH CALCULATION

Condition	Remaining Concentration	pH Calculation
$C_H > C_{OH}$	$C_H^r = C_H - C_{OH}$	$pH = -\log(C_H^r)$
$C_H < C_{OH}$	$C_{OH}^r = C_{OH} - C_H$	$pH = -\log(\frac{10^{-14}}{C_{OH}^r})$
$C_H = C_{OH}$	$C_{OH} = C_H = 10^{-7}$	$pH = 7$

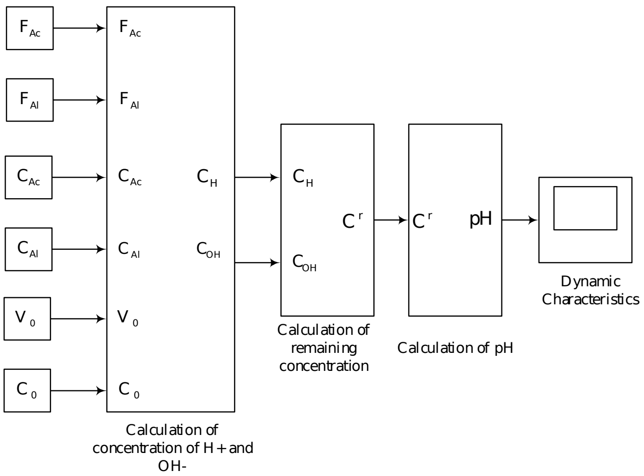

Fig. 2: Block diagram of pH model.

The concentration of the H^+ and OH^- are

$$C_H = C_o + 2F_{Ac}C_{Ac}t \tag{4}$$

$$C_{OH} = 2F_{Al}C_{Al}t \tag{5}$$

The amount of H^+ and OH^- used for the reaction in (1) is with the ratio of 1:1. Thus, depending on the amount of H^+ and OH^- in (4) and (5), the resultant remaining pH will be given in Table I. The resultant block diagram of pH model from the above modeling procedure is given in Fig. 2.

The titration curve with $C_{Ac} = C_{Al} = 0.5$, $F_{Ac} = 25ml$ and by varying F_{Al} is shown in Fig. 3. From the curve it can be seen that the behavior of neutralization process is highly nonlinear. The curve depends on the concentration of the acid and alkaline involved in the reaction process. Thus it shows that the process gain can vary significantly and this poses an important challenge for pH control applications. The S–shaped titration curve also shows that the most sensitive point on the curve is in the region where the pH value is 7. At this point, for a very small change of input a significant change in output should be expected.

C. Controller Design and Optimization

The controller design is in two phases, first the PID design using Ziegler–Nichols tuning method and second the optimization technique using the PSO algorithm.

These two phases are explained as follows:

1) Ziegler–Nichols Tuning Method: The transfer function of the PID controller is

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{6}$$

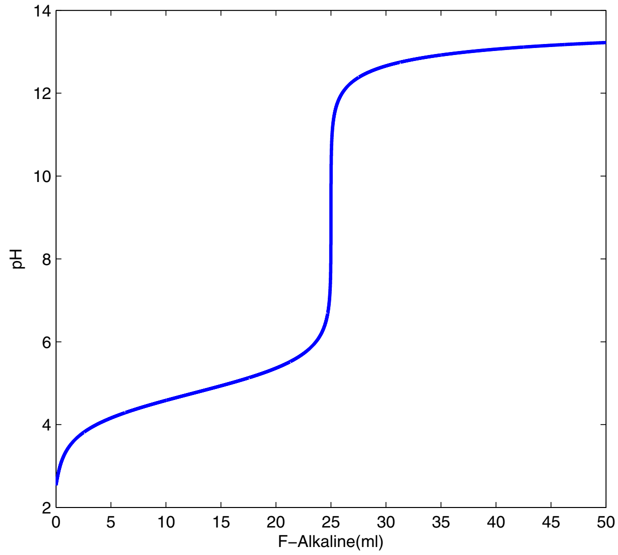

Fig. 3: Titration curve

TABLE II: ZIEGLER-NICHOLS FORMULA

Controller Type	K_p	K_i	K_d
P	$0.5K_u$	–	–
PI	$0.45K_u$	$1.2K_P/T_u$	–
PID	$0.6K_u$	$2K_p/T_u$	$K_pT_u/8$

The three tunable parameters of PID –proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) play important roles in achieving the desired control performance. The ZN tuning method is a heuristic tuning method for PID controller. It is performed by setting integral (K_i) and derivative (K_d) gains to zero. The proportional gain, (K_p) is increased from zero until it reaches the ultimate gain, (K_u) at which the output of the control loop system has stable and consistent oscillations. The ultimate gain (K_u) and the ultimate oscillation period (T_u) are used to set the controller gains. The formula for ZN is given in Table II [16].

2) The PSO Algorithm: The PSO algorithm is based on a swarm of particles. These particles are moved around in the search–space according to a few simple mathematical formula over the particles position and velocity. Each particles movement is determined by its local best known position and are guided towards the best known position in the search–space. When improved positions are being discovered these will then come to guide the movements of the swarm. The process is repeated until to get the adequate solution.

The movement of a swarm particle x_t at time t to that $t+1$ is facilitated by updating its velocity and position. The velocity v_t of the particle x_t at time t is updated using the formula

$$v_{t+1} = wv_t + c_1rand_1(x_t - p_{best}) + c_2rand_2(x_t - g_{best}) \tag{7}$$

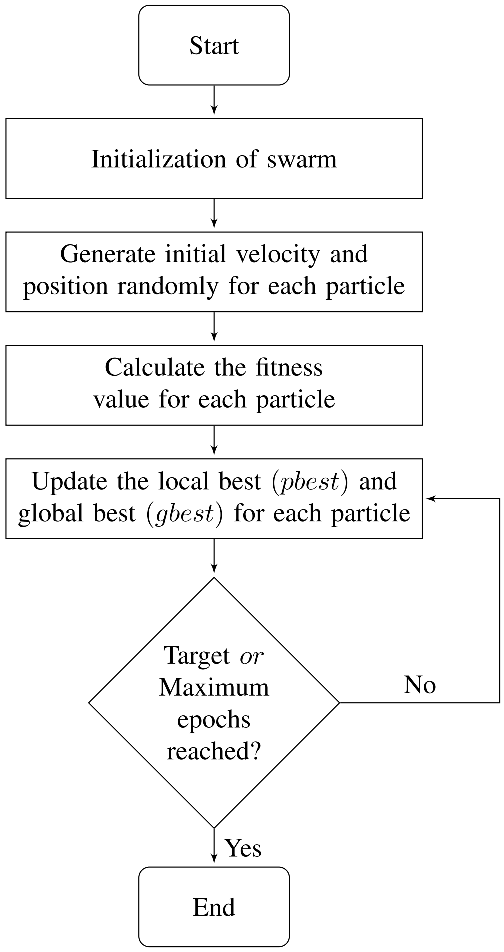

Fig. 4: Flowchart for implementation of PSO.

where,

- $rand_1$ and $rand_2$ are random numbers between 0 and 1.
- c_1 is cognitive coefficient and c_2 is social coefficient.
- p_{best} and g_{best} are particle best and global best respectively.
- w is inertia weight.

A swarm particle updates its position using updated velocity defined in Equation. 7. The formula used for this purpose is

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

The implementation of PSO algorithm is shown in Fig. 4 and the pH process model with PSO based PID controllers is shown in Fig. 5. As shown in the figure, the tuning of PID controller involves obtaining proper parameters K_p, K_i and K_d to ensure the system has better control performance, corresponding objective function is defined according to the required specifications. In this work, integral square error (ISE) is considered as an objective function. The control objective is to maintain the pH in its desired level i.e., 7.

$$J(\theta) = ISE = \int_0^t e^2(t)dt \tag{9}$$

where, $\theta = [K_p, K_i, K_d]$ are parameters to be optimized.

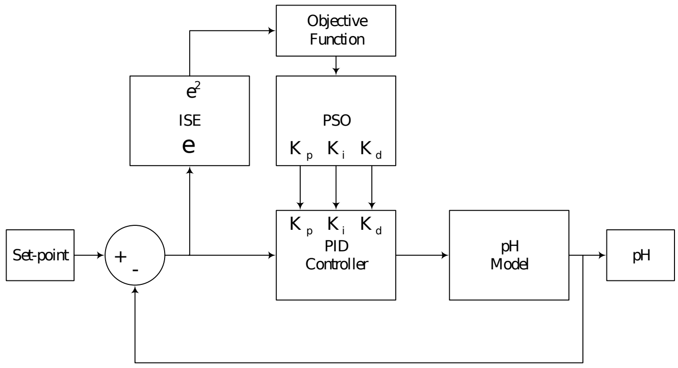

Fig. 5: Block diagram of pH model with PSO based PID.

TABLE III: MODEL'S PARAMETERS

Parameter	Value
Initial volume of the Tank (V_o)	$1L$
Concentration of Acid (C_{Ac})	$0.5Mol/L$
Concentration of Alkaline (C_{Al})	$0.5Mol/L$
Flow-rate of Acid (F_{Ac})	$0.025L/s$

Therefore, the optimum parameters of PID controller are obtained using PSO algorithm to search for the convergent minimum value of performance index ISE as shown in Equation. 9.

III. RESULTS & ANALYSIS

The model parameter values used for the simulations are mentioned in Table III. The tuned parameter of ultimate gain (K_u) and the ultimate oscillation period (T_u) by using ZN tuning method are 1 and $1.5s$ respectively. The PSO parameters used for the simulations are presented in Table IV. The PID parameters tuned with ZN and PSO are shown in Table V.

The regulatory response of the pH model with ZN based PID and PSO based PID is shown in Fig. 6. From the figure it is observed that ZN methods shows oscillations compared to PSO tuned PID. Analysis of the performance

TABLE IV: PSO PARAMETERS

Parameter	Value
Size of swarm (n)	10
Maximum number of bird steps	10
Dimension of the problem (d)	3
Cognitive coefficient c_1	1.49
Social coefficient c_1	1.49
Inertia weight (w)	0.9

TABLE V: PID PARAMETERS

Parameter	ZN Method	PSO method
K_p	0.6000	-0.5153
K_i	0.4800	-0.5687
K_d	0.1125	-0.1780

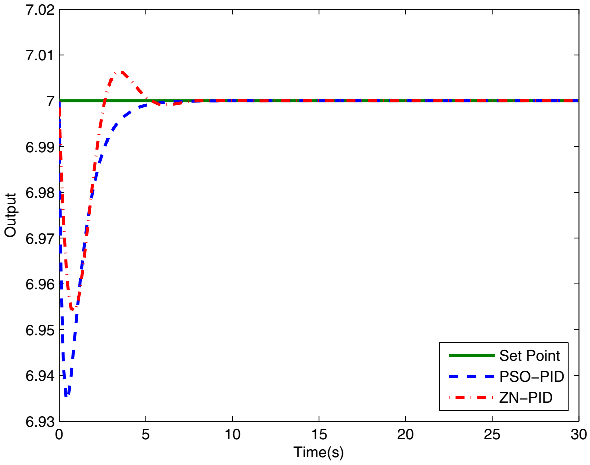

Fig. 6: Regulatory response of pH model with ZN and PSO based PID's.

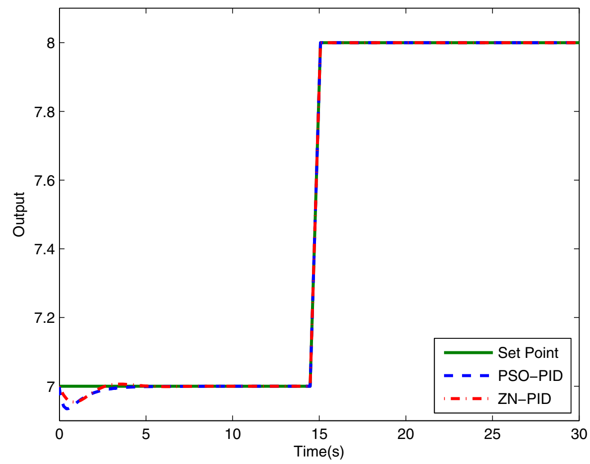

Fig. 7: Set-Point change at $t = 15s$ from pH $= 7$ to pH $= 8$.

of both controllers is presented in Table VI. The response of ZN–PID shows overshoot and larger settling time compared to PSO–PID. Even though it is faster with shorter response time (t_r). The PSO–PID provides null % overshoot and better settling time.

The robustness of the controller to change in set–point is evaluated over a set–point change at $t = 15s$ from pH $= 7$ to pH $= 8$ be shown in Fig. 7. The disturbance rejection capability of the controller is shown in Fig. 8. Here, the disturbance of 10% of set–point value is applied at two instances, at $t = 15s$ and $t = 35s$. It can be concluded that

TABLE VI: PERFORMANCE ANALYSIS

Controller	t_r	t_s	$\%M_p$
ZN–PID	2.6	11.5	0.086
PSO–PID	3.2	9.1	0

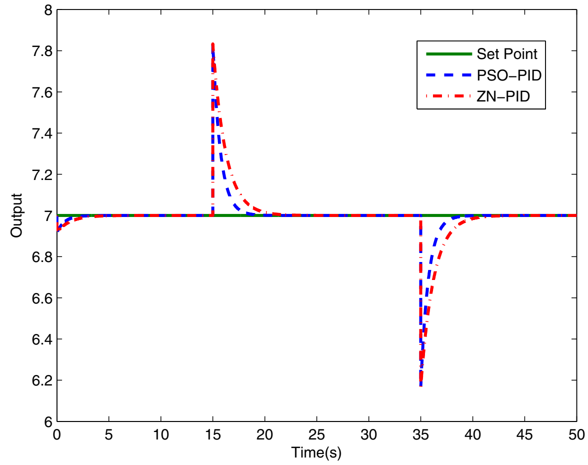

Fig. 8: Performance of the controller over a disturbance of 10% of set–point at $t = 15s$ and $t = 35s$.

PSO tuned PID is more robust to disturbance and set–point change compared to ZN tuned PID.

IV. CONCLUSION

The fundamental model of pH neutralization process plant is developed by taking into consideration of the overall plant's dynamics. The model is validated by using open loop test. The PID controller is then tuned by using ZN and PSO methods. The effectiveness of the controller is evaluated in terms of set–point tracking and disturbance rejection. The results shows that PSO tuned PID offers better performance compared to ZN tuned PID.

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