Original Article

Fractional Order Predictive Proportional Integral Control of pH in Effluents of Industrial Plants

J. Susai Mary, P. R. Hemavathy, S. Kiran

Department of Electronics and Instrumentation Engineering, BS Abdur Rahman Crescent Institute of Science and Technology, Chennai, Tamil Nadu, India

Abstract

Aim: A robust and advanced controller for pH monitoring and control is necessary in industrial processes inorder to treat the effluents to protect the flora and fauna in the environment. Advanced controllers such as fractional controllers could be used for effective control with increased accuracy and reliability. **Materials and Methods:** This study includes a comparison of conventional controllers with advanced fractional order controllers to improve the performance of pH control in effluents from the industrial plants. **Results:** A fractional order predictive proportional integral (FOPPI) controller for effective control of pH was designed and simulated. This controller includes the advantages of a smith predictor for dead time compensation and the robustness of a fractional order controller. The presented method shows an improvement in control performance in terms of rise time (32 s), settling time (140 s), lesser oscillations (2%), and lesser integral of the absolute error of 171. **Conclusion:** FOPPI provides efficient control of pH in all regions of the titration curve and can be used for the control of pH in industrial waste water.

Keywords: Fractional filter, fractional order predictive proportional integral, industrial effluents, internal model control, pH control

INTRODUCTION

pH control finds applications in various industries such as waste water treatment plants, biotechnology, food processing, pharma, and also in all chemical processing plants.[1] Mainly in industrial plants, the pH of waste water that is let out from the plant should have a pH of 6–8. The treated water is often reused for other purposes such as watering of plants, flushing of toilets, etc.[2] The pH neutralization process is highly nonlinear and this characteristic makes the control of pH a hard task.[3] However, there is a deliberate need to maintain the pH value at a required level to comply with the environmental and quality standards.

Many control strategies have been proposed by researchers for the control of pH in various applications. Before the advent of advanced controllers, proportional integral derivative (PID) controllers have been for the control of various processes. It is a combination of proportional (P), integral (I), and derivative (D) modes. The *P* controller improves the speed of response and also improves the stability. The integral mode helps to the elimination of offset and the derivative mode reduces the peak error and provides quick recovery.[4] These controllers act similar to a human expert system. The use of conventional PI and PID controllers becomes a question of trust when used for nonlinear process, systems with uncertainty, large dead times, and high frequency noise.[5-7] Hence, enhanced PID controllers and advanced controllers are used for the control of pH and are the need of the hour. pH control in a fed batch neutralization process through model-based PI controller was simulated and compared with conventional PI controller. The results show that model-based PI gives superior performance.[8]

Enhanced PID controllers such as fractional-order PI, predictive PI (PPI), and nonlinear PI have been used in various research papers to control processes with nonlinearity and long dead times.[8-12] A study to improve the pH process performance using

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Address for correspondence: Dr. J. Susai Mary,
Department of Electronics and Instrumentation Engineering, BS Abdur
Rahman Crescent Institute of Science and Technology, Chennai - 600 048,
Tamil Nadu, India.
E-mail: susaimary.eie@crescent.education

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conventional PI and fractional order PID control shows that fractional PID has better control effort and dynamic response.[13] A fractional filter internal model control (IMC) PID controller designed for a second order process to improve the performance and robustness for set point and disturbance rejection was discussed in.[14] A set point-weighted fractional PID for a pH process to obtain set point and load regulation was proposed and optimal controller parameters were obtained using accelerated particle swarm optimization. The proposed approach gives better performance than PID and Fractional PID.[11]

Adaptive algorithms such as model reference adaptive control and self-tuning regulators find wide application in pH control. These controllers have the ability to control the pH of the process in all the regions of the pH curve. A nonlinear model predictive controller (NMPC) based on selforganizing migrating algorithm has been proposed and compared with adaptive PID controllers. The results prove that the NMPC outperforms the adaptive PID.[15] However, these controllers are complex to design, need an accurate reference model of the plant which will correlate well with the actual process to be controlled.[16,17]

This paper presents a control scheme for pH control of effluents in industrial process plants. The control of pH is difficult, especially in the neutral region where the pH is 7. If the pH is above or below the desired value, it will affect the plants and animals and also will create adverse effects on the human beings. Hence, there is a need for a robust and reliable control scheme for control of pH in all the regions of the titration curve. A fractional order PPI (FOPPI) controller proposed by Devan *et al*.[9] is used in this study. This type of control has not been attempted for pH control of industrial effluents and the results prove that the FOPPI performs well in all the region of the pH curve, specifically the second region with lesser rise time of 34 s, settling time of 140 s, peak overshoot of 2%, and reduced integral of the absolute error (IAE) of 171 compared to other controllers. A comparison of the proposed method with conventional PI, IMC PI, and IMC PI with fractional filter has been done to prove the effectiveness of the method.

MATERIALS AND METHODS

The schematic of the plant under consideration to represent an industrial set up for the control of pH is shown in Figure 1. It consists of a process tank in which a constant flow of hydrochloric acid (HCl) is neutralized with a manipulated flow rate of sodium hydroxide (NaOH) continuously to maintain the desired pH.

The model equations governing the pH process plant are as follows:[10]

The electro-neutrality equation of the acid and base is (Eq. 1)

$$\left[N_a^+\right]+\left[H^+\right]=\left[Cl^-\right]+\left[OH^-\right] \tag{1}$$

And $[H^+]\,[OH^-] = K_w$, where $K_w = 10^{-14}$ is the water dissociation constant.

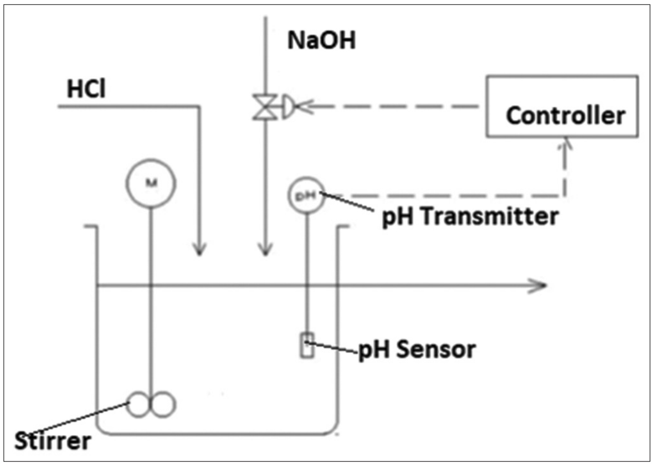

Figure 1: Schematic of the pH industrial process plant. HCl: Hydrochloric acid, NaOH: Sodium hydroxide

The process output for pH is expressed as (Eq. 2)

$$pH = -\log_{10}\left[H^+\right] \tag{2}$$

And the state equations are defined by (Eqs. 3 and 4)

$$\dot{X}_a = \left[\frac{F_a * C_a - \left(F_a + F_b\right) * X_a}{V}\right] \tag{3}$$

$$\dot{X}_b = \left[\frac{F_b * C_b - \left(F_a + F_b\right) * X_b}{V}\right] \tag{4}$$

Where X_a and X_b are the acid and base flow rates. $V = 5l$ s the volume of the process tank, $C_a = 0.1N$ and $Cb = 0.2N$ are the concentration of HCl and NaOH solutions. The other equations of the process plant include, (Eqs. 5-7)

$$X_b + 10^{-y} = X_a + K_w / 10^{-y} \tag{5}$$

$$X_b + 10^{-y} = X_a + 10^{-14} / 10^{-y} \tag{6}$$

$$X_b + 10^{-y} = X_a + \frac{10^{(y-14)}}{10^{-y}} \tag{7}$$

On rearranging equations 5–7, we get (Eq. 8)

$$H(X,Y) = X_a - KX_b + 10^{-y} - 10^{y-14} = 0 \tag{8}$$

The mathematical equalities of the pH process are simulated by MATLAB (Version: R2020b) Simulink. The open loop input and output characteristics are obtained by varying the base flow rate in steps of 10%, as shown in Figure 2.

From the I/O characteristics, in order to determine the transfer function and for controller design the process output is divided into three linear regions: Region 1 (0<pH<1.6), Region 2 (1.6<pH<12.26) and Region 3 (12.26<pH<14). Each region is approximated to represent a first order plus dead time (FOPDT) process (Eqs. 9-11)

$$T.F\left(R1\right) = \frac{K_p}{\tau_p s + 1}e^{-\theta s} = \frac{2.593}{3.2s + 1}e^{-0.5s} \tag{9}$$

$$T.F\left(R2\right) = \frac{K_p}{\tau_p s + 1}e^{-\theta s} = \frac{53.035}{1.5s + 1}e^{-0.5s} \tag{10}$$

$$\mathrm{T.F}\left(\mathrm{R3}\right)=\frac{\mathrm{K_p}}{\tau_{\mathrm{p}}\mathrm{s}+1}\mathrm{e}^{-\theta s}=\frac{1.4}{2\mathrm{s}+1}\mathrm{e}^{-0.5s} \qquad (11)$$

In many industrial process plants, PI and PID controllers are used commonly due to its simple design, easy tuning and operational advantages.[11] The controllers used in this study are discussed in the following sections.

Proportional integral controller

In general, the control equation of a PI controller is given as (Eq. 12)

$$\mathrm{U}=\mathrm{K}_c\left[\mathrm{e}+\frac{1}{\mathrm{T_i}}\int \mathrm{edt}\right] \qquad (12)$$

Where K_c is the proportional gain, T_i is the Integral time and e is the error.

For a first order transfer function with dead time, the controller settings are defined by Cohen and Coon.[18] The Cohen Coon method is an offline method used for tuning and evaluation of the initial control parameters (Eqs. 13 and 14).

$$\mathrm{K}_c=\frac{0.9}{\mathrm{K_p}}\left(\frac{\tau}{\mathrm{t_d}}+0.092\right) \qquad (13)$$

And

$$\mathrm{T_i}=3.33\mathrm{t_d}\left(\frac{\tau+0.092\mathrm{t_d}}{\tau+2.22\mathrm{t_d}}\right) \qquad (14)$$

IMC based proportional integral controller

The IMC proposed by Rivera *et al*.[19] is the widely used PID tuning method for a nonlinear process approximated as a first order system with dead time owing to its simplicity and robustness. IMC is a model-based controller, and hence, it accounts for disturbance rejection and changes due to model uncertainties.

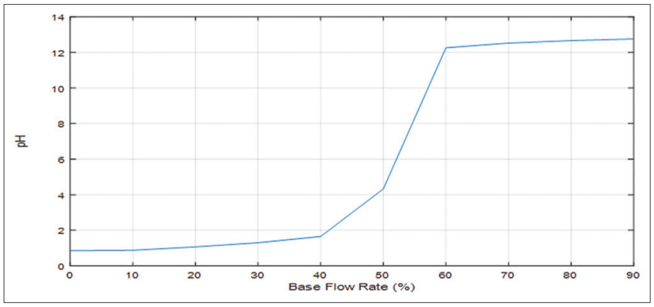

Figure 2: Open loop I/O characteristics

The controller settings for a IMC based PI controller are given in Eqs. (15 and 16)

$$\mathrm{K}_c=\frac{\tau_{\mathrm{p}}+0.5\theta}{\mathrm{K_p}\left(\lambda+0.5\theta\right)} \qquad (15)$$

$$\mathrm{T_i}=\tau_{\mathrm{p}}+0.5\theta \qquad (16)$$

Where $\mathrm{K_c}$ is the Proportional gain and T*i* is the Integral time. It is also recommended that the filter factor $(\lambda) > 0.80$, because of the model uncertainty due to pade approximation.

Fractional filter-based internal model control

To overcome the model uncertainties and accommodate the changes due to the dynamic behaviour of the plant, a controller that ensures the performance and stability for all plant realizations should be designed. This leads to the design of a fractional filter for an IMC based PI controller. The structure for fractional filter is formulated as a Oustaloup's approximation (Eq. 17).[20]

$$F\left(s\right)=\frac{1}{S^{\gamma}} \qquad (17)$$

Where γ is the integer order of the filter and the other controller settings are the same as IMC controller.[21]

Fractional order predictive proportional integral controller

The FOPPI controller with set point and noise filtering as proposed by Devan *et al*.[9] is given in Eq. 18,

$$\mathrm{U}\left(\mathrm{s}\right)=\mathrm{K}_c\left(1+\frac{1}{\mathrm{T_i}\mathrm{s}^{\lambda}}\right)\mathrm{E}\left(\mathrm{s}\right)-\frac{1}{\mathrm{T_i}\mathrm{s}^{\lambda}}\left(1-\mathrm{e}^{-\mathrm{s}\theta}\right)\mathrm{U}\left(\mathrm{s}\right) \qquad (18)$$

Where λ, the order of integration and takes the value between 0 and 1. A set point and noise filter are also added to improve the control performance. The filter structure is $\mathrm{F}\left(\mathrm{s}\right)=\mathrm{F}\left(\mathrm{N}\right)=\frac{1}{1+s\mathrm{T_f}}$, where $\mathrm{T_f}=\frac{\mathrm{K}}{\theta}$.

The control structure for a FOPPI is shown in Figure 3.

Adaptive fractional order predictive proportional integral with fuzzy gain scheduling

The controllers discussed so far are not capable of controlling the process in the entire range due to its changing parameters. Hence, there is a need for frequent online returning which

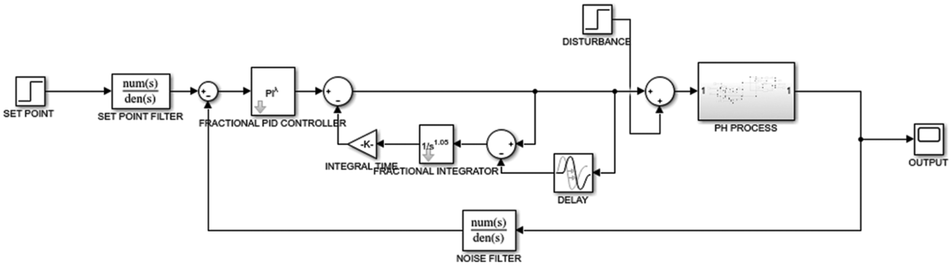

Figure 3: FOPPI structure for a pH process. FOPPI: Fractional order predictive proportional integral

requires controllers with adaptive online based parameter estimation. This can be achieved through knowledge-based systems such as fuzzy control along with some knowledge on the states of the system.[10] A fuzzy gain scheduling algorithm is developed for this purpose. A sugeno type fuzzy inference system with constant membership functions serves to solve the problem of changing controller parameters. This algorithm helps in scheduling the controller parameters based on the output of the pH process, as shown in Figure 4.

Ethical clearance

No human, animal or other things under human subjects are used in this study. The study focusses on the fundamental physics and applications in pH measurement.

RESULTS

The results of the control algorithms such as PI, IMC-based PI, Fractional Filter with IMC PI, and FOPPI on an industrial pH process (for all regions) are presented. A comparison is done based on the performance of the time domain characteristics such as rise time (T_r) which is time taken to reach from 0% to 100% of the final value for the first time, settling time (T_s) is the time taken for the output to reach steady state value, peak overshoot ($\%M_p$) which is the deviation of the response from the output at the peak time and Integral of Absolute error.

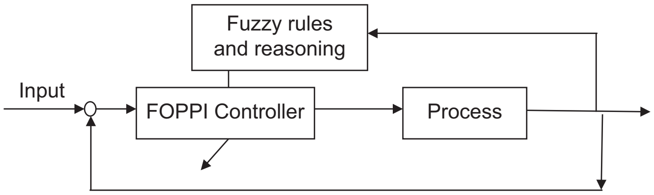

Figure 4: FOPPI control with fuzzy gain scheduler. FOPPI: Fractional order predictive proportional integral

IAE is defined as (Eq. 19)

$$\mathrm{IAE} = \int_0^\infty \left|e(t)\right| dt \tag{19}$$

The graphical comparison of outputs of all the three regions of the pH control is shown in Figure 5a-c and the adaptive FOPPI with both set point and disturbance rejection is shown in Figure 6. The controller settings and the time domain performance for the various regions are listed in Table 1.

DISCUSSION

Matausek and Sekara, Bharathi *et al.*[6,8] have proposed control schemes such as IMC for effective control of pH. Renganayakalu *et al.*[15] have proved that an IMC-based controller with Fractional filter gives best results for second order process with dead time. The only drawback of this controller is that it has a larger rise time compared to PI controllers. The previous study done by Devan *et al.*[9] in which they have proposed the FOPPI controller and proved that the controller performs well for a FOPDT process with reduced rise time, settling time, and peak overshoot. Hence, the feasibility of FOPPI controller for pH control of industrial effluents was considered for this study and the output was compared with other controllers which are currently applied to pH control.[8]

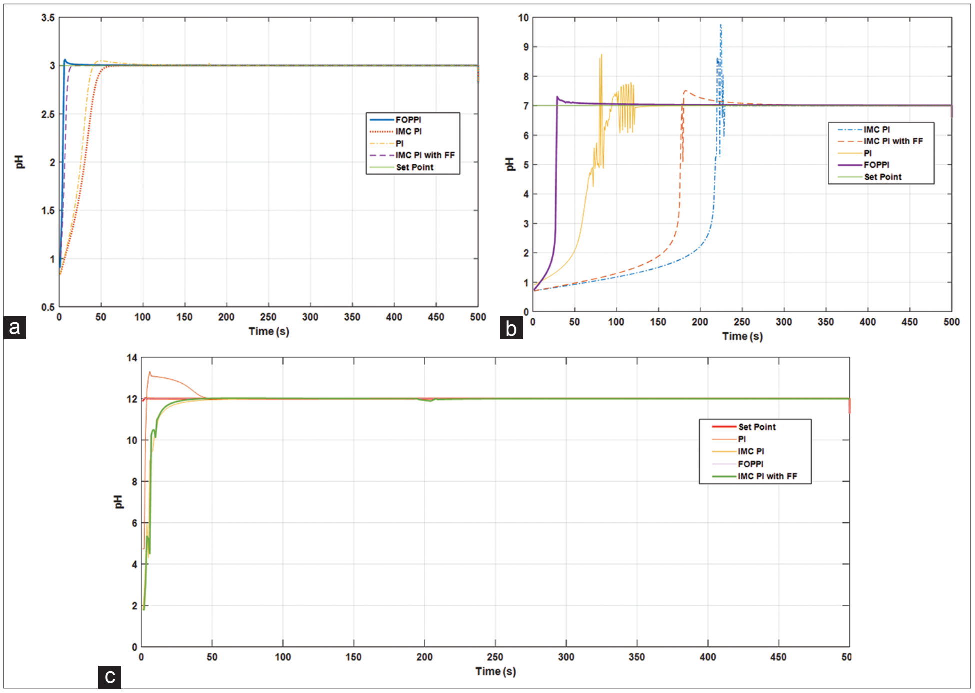

Figure 5: Comparison of PI, IMC PI, fractional filter IMC PI and FOPPI (a) Region 1 (b) Region 2 (c) Region 3. FOPPI: Fractional order predictive proportional integral, IMC: Internal model control

Table 1: Controller settings and performance

Process	Transfer function	Controller	Controller parameters		Performance				
			Kp	Ki	λ	t_r (s)	t_s (s)	IAE	Percentage Mp
Region 1	$\frac{2.593}{3.2s+1}e^{-0.5s}$	PI	2.25	1.7943	-	45	100	175	1
		IMC PI	1.1569	0.3353	-	55	70	59	-
		IMC PI with FF	1.1569	0.3353	1.05	10	12	172	-
		FOPPI	2.148	5.23	1.05	5	10	9.95	5
Region 2	$\frac{53.035}{1.5s+1}e^{-0.5s}$	PI	0.052	0.053	-	90	150	1456	15
		IMC PI	0.0286	0.0163		220	230	1225	28
		IMC PI with FF	0.0286	0.0163	1.05	175	300	1120	5
		FOPPI	0.0875	0.405	1.05	32	140	171	2
Region 3	$\frac{1.4}{2s+1}e^{-0.5s}$	PI	2.63	2.40	-	3	45	76.52	1.2
		IMC PI	1.3975	0.6211	-	50	55	68.84	-
		IMC PI with FF	1.3975	0.6211	1.05	30	35	58.65	-
		FOPPI	6.09	29.43	1.05	2	3	25.82	-

PI: Proportional integral, IMC: Internal model control, IAE: Integral of the absolute error, FOPPI: Fractional order predictive proportional integral

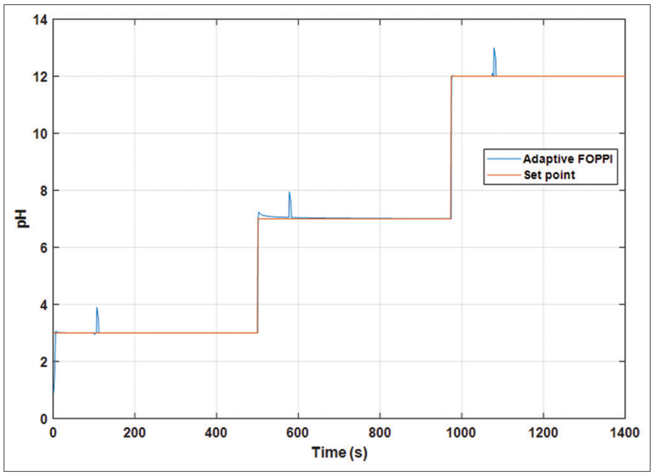

Figure 6: Adaptive FOPPI with set point tracking and disturbance rejection. FOPPI: Fractional order predictive proportional integral

The performance of controllers PI, based Proportional Integral Controller (IMC), IMC fractional filter, and FOPPI of region 1 and 3 is shown in Figure 5a and c and it was found that all the controllers have similar control output except with slight changes in rise time and settling time. However, FOPPI has better dynamic characteristics compared with other controllers.

From the results of the region 2 as shown in Figure 5b, it is found that the performance of PI, IMC, and IMC fractional filter controllers is not satisfactory and there are excess oscillations. The control of pH is considered to be critical in region 2. The FOPPI presented in this study has lesser rise time of 32 s, settling time of 140 s, peak overshoot of 2% and IAE of 171 which is better compared to other controllers. An adaptive fuzzy for FOPPI has been applied to simulate the dynamic changes in pH value and shift in the regions from region 1 through region 3. The controller output [Figure 6] shows the effective adaptiveness of controller response toward the changes in the pH value throughout the range.

CONCLUSION

The study was conducted with an intention to address the controller performance issues in the pH neutral region which is an essential quality measure for industrial effluent treatment. FOPPI controller performance is analyzed and compared with various industrial controllers in region 2. The study clearly shows the limitations of the PI control which has higher rise time of 90 s, settling time of 150 s which delays the control action. Furthermore, the PI control is not recommended for this process because of higher IAE (1456) and peak overshoot (15%).

It is found that the IMC-based PI and fractional filter with the IMC-based PI control gives lesser error (IAE of 1225 and 1120) compared to PI control but has a higher rise time (220 s and 175 s). To further improve the effectiveness of the control of pH a FOPPI controller was applied and analysed. FOPPI controller has better rise time (32 s), settling time (140 s), peak overshoot (2%), with lesser IAE (171).

A fuzzy scheduling algorithm is designed to evaluate the adaptiveness at various regions of the pH process and it shows an effective changeover of controller outputs. The proposed control algorithm can be implemented to improve the robustness of the controller and performance of the process.

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Conflicts of interest

There are no conflicts of interest.

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