Design and Implementation of an Intelligent PI Controller for a Real Time Non Linear pH Neutralization Process

Dr.M.Kandasamy[1], Dr.S.Vijayachitra[2]
Associate Professor, Department of EIE, Erode Sengunthar Engineering College, Erode
kandasamy77@gmail.com
Professor, Department of EIE, Kongu Engineering Collge, Erode
svijayachitra@kongu.ac.in

ABSTRACT

In many chemical processes, pH is one of the most important parameter and control of the pH is highly non linear due to the complex nature of processes. PID controllers are widely used in process industries to control linear, non-linear and stable, unstable systems. Selection of the suitable controller tuning procedure is important to improve the performance of the PID controller and hence the process variable can be controlled in better manner. In this work, Firefly Algorithm (FA) based intelligent PI controller is attempted for a Non Linear pH control process in real time. The effectiveness of the FA controller is studied in the selected operating regions and the results are validated with Relay Feedback (RFB) method and Particle Swarm Optimization (PSO) method based controllers in the simulation environment. The simulation results indicated that the steady state performance and error performance indices of the FA controller are better than the RFB and PSO controller in the selected operating regions. The FA controller is also implemented in the real time laboratory pH control system, the results confirm that the servo response and regulatory response of the proposed intelligent controller provides better performance with the FA based PI Controllers.

Keywords: pH , PI Controller, Relay Feedback , Particle Swarm Optimization, Fire Fly Algorithm.

Introduction

Control of pH plays a very important role in many chemical processes such as wastewater treatment, biological reaction, fatty acid production plant, production of pharmaceuticals, fermentation, and food production etc. Design and control of a pH process is a highly tedious task and challenging, due to the slope of the process nonlinearity can be very steep around the neutralization region and small changes in the influent stream concentration can result in tremendous changes in pH [1]. In addition, performance of the practical process deviates from modeling output due to the sudden change in operating point, change in gain and disturbances in load conditions [2]. In pH process systems, the prime concern is small change in the composition specifications in the process could lead to great divergence in pH values which affect the stability of the system. This arouses the curiosity of researchers and engineers who investigated the development of empirical models and proposed various control techniques to be applied with industrial pH processes [3,4]. Especially in textile wastewater plants, it is complicated to control pH due to the presence of weak organics (acid or base), so the pH value of wastewater can influence the property of pollutants. The pH in the range of 4 to 11 for treatment of textile industrial wastewater is neutralized by using either H2SO4 or NaOH to adjust the pH of the solution [5].

Now a day's many of chemical process industries use PID controllers for linear, non linear, stable and unstable process. The key merits of the PID controllers over the advanced control techniques are as follows: (i) available in a variety of structures such as series, parallel, and so forth; (ii) provides an optimal and robust performance for a variety of processes; (iii) supports online/offline tuning and retuning based on the performance requirement of the process under control (iv) simple structure and which can be easily implementable in analog or digital form; (v) along with the basic and the modified structures, which also supports the one degree of freedom (1DOF), 2DOF, and 3DOF controller structures[6]. The performance of the PID controller is based on the controller parameters such as Kp,Ki and Kd. Tuning of the controller parameters for the pH system is highly difficult due to its complexity nature. Many research works have been attempted to find out the optimum values of controller parameters by various tuning methods includes Bacteria Foraging Optimization (BFO) algorithm [7,8], Genetic Algorithm (GA) [9,10] and Particle Swarm Optimization (PSO) [11,12] for the different close loop system problems.

PSO is a promising optimization technique which models the set of potential problem solutions as swarm of particles moving about in virtual search space. The method was inspired by movements of flocking birds/schooling fishes and their interaction with their neighbours in the group [13, 14]. Yang has developed Firefly Algorithm (FA) in 2007. This is a metaheuristic algorithm, inspired by the flashing behaviour of fireflies. The primary purpose of a firefly's flash is to act as a signal system to attract other fireflies to identify its mate as well as share the information of its pray [15].

More researches have been attempted on firefly algorithm to find out optimization solution for different engineering problems [16 - 18].

In this present work, PI based Firefly algorithm is proposed for nonlinear pH neutralization process. The predictable controller parameters are tested in simulated environment and real time process; Also, the results of FA based PI controller have been compared with Relay feedback method and PSO based PI controller.

The further part of the paper is organized as follows: Section 2 presents the overview of the real time pH neutralization system and mathematical modeling of the setup. The section 3 gives a description of Relay Feedback method, PSO and FA based optimization. The simulated & real time system result is discussed in the section 4 and followed by the conclusion of the present work in the section 5.

Real Time Experimental Setup

The laboratory type real time experimental setup of pH neutralization is shown in Figure 1. The system consists of pH Transmitter, Control Valve with Positioner, Electro Pneumatic Convertor, Process Tank, Solution Tanks, Stirrer, Solenoid Valve, Level Switch, Pressure Regulator, Pressure Gauge, Digital Panel Meter and a personal computer (PC). The pH transmitter is connected with the computer through USB module interface (VUDAS – 100). This module has 16 channel ADC port for inputs & 8 channel DAC port for outputs. Table 1 shows the specifications of the pH neutralization process system.

The solution tank-1 is filled with strong acid (Hydro Choleric Acid, HCL, 0.1N) and solution tank-2 is filled with strong base (Sodium Hydride NaOH, 0.1N). The control valve-1 (CV-1) is used to adjust the acid flow and the control valve-2 (CV-2) is used to adjust the base flow rate. Both the control valves are of equal percentage category and it is operating by pneumatic signal of (3-15) psi. The "Yokogawa" make pH sensor is used to measure the pH of the process tank and the measured value is converted by its transmitter into (4-20) mA. It is proportional to pH (0-14) of the solution. The pH transmitter is connected with the computer through USB module interface. The LabVIEW based PI Controller controls the process. According to the given set point and current value of the pH, the PI controller takes necessary control action on control valves for adjusting the flow rate of strong acid and strong base in accurate. This procedure brings the pH of the process tank according to the set point.

Figure 1 Real Time Experimental Setup of pH Neutralization Process

1 Mathematical Model of pH Process Tank

The process tank is filled with strong base as initial process and its pH is measured as 12.62. The solution tank -1 and solution tank - 2 are filled with strong acid (Hydro Choleric Acid, HCL, 0.1N) and strong base (Sodium Hydride NaOH, 0.1N) respectively. The control valve CV-2 which controls the flow rate of base is fixed at 50% open and remains constant for the entire process. The control valve CV-1 controls the flow rate of acid is positioned at 10% open by setting the DAC output and thereby new steady state is achieved in the process tank. The steady state of

the pH is noted against DAC value. This procedure is repeated for every 10% additional DAC value to the maximum of 100% (until 100% opening of CV-1) consecutively. The neutralization curve is plotted between percentage of DAC and corresponding steady state pH which is shown in Figure 2.

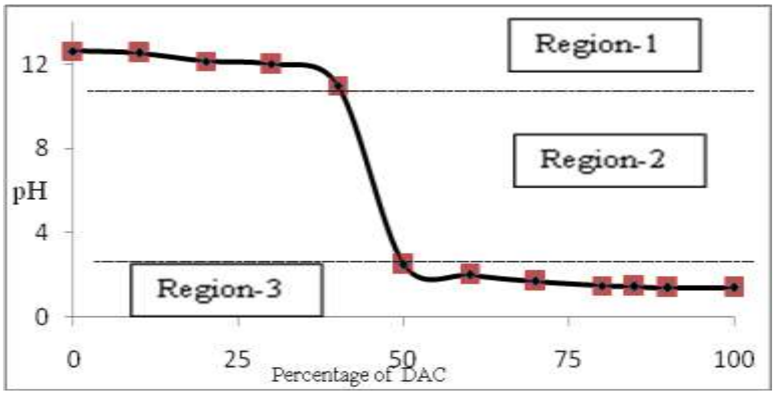

Figure 2 Process of pH Neutralization

Table 1 Specifications of Experimental Setup of pH Neutralization

Description of components	Specifications
pH Transmitter	Make : Yokogawa Range : (0 to 14)pH Output : (4 to 20)mA DC Accuracy : ± 0.5% of full scale
Control Valve with Positioner	Make : RK controls Type : Globe control valve Size : 3/4 "flanged Plug Chance : Equal % Valve action : Air to open
Electro Pneumatic Convertor	Make : Watson Smith Supply : 20 Psi constant pressure Input Signal : (4 to 20)mA Output : Pneumatic signal (3 to 15) psi.
Process Tank	Material : Acrylic Height : 300mm Diameter : 160 mm
Solution Tank (Acid, Base and Water)	Material : Acrylic Height : 300mm Diameter : 160 mm
Stirrer	Make : Pranshu Supply : 8VDC Torque : 1.5 kg /cm2
Solenoid Valve	Make : Compare Supply : 230V AC Range : (0-2) bar
Pressure Regulator	Make : PLACKA Instruments& Controls/ABB. Max. input : 18kg / cm2 Output : (0.2 -1) Kg / cm2
Pressure Gauge	Make : Waaree/manometer Body material: SS Size : 2.5"
Digital Panel Meter	Make : MECO/ Nippen Range : (0-200) mA Supply : 230V AC/50Hz

From the Figure 2, it is shown that the pH neutralization process is highly non-linear. The objective of the proposed work is to obtain the three different models at various operating regions as in the Figure 2. The pH neutralization process is represented in the form of First Order plus Time Delay (FOPTD) Model such as.

$$G(s) = \frac{K_p e^{-\theta s}}{\tau_p s + 1} \quad \dots (1)$$

The mathematical model is obtained at pH value of 12 for the region-1 by open loop transient response. Initially pH 12 is maintained by regulating the acid flow rate by control valve CV-1. Then a step change with a magnitude +10% DAC output is given to the control valve CV-1. The transient response is obtained by plotting graph of pH variation with respect to time. The process gain K_p and time constant τ_p are obtained by the process reaction curve [19, 20] from the transient response.

The similar procedure is repeated to obtain process gain K_p and time constant τ_p at the operating point's pH 7 and pH 2 for the region 2 and region 3 respectively. The process delay (θ) is approximately considered as 20 % of the time constant τ_p [20,21]

The obtained FOPTD model parameters are reported in the Table 2.

Table 2 FOPTD model parameter for three operating regions

pH Regions	Model parameters		
	Process Gain K_p (% / %)	Time Constant τ_p (Min.)	Process Delay θ (Min.)
Region – 1 (At pH: 12)	6.117	8.75	1.75
Region – 2 (At pH: 7)	3.686	7.50	1.50
Region – 3 (At pH: 2)	0.2137	9.50	1.90

4 Methods of PI Controller Tuning

There are various tuning processes are used to find out the PI controller parameters K_p and K_i to confirm the minimum time domain specifications. In this study, Relay Feedback, PSO and FA methods are used to find out the optimum controller parameter values.

4.1 Relay Feedback Method

Astrom and Hagglund (1984) suggested the relay feedback test to generate sustained oscillations as an alternative to the conventional continuous cycling technique. Since it is the closed loop test, the process will not drift away from the nominal points as well as it identifies process information around the important frequency to obtain the controller parameters [22].

4.2 Particle Swarm Optimization (PSO) Method

Particle Swarm Optimization (PSO) method, proposed by Kennedy and Eberhart (1995), is a most powerful computational algorithm technique based on swarm intelligence[13]. The method is based on the inspiration of social activities in flock of birds and school of fish. This optimization technique is applied in various engineering problems due to simple implementation procedure and high computational efficiency [23 ÷ 25]. Compared with other population-based stochastic optimization methods, such as GA and Ant Colony Algorithm (ACO), the PSO have superior search performance for many hard optimization problems, with faster and more stable convergence rates [26].

PSO consists of a swarm of particles. The swarm is initialized with arbitrary positions "Si" and their velocities "Vi". Initially each particle in the swarm resides at a position randomly throughout in the search space of dimension. The particles fly over the search space with a certain velocity. The quality of particle position determines the fitness of each particle in the swarm. The velocity (both direction and speed) of each particle is based on the supervision of the Objective Function (OF), own flying experience and their neighbors' flying experience. During the optimization search, each particle remembers its own best position found so far, which is denoted p_{best}. Also, it obtains the global best information that is found so far by its neighbors, which is denoted g_{best}. The updated velocity of each particle can be calculated using the present velocity and the distance from p_{best} and g_{best}.

The velocity update is expressed mathematically as

$$Vi(k+1) = W_iV_i^k + C_1 xR_1x (p_{best} - S_i^k) + C_2 xR_2x (g_{best} - S_i^k) \quad \ldots (2)$$

Where, $Vi^{(k+1)}$ = Updated velocity of particle i; Vi^k = Current velocity of particle i at iteration k; Wi = Different inertia weight of particle i; C_1, C_2 are cognitive and global learning rate; Si^k = Current position of particle i at inertia k; R_1, R_2 are random number between 0 and 1.

The updated position is modified based on the present position and updated swarm position. It is described by the equation (4)

$$S_i^{(k+1)} = S_i^k + V_i^{(k+1)} \quad \ldots \quad (3)$$

The parameter W_i is inertia weight that increases the overall performance of PSO. The larger value of W_i can favour higher ability for global search and lower value of W_i implies a higher ability for local search.

The PSO algorithm is simulated to obtain optimal PI controller parameters with the following values. Dimension of search space is two (i.e., K_p and K_i); C_1 and C_2 are set with 2.0 and 1.5 respectively. The inertia weight "*W*" is set as 0.9; Size of the swarm is 15.

4.3 Firefly Algorithm (FA) Method

A chemically produced light is generated by fireflies at their lower Abdomen. The induced light pattern is used to establish communication with neighbour firefly to share the information about its food and also for mate. The firefly algorithm use the following three idealized rules [27].

All the fireflies are unisex so that one firefly is attracted by other fireflies regardless of their sex.

The attractive signals of fireflies are proportional to its brightness of the light. Both attractiveness and brightness are reducing when the distance between the fireflies are increasing. Also, less bright firefly move towards another firefly which induces more luminance. In case, all fireflies have lesser luminance, they move randomly till identify the brighter firefly.

The brightness of a firefly is related with the analytical form of the objective function and it is assigned to guide the search process.

For a maximization problem, brightness of a firefly is considered as to be proportional to the value of cost function.

Fundamentals of the FA

The most important parameters which decide the efficiency of the FA are the variation of light intensity and attractiveness between neighbouring fireflies. Both the parameters are affected when the fireflies maintain more distance between each of them.

The equation (5) expresses the variation of brightness in the Gaussian form,

$$I(r) = I_0 e^{-\gamma r^2} \quad \ldots (4)$$

Where I = New light intensity, I_0 = Original light intensity, γ = light absorption coefficient and

r = Distance between fireflies.

Firefly's attractiveness is proportional to the light intensity of the nearby firefly. The attractiveness β of firefly can be given by

$$\beta = \beta_0 e^{-\gamma r^2} \quad \ldots. \quad (5)$$

Where, β = attractiveness coefficient, and β_0 = attractiveness at r = 0.

The equation (6) can be approximated into a simple exponential format to ensure easy analysis and faster calculations.

$$\beta = \frac{\beta_0}{1+\gamma r^2} \quad \ldots. \quad (6)$$

The equation (6) describe a characteristic distance Γ = 1/*γ* over which the attractiveness significantly changes from β0 to $\beta_0 e^{-1}$. The attractiveness function *β(r)* can be any monotonically decreasing functions and it is given by

$$\beta(d) = \beta_0 e^{-\gamma r^m} \quad \text{Where } m \geq 1 \quad \ldots (7)$$

For a fixed γ, the characteristic length becomes

$$\Gamma = \gamma^{-1/m} \rightarrow 1,\ m \rightarrow \infty$$

Conversely, for a particular length scale Γ, in an optimization problem, the parameter γ can be used as a typical initial value. This value is

$$\gamma = 1/\Gamma\, m \quad \ldots (8)$$

The Cartesian distance between two fireflies *i* and *j* at x_i and x_j, in the *n* dimensional search space can be mathematically expresses as

$$r_{i,j} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{n}(x_{i,k} - x_{j,k})^2} \quad \ldots\ldots\ldots\ldots..(9)$$

The movement of firefly i is attracted by another brighter firefly j is given by

$$x_{i\,new} = x_i + \beta_0 e^{-\gamma r_{i,j}^2}(x_j - x_i) + \psi \quad \ldots (10)$$

Where, x_{inew} is updated (present) position of firefly, x_i is initial position of firefly and $\beta_0 e^{-\gamma r_{i,j}^2}(x_j - x_i)$ is attraction between fireflies

Also the parameter $\psi = \alpha \notin_i$. Where, $\notin_i$ is vector of random number which is drawn from a Gaussian distribution and α is randomization parameter. The equation 10 implies that the updated position of the i^{th} firefly depends on initial position of the firefly.

In this study, the firefly algorithm is assigned with the following values to obtain controller parameters. Number of fireflies (n) = 10, $\beta_0 = 1$, $\gamma = 6$ $\alpha_0 = 0.5$ (gradually reduced to 0.1 in steps of 0.001 as iterations proceed) and the total number of run is chosen as 1,000

In this work, PSO and FA algorithms are implemented to obtain the optimized PI controller parameters such as K_p and K_i for the neutralization process using Multi Objective Performance Index (MOPI). This index determines the efficiency of the search algorithms. The Integral Absolute Error (IAE), Integral Square Error (ISE), Peak Overshoot (M_p), Settling Time (t_s) and Rise time (t_r) are considered as MOPI parameters to find out optimum controller values. The MOPI is for this study is

$$J_{min}(K_p, K_i) = (w_1.ISE) + (w_2.IAE) + (w_3.M_p) + (w_4.t_s) + (w_5.t_r) \ldots.(11)$$

Where, dimension of the search is Two (K_p and K_i); The weighting function values are assigned as

$w_1 = w_2 = w_3 = 10$; $w_4 = w_5 = 6$.

5 Results and Discussion

Relay Feedback method, PSO and FA methods are used to find out the optimum values of PI Controller parameters for the pH process. The obtained controller parameters Proportional gain (K_p) and Integral gain (K_i) values are reported in the Table 3. The Servo response and Regulatory response tests are also carried out to identify the best method for the pH process. Performance study is carried out to indicate effectiveness of the FA based PI controller

5.1 Servo Response

The controller with faster set point tracking is always preferred in process industries. The servo response test is carried out to observe the effectiveness of set point tracking of the controllers. The FA based controller values are applied in the simulation mode to study the performance of the pH control process in three different regions. The simulation is also carried out for RFB and PSO based controller and the results are then compared. The Figure 3 shows the servo response of the PI controllers for the operating region-1. The consolidated performance indices Table 4 provides the performance of the different controllers in the all three regions. From the table 4 it is indicated that FA based PI controller provides better set point tracking compared with the RFB method and PSO method. The performance indices such as Integral Absolute Error (IAE), Integral Square Error (ISE), Integral Time Absolute Error (ITAE) and Integral Time Square Error (ITSE) are comparatively low in FA based PI controller than the RFB and PSO based controller.

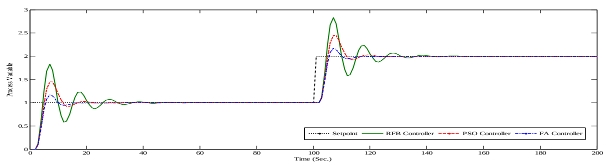

Figure 3. Servo response of PI controller at operating region -1

5.2 Regulatory Response

In chemical industries pH values are varied frequently due to various parameter changes and nature of processes. Regulatory tests are carried out in all operating regions to identify the best controller which can able to control the pH process under load disturbance condition. Figure 4 shows the regulatory response of the controllers at the operating region 1. Simultaneously all the three controllers are applied with a step disturbance. From the result it is indicated that FA based PI controller eliminates the effect of disturbance much faster than RFB and PSO controllers. Table 4 depicts that the FA controller provides good performance indices than the RFB and PSO based controllers in all regions.

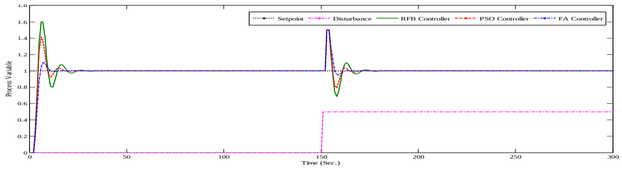

Figure 4 Regulatory response of PI controller at operating region –1

6 Real Time Analysis

The performance of PSO and FA based PI Controller is validated in real time environment on Non-linear pH neutralization process system for all the operating regions.

The operational point of pH 11, pH 7 and pH 2.5 are selected from the region 1, region 2 and region 3 respectively to conduct the real time servo response tests. Figure 5 depicts the servo reference of set point tracking of +10 % at the operating point of pH 11 belongs to region 1 for the PSO and FA based controllers. The test result indicated that the FA controller reached the set point within the minimum settling time when compared with the PSO Controller. The servo test results in the other two regions indicated that FA controller has better performance than the PSO controller.

The performances of the controllers are also tested in the load disturbance conditions by applying buffer water to the pH process tank. The flow rate with 1 lpm of water is fed to the process tank to make the process into disturbed. Similar to the servo response, the regulatory test is also conducted in all regions at the operating of pH 12, pH 10 and pH 2.5. Figure 6 indicates the performance of the PSO controller and FA controller against the step disturbance of buffer water at operating point of pH 12. The test result depicts that the FA controller has less oscillatory performance and quickly settled at the set point than the PSO based controller. Table 5 shows the performance Indices of the PSO and FA controller for the real time servo response and regulatory response. Table 5 depicts that error performance indices of the servo response and regulatory response for the FA controller is comparatively better than PSO controller in all regions.

Table 3 PI Controllers Parameters at different operating regions

Operating Regions	Relay Feed		PSO		FA	
	K_p	K_i	K_p	K_i	K_p	K_i
Region - 1	0.6069	0.1839	0.5069	0.1092	0.5021	0.0498
Region - 2	1.1014	0.3442	1.1435	0.2289	0.8585	0.1154
Region- 3	18.7241	5.2011	16.2542	3.0847	14.2547	1.5874

Table 4 Performance Indices of different PI controller tuning for Servo response and Regulatory response

Operating Region	Servo Response								Regulatory Response			
	Tuning Method	% of M_p	t_r (Sec.)	t_s (Sec.)	IAE	ISE	ITAE	ITSE	IAE	ISE	ITAE	ITSE
Region-1	RFB	41.45	4.6	33.0	17.52	9.962	1033.0	545.9	14.6	6.845	886.6	244.7
	PSO	22.4	5.5	19.0	10.36	6.529	564.4	342.8	8.153	4.25	451.4	140.3
	FA	8.55	5.6	17.5	7.812	5.473	417.8	282.2	6.043	3.505	327.3	112.1
Region-2	RFB	29.95	4.4	21.5	11.11	6.636	613.7	351.0	8.334	4.147	464.4	137.7
	PSO	20.75	4.45	15.0	8.173	5.234	437.5	271.5	6.13	3.271	331.2	105.3
	FA	5.2	5.7	12.5	6.541	4.94	341.4	253.7	4.906	3.088	198.5	97.76
Region-3	RFB	38.8	4.8	37	17.84	10.23	1052	561.4	13.38	6.397	797.6	225.4
	PSO	22.15	5.5	20.5	10.9	6.931	596	364.6	8.177	4.332	452.2	142.9
	FA	7.3	6.4	15.0	8.158	5.784	445.8	316.6	6.297	3.825	338.3	118.0

Table 5 Performance Indices of PI controllers for Servo and Regulatory response.

Operating Region	Tuning Method	Servo Response		Regulatory Response	
		IAE	ISE	IAE	ISE
Region-1	PSO	247.35	149.19	78.10	17.55
	FA	150.79	82.52	46.04	6.50
Region-2	PSO	185.52	71.42	62.47	12.25
	FA	98.06	32.86	44.27	8.14
Region-3	PSO	53.09	7.45	87.30	27.00
	FA	33.14	2.99	46.01	8.04

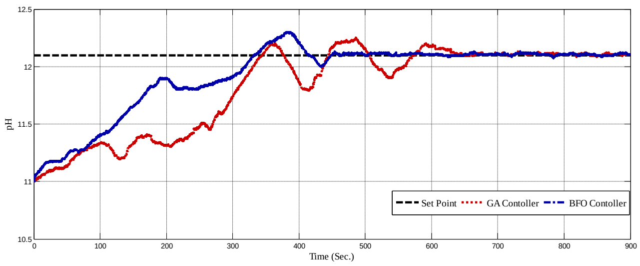

Figure 5 Servo response for set point tracking of +10 % at the operating point of pH 11

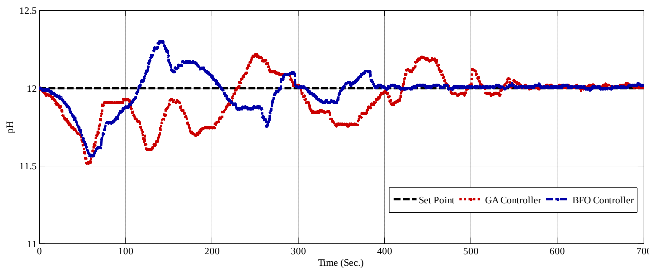

Figure 6 Regulatory response at the operating point of pH 12.

Conclusion

A Firefly algorithm based PI controller is designed for a non linear pH process. The performance of the controller is tested in the simulation environment against Relay Feedback controller and Particle Swarm Optimization controller. The test result indicated the effectiveness of the Firefly algorithm based control technique in the non linear system. Also the Firefly algorithm controller and Particle Swarm Optimization controller are tested in real time using the laboratory type pH control trainer. The Servo response and Regulatory response tests are carried out to study the performance of the controllers. Both the simulation and real time process tests proved that the response is better for Firefly algorithm controller compared to Particle Swarm Optimization controller. The result is also validated by IAE and ISE values. It is concluded that for a nonlinear pH control system the Firefly algorithm based PI controller outperforms well when compared to Relay Feedback and Particle Swarm Optimization based PI control.

REFERENCES

[1] Rodriguez, J. L., Loparo, K. A., Modeling and identification of the pH processes. In Proceedings of the American Control Conference, 6 (2004), pp. 5483-5488.

[2] A.D. Kalafatis, L.Wang and W.R. Cluett, Identification of time-varying pH processes using sinusoidal signals, Automatica, 41(4) (2005) , pp. 685-691.

[3] Shebel A. AlSabbah, Mohammad A. Al-Khedher, Mohammad K. Abu Zalata & Tariq M. Younes, Evaluation of Multiregional Fuzzy Cascade Control for pH Neutralization Process, International Journal of Research and Reviews in Applied Sciences, 10 (2), 2012.

[4] Luyben W.L., Process Modeling, Simulation and Control for Chemical Engineers, McGraw-Hill, Ohio, 1989.

[5] Norazzizi Nordin, Siti Fathrita Mohd Amir, Riyanto and Mohamed Rozali Othman, Textile Industries Wastewater Treatment by Electrochemical Oxidation Technique Using Metal Plate, International Journal of Electrochemical Science, 8 (2013) , pp. 11403 – 11415.

[6] Rajinikanth V. and K. Latha, Controller Parameter Optimization for Nonlinear Systems Using Enhanced Bacteria Foraging Algorithm, Applied Computational Intelligence and Soft Computing, (2012) doi:10.1155/2012/214264.

[7] Jain T. and M. J. Nigam, Optimization of PD-PI controller using swarm intelligence, International Journal of Computational Cognition, 6 (4) (2008) , pp. 55–59.
[8] Ali A. and S. Majhi, Design of optimum PID controller by bacterial foraging strategy, Proceedings of the IEEE International Conference on Industrial Technology, (2006) , pp. 601– 605.
[9] Kim D. H., Hybrid GA-BF based intelligent PID controller tuning for AVR system, Applied Soft Computing Journal, 11(1) (2011),pp. 11–22.
[10] Kim D. H., A. Abraham, and J. H. Cho, A hybrid genetic algorithm and bacterial foraging approach for global optimization, Information Sciences, 177 (18) (2007) , pp. 3918–3937.
[11] Biswas, A., S. Dasgupta, S. Das, and A. Abraham, Synergy of PSO and bacterial foraging optimization - a comparative study on numerical benchmarks, Advances in Soft Computing, 44 (2007) , pp. 255–263.
[12] Korani, W. M., H. T. Dorrah, and H. M. Emara, Bacterial foraging oriented by particle swarm optimization strategy for PID Tuning, Proceedings of the 8th IEEE International Conference on Computational Intelligence in Robotics and Automation, Korea, (2009) pp. 445–450.
[13] Kennedy, J and R.C. Eberhart, Particle swarm optimization, In Proceedings of IEEE international conference on neural networks, (1995) , pp. 1942-1948.
[14] Jim Pugh, Alcherio Martinoli, and Yizhen Zhang, Particle Swarm Optimization for Unsupervised Robotic Learning, Proceedings of IEEE swarm intelligence symposium (SIS), (2005), pp. 92-99
[15] Yang X. S., Nature-Inspired Metaheuristic Algorithms, Luniver Press, UK, 2008.
[16] Amir Hossein Gandomia, Xin-She Yang, Amir Hossein Alavi, Mixed variable structural optimization using Firefly Algorithm, Computers & Structures, 89 (2011) , pp. 2325–2336.
[17] Senthilnath J., S.N. Omkar, V. Mani, Clustering using firefly algorithm: Performance study, Swarm and Evolutionary Computation, 1 (3), (2011) , pp. 164–171.
[18] Raja N.S.M., Manic, K.S. and Rajinikanth,V., Firefly Algorithm with Various Randomization Parameters: An Analysis, In B.K. Panigrahi et al. (Eds.): SEMCCO 2013, Part.1, Lecture notes in computer science (LNCS 8297), (2013) , pp. 110–121.
[19] Gopal M, Control Systems Principles and Design, 2nd Edition, TATA McGraw Hill, New Delhi, (2002)
[20] Meenakshipriya, B., Saravanan, K., Krishnamurthy, K. and Bhaba, P. K., Design and implementation of CDM-PI control strategy in a pH neutralization system, Asian Journal of Scientific Research, 5 (3) (2012) , pp. 72-92.
[21] Swati, D, V.S.R. Rao, R.Pickhardi and M.Chidambaram, Non-Linear PI controller for time delayed pH System, Indian Chem. Eng., 50 (2) (2008) , pp. 93-105
[22] Astrom, K.J. and Hagglund. T, Automatic tuning of simple regulators with specifications on phase and gain margins, Automatica, 20 (5) (1984) , pp. 645-651.
[23] Banu U. S. and G. Uma, Fuzzy gain scheduled continuous stirred tank reactor with particle swarm optimization based PID control minimizing integral square error, Instrumentation Science and Technology, 36 (4) (2008) , pp. 394-409.
[24] Arumugam M. S. and M. V. C. Rao, On the performance of the particle swarm optimization algorithm with various inertia weight variants for computing optimal control of a class of hybrid systems, Discrete Dynamics in Nature and Society, (2006) Article ID 79295.
[25] Rajinikanth V. and K. Latha, Set point weighted PID controller tuning for unstable system using heuristic algorithm, Archives of Control Science, 22(4) (2012) , pp. 481-505.
[26] Latha, K., V. Rajinikanth, and P. M. Surekha, PSO-based PID controller design for a class of stable and unstable systems, ISRN Artificial Intelligence, (2013) vol. 2013, Article ID 543607.
[27] Pal S.K., C.S. Rai, A.P. Singh, Comparative Study of Firefly Algorithm and Particle Swarm Optimization for Noisy Non-Linear Optimization Problems, International Journal Intelligent Systems and Applications, (2012) , pp.50-57.

Author' biography

M.Kandasamy is working as a Associate Professor in the department of Electronics & Instrumentation Engineering in Erode Sengunthar Engineering Colleg, Erode, India. The author has completed his Ph.D in Anna University, Chennai. His field of interest is Optimization techniques, PID controller tuning. He has published many research articles in various international journals.

Dr.S.Vijayachitra is working as a professor in the department of Electronics & Instrumentation Engineering in Kongu Engineering College, Perundurai, Erode India. The author's area of specialization is Transducer Engineering, Process Modeling and Optimization, Soft Computing and Industrial Instrumentation. She has published 31 research papers in national journals and 63 research papers in international journals. She also published 6 number of books in the field of Electronics, Communication and instrumentation Engineering.