IJCTA, 8(3), 2015, pp. 867-875

Experimental Investigations on Fractional Order PI$^{\lambda}$ Controller in pH Neutralization System

B. Meenakshipriya, M. Prakash and C. Maheswari

Abstract: This work mainly discusses on to design and analysis the fractional order based PI controller for a strong acid and strong base pH neutralization system. The dynamic model of pH system is developed using Lab scale-pH Neutralization system. In this pH neutralization system, they are considered Sodium hydroxide and Hydrochloric acid as reactants. To obtain the process reaction curve, a process stream of strong base (NaOH) enters to the inlet feed and it is being neutralized by a strong acid (HCl). From the obtained reaction curve, the pH neutralization system is approximated as FOPTD model using experimental step test method. The simulation and experimental runs are carried out with proposed fractional order based PI controller and compared with existing controllers like Ziegler and Nichols PI controller (ZN-PI) and internal model based PI controller (IMC-PI). The result shows the enhanced performance of fractional order based PI controller than the classical controllers.

Keywords: pH neutralization system, Time delay system, PI control, Fractional order control.

1. INTRODUCTION

Most process industries generate wastewater as an offshoot of their production. The important and general technique used in wastewater treatment system is the neutralization. The purpose of the neutralization is to regulate or control the pH value of the wastewater so that it does not have impact over the environment. The control of pH has been recognized as a challenging problem due to the severe nonlinearity and time varying nature of dynamic characteristics. This is normally true when there is a need to keep up the pH value between the range of 6 to 8 is known as critical points, in the influence of the strong acids and strong bases (Gomez et al 2004).

Several control strategies are reported in the literature to control the problems in pH system such as Gain scheduling technique (Hsiao-Chung Chan and Cheng-ChingYo 1995), Model predictive controller (Mohammed Mehdi Arifi et al 2006), neuro controller (Elarafi and Hisham 2008), linear and nonlinear adaptive controller (Salam al-dawery et al 2009),CDM based controllers (Meenakshipriya et al 2011 and Meenakshipriya et al 2012), fuzzy controller (PraikshitKishore Singh et al 2013), genetic based controller (Ibrahim et al 2013) and Internal model controller (Florance Mary and Ananda Natarajan 2015). Since there have been significant developments in control strategies for pH control, in order to improve the performance of PI controller, the various research activities has been carried out based on the methods and analysis of fractional calculus. Fractional calculus is the generalization of integer order calculus in which the non-integer orders are included in differentiator and integrator commonly known as λ and μ(Podlubny1999). Several researchers used fractional order controller for improving the system quality performances (Monje et al 2007, Das et al 2009 and Padula and Viviol 2011), since it consists of three

---

Department of Mechatronics Engineering, Kongu Engineering College, Perundurai– 638052
E-mail: b.meenakshipriya@gmail.com[1], prakashrkp1992@gmail.com[2], maheswarikec@gmail.com[3]

tuning parameters such as K_p, K_i and λ. Hence, this work proposed Fractional Order based PI^{λ} controller for the pH neutralization process to approximate the performance under the following conditions like stability criteria, robustness performance and time domain performance.

2. PH SYSTEM MODELING

2.1. Experimental Setup

The details pertaining to experimental work carried out in the laboratory scale pH neutralization system are described in this section and the Figure.1 shows the experimental setup. The experimental setup consists of four glass tanks made up of transparent perplex glass for acid, base, water and process/mixing, each tank consisting a 5.3 liters of maximum storage capacity. To maintain constant head in the system, level sensors have been employed. The strong acid (Hydrochloric acid HCl, 0.1N) and strong base (Sodium hydroxide NaOH, 0.1N) solutions are prepared in feed tanks having a 100 liters of storage capacity, from which the solution is pumped by using the fractional submersible pump to the respective tanks. The equal percentage control valves which normally open (Cv of 0.16) is used to control the flow rate of both the streams individually. To set up a disturbance, a ¼” needle valve is provided to increase the buffer (water) flow rate in the buffer stream.

The process stream of strong base (Sodium hydroxide NaOH, 0.1N) enters into a mixing tank through control valve CV2 and maintained as a constant flow rate of 0.5 lpm throughout the process. It is being neutralized by HCl of 0.1N through another control valve CV1 which is controlled by PI controller. To avoid overflow in mixing tank, the overflow line is maintained the constant volume of liquid (3.5 liters). A motorized agitator is used to keep up the same degree of homogenization in mixing tank through a constant speed of 200 rpm. The pH value of the solution is measured by pH sensor which is placed in the mixing tank. The output of the pH sensor is converted into 4–20 mA of current signal with a transmitter is powered by a 24 V DC power supply. The pH system is interfaced with the PC with specially designed microcontroller based (VDPID-03) control unit. The unit consists of facilities like a multifunction, high-speed Analog to Digital Converter (ADC) interface board with 8 channel ADC and 2 channel DAC facilities which is used to send the control signal to control valves individually. It helps to implementing real time control algorithm written in MATLAB/SIMULINK platform.

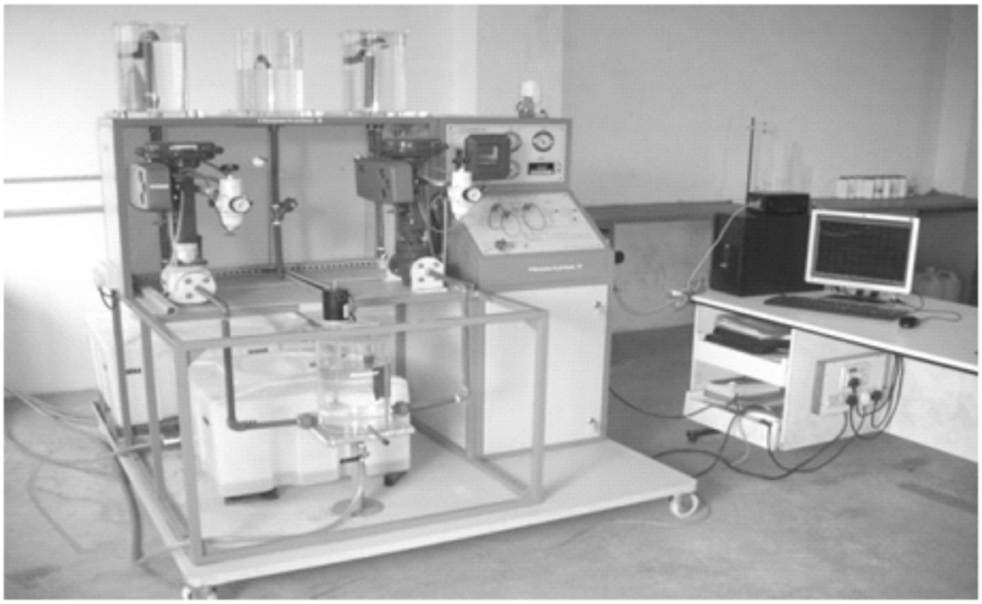

Figure 1: Experimental setup of pH neutralization system

The current signal from the pH transmitter is converted into a voltage signal (0 – 5 V) by using Current to Voltage Converter. The analogue voltage signal is converted into digital signal by ADC. The digital signal from VDPID – 03 unit is fed as input to the PC based controller and it is compared with its set point at which the pH value is to be controlled. In the PC based controller, the output voltage signal (0 – 5 V) is in digital signal and it is converted into an analogue signal by DAC. Then the Voltage to Current converter is used to convert the voltage signal into a current signal of (4 – 20 mA). The output current signal from VDPID-03 unit is converted as a pneumatic signal (3-15 psig) using current to pressure (I/P) converters. The output of I/P converter is intended for to trigger the control valves (CV1 and CV2) which acts as a final control element. Since the flow rate of alkaline is maintained as constant, by controlling the acid flow rate loads, then the pH system brings to its preferred pH value.

2.2. Process Modelling

In this work, for the design of controllers, the pH system is represented as FOPTD transfer function model. For this, the two nominal operating points of pH 11 and 3 are considered for model identification. These points are close to the inflection point which means slope of the curve changes drastically here. In the open loop scheme, to regulate the acid flow rate the operating point of pH 11 is maintained. At this point, DAC output with a step change of magnitude ±10% is specified to the control valve located in the acid flow stream. As a result, the pH probe is used to recorded the variation in pH value through against time until it reaches a new steady state value. The recorded data is plotted beside with time to get the process reaction curve. From the obtained process reaction curve, the First Order (FO) model parameters are process gain Kp, process time constant τ of the pH system are determined. Similarly, the FO model parameters are identified by performing the step test with same magnitudes at further operating point of pH 2. The identified model parameters are shows in Table 1.

Table 1

Model parameters at operating point 11 and 2

Operating points (OP) (In pH value)	*Step magnitude (In DAC Output)*	K_p	*τ(min)*
11	+10%	7.0861	9.74
	-10%	0.3606	14.48
2	+10%	0.1559	9.56
	-10%	7.0921	8.54

Among all these models, the larger process gain and smaller time constant are chosen as a model parameter. Hence, the parameters for the DAC output of -10% changes at the operating point of pH 2 are selected to represent the pH system. The obtained model is denoted as

$$G(s) = \frac{K_p}{\tau_p s + 1} e^{-\theta s} = \frac{7.0921}{8.54s + 1} e^{-1.71s} \tag{1}$$

At this point, the process delay (θ)is approximately considered as 20% of the process time constant.

3. DESIGNING OF PI CONTROLLERS

3.1. Zigler and Nichols PI controller (ZN-PI)

ZN-PI tuning rules is the classical “closed loop” tuning rule which is normally considered as the aggressive tuning rule. In the Ziegler-Nichols procedure the first step is to produce continuous oscillations with a P-controller, and from this to get the “ultimate” gain, corresponding “ultimate” period. Zigler and Nichols recommended the following ZN-PI tunings are:

$$\text{Proportional gain, } K_c = \frac{0.9\tau_p}{\theta k_p} \tag{2}$$

$$\text{Integral time, } T_i = 3.33\theta \tag{3}$$

3.2. Internal Model Based PI Controller (IMC-PI)

IMC PI tuning rules which have achieved well-known industrial acceptance by its robust settings which consequences in great responses when it comes to set point changes and disturbances toward the inside directly at the process output. The tuning rules are as follows,

$$\text{Proportional gain, } K_c = \frac{\tau_p + 0.5\theta}{k_p(\lambda)} \text{ where } \lambda = 1.7 * \theta \tag{4}$$

$$\text{Integral time, } t_i = \tau_p + \frac{\theta}{2} \tag{5}$$

3.3. Fractional Order based PI Controller (FO-PI)

The FO-PI controller tuning rules are derived based on F-MIGO for standard FOPTD model and it is specified by,

$$K_c = \frac{1}{K_p}\left(\frac{0.2978}{\tau + 0.000307}\right) \text{ where } \tau = \frac{\theta}{\theta + \tau_p} \tag{6}$$

$$T_i = \tau_p\left(\frac{0.8578}{\tau^2 - 3.402\tau + 2.405}\right) \text{where } \tau = \frac{\theta}{\theta + \tau_p} \tag{7}$$

$$\lambda = \begin{cases} 1.1, & \text{if } \tau \geq 0.6 \\ 1.0, & \text{if } 0.4 \leq \tau < 0.6 \\ 0.9, & \text{if } 0.1 \leq \tau < 0.4 \\ 0.7, & \text{if } \tau < 0.1 \end{cases} \text{ where } \tau = \frac{\theta}{\theta + \tau_p} \tag{8}$$

The PI controller settings for the above said controllers are worked out based on the FOPTD model given in equation (1) and it is provided in the Table 2.

Table 2

Tuning Parameters of PI controllers

PI Controllers	*PI Controller Parameters*		
	K_c	T_i *(sec)*	$K_i = \frac{K_c}{T_i}$
ZN-PI	0.6337	5.69	0.1113
IMC-PI	0.4556	9.395	0.048
FO-PI	0.247	3.947	0.0625

4. RESULT AND DISCUSSION

4.1. Simulation Studies

The simulation runs are carried out with ZN-PI, IMC-PI and FO-PI controllers at the different operating points (pH8 and pH2) in MATLAB/SIMULINK platform as shown in the Figure 2. The Closed loop simulated transient responses are recorded as exposes in Figures 3 and 4. The performance actions are calculated in terms of error indices (ISE, IAE and ITAE) and quality indices (t_r, t_s and %Mp) and it is reported in Table 4.1. The results reveals that the proposed FO-PI controller efficiently tackles the variations in gain and yields a fair transient response with minimum error values, acceptable values of settling time and minimum overshoot, whereas the other controllers fail to perform satisfactorily at all operating points.

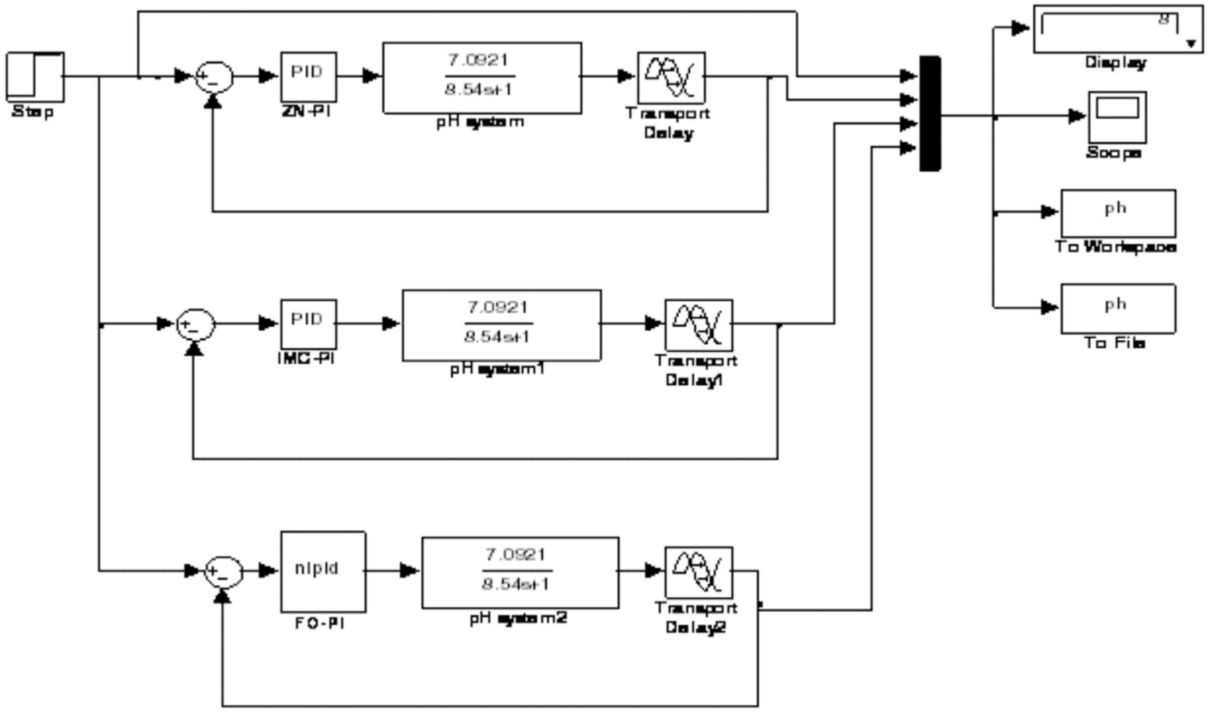

Figure 2: Closed loop PI controller structure in MATLAB/SIMULINK platform

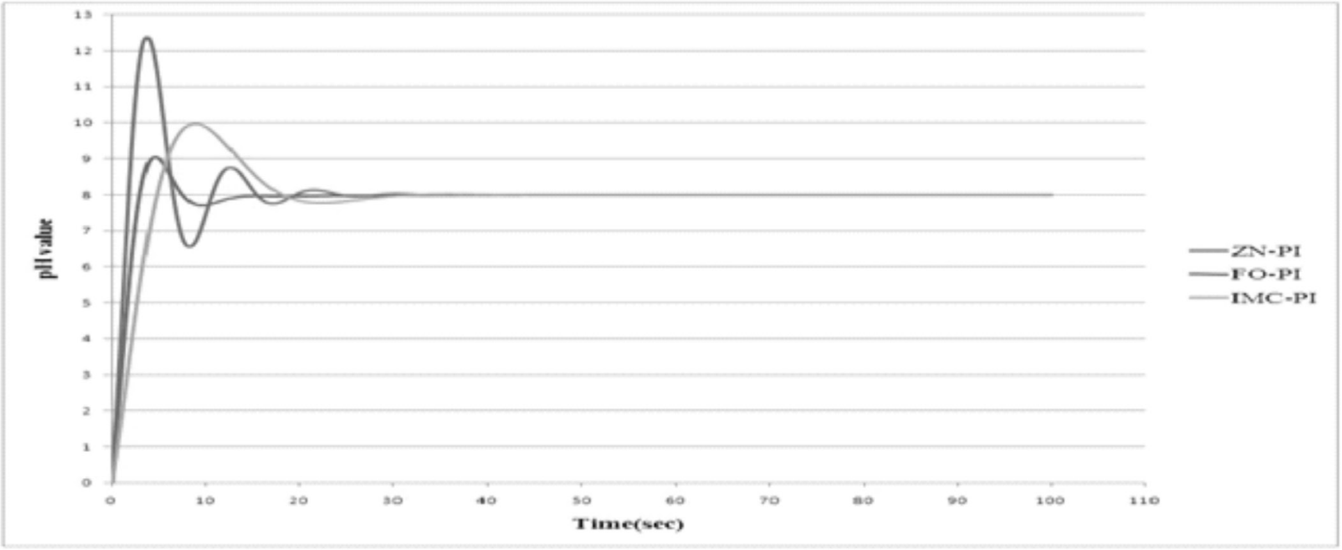

Figure 3: Closed loop response at the operating point of pH 8

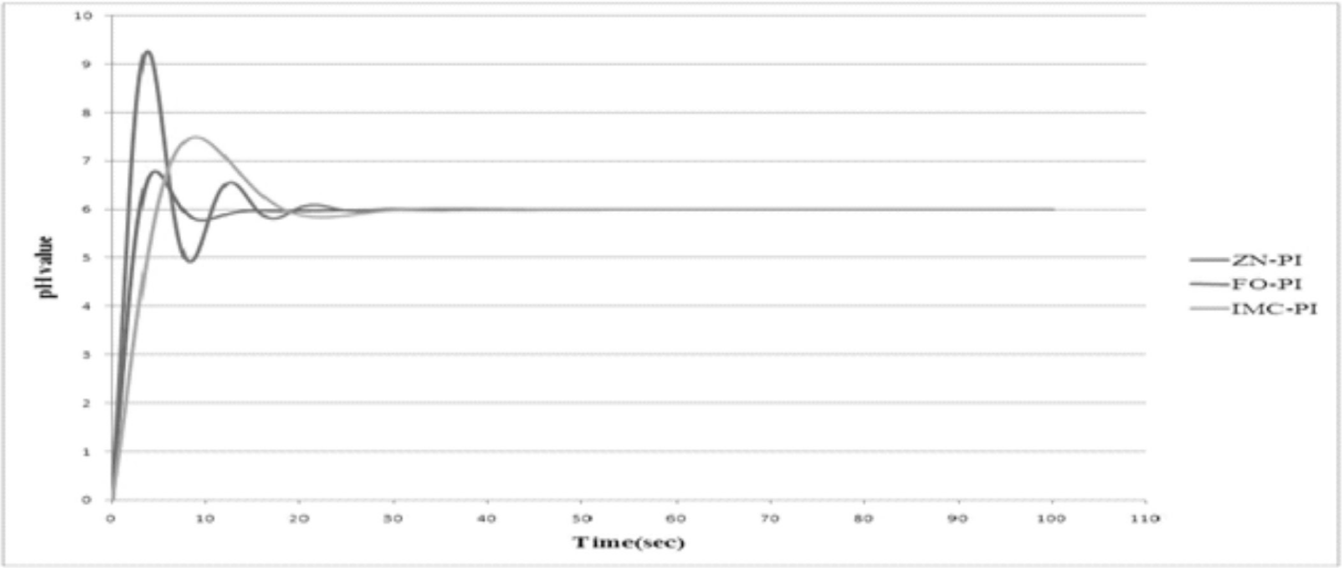

Figure 4: Closed loop response at the operating point of pH 6

Table 3

Performance Measures of PI Controllers at the Operating Point of pH 8 and 6

Performance measures	*8*			*6*		
	ZN-PI	*IMC-PI*	*FO- PI*	*ZN- PI*	*IMC- PI*	*FO - PI*
ISE	8883.139	11785.23	15048.91	4996.766	6629.19	11266.19
IAE	8528.631	3487.598	1560.71	4730.884	2615.699	1170.533
ITAE	14066.88	15272.82	5129.277	10529.67	9244.888	3835.252
t_r (sec)	1.8	4.68	2.94	1.8	4.71	2.94
t_s (sec)	31.25	29.6	13.41	31.57	30.29	13.61
$\%M_p$	54.16	25	13.33	54.25	25	12.5

4.2. Experimental Studies

In this section, the performance of ZN-PI, IMC-PI and FO-PI controller is evaluated at the operating point of pH 10 in the Lab scale pH Neutralization system using load rejection test. A step disturbance is introduced into the system by way of increasing the buffer (water) flow rate from 0 to 1 lpm. The response to this disturbance is shown in Figures 5 - 7. From the figures, it is clearly noticed that only FO-PI controller damp the disturbance in a shorter time and it produces fast response with low peak error than the other classical controllers. The performance measures are calculated and are given in Tables 4. From the performance measures, it is confirmed that the FO-PI controller is also successful in load rejection.

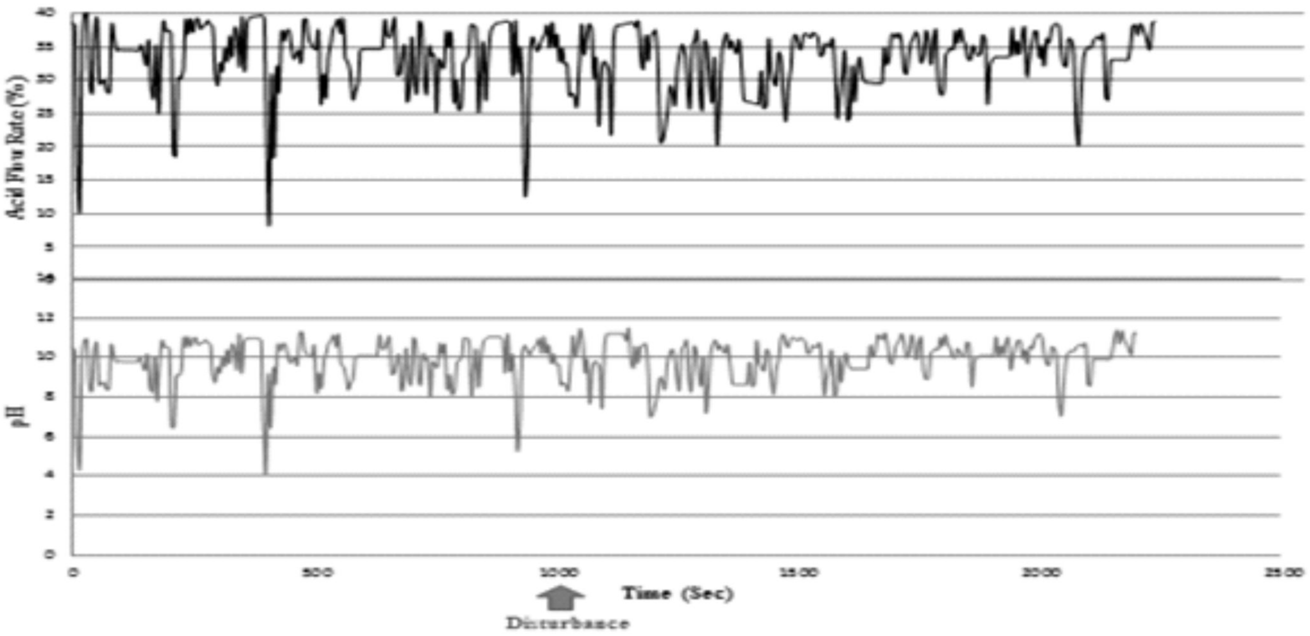

Figure 5: Regulatory response of ZN-PI controller (pH 10)

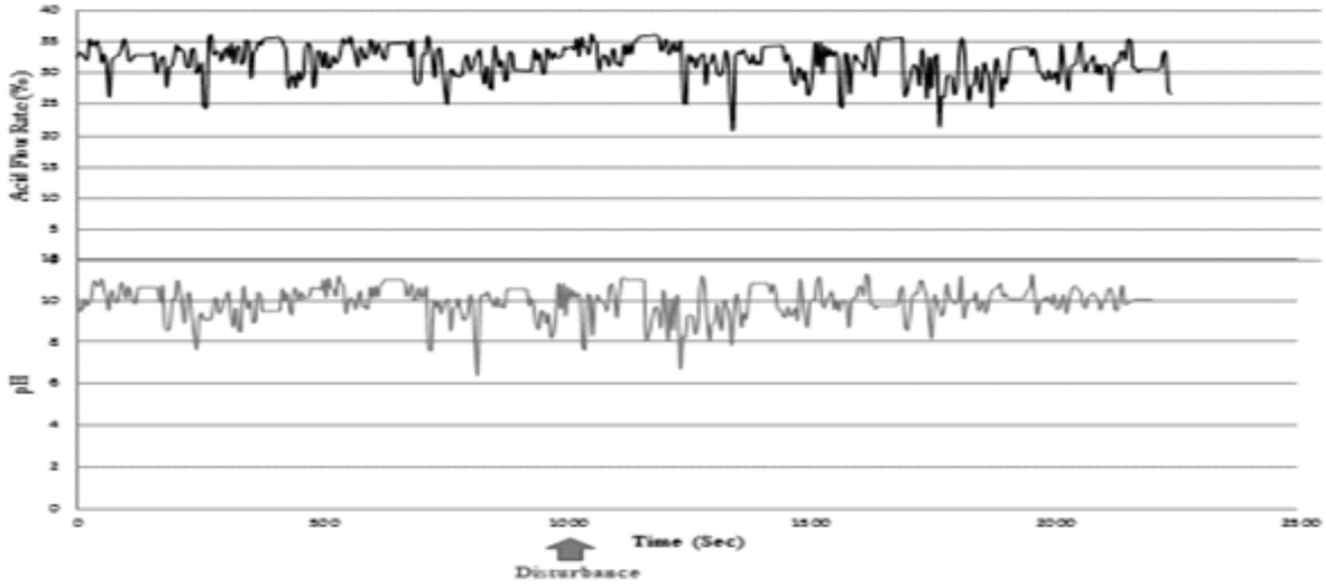

Figure 6: Regulatoryresponse of IMC-PI controller (pH 10)

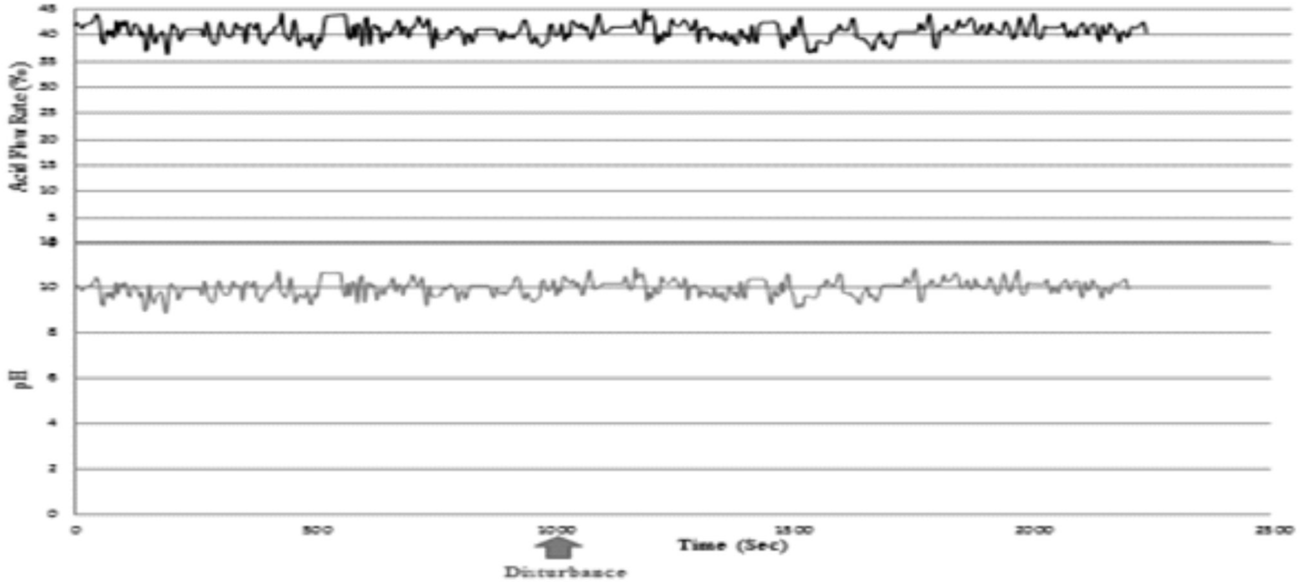

Figure 7: Regulatory response of FO-PI controller (pH 10).

Table 4

Performance Measures of the ZN-PI, IMC-PI and FO-PI Controllers (pH 10)

Performance Measures	*ZN-PI*	*IMC-PI*	*FO-PI*
ISE	527.40	250.70	54.79
IAE	353.27	249.04	124.05
ITAE	358041.6	254319.7	132142.7

5. CONCLUSION

The work has been undertaken with a vision to analyze an impact of fractional calculus in the development of classical control theory through challenging pH control problem. For this investigation, a Fractional Order based PI controller (FO-PI) were designed to overthrow the problem in pH control. The performance, robustness and load rejection characteristics of FO-PI controller was analyzed by conducting simulation and experimental studies at different operating points of pH 6, 8 and 10. The experimental as well as simulation results proved that the FO-PI controllers took corrective action even in the presence of nonlinearity and enhanced the performance in all aspects when compared to existing classical controllers. Finally, it is concluded that the Fractional Order Controller furnishes a convenient and flexible design under the following conditions are satisfied like stability, robustness and time domain performance, which provides enhanced performance in terms of the set point tracking and disturbance rejection capabilities.

References

[1] Hsiao-Chung Chan, Cheng-Ching Yo, "Auto-tuning of Gain-Scheduled pH control: An Experimental study", *Industrial and Engineering Chemistry Research*, Vol. 34, pp. 1718-1729, 1995.

[2] Podlubny, I, "Fractional-order systems and $PI^{\lambda}D$ controllers", *IEEE Transactions on Automatic Control*, vol. 44, no. 1, pp. 208-214, 1999.

[3] Mohammad Mehdi Arefi, Allahyar Montazeri, Javad Poshtan and Mohammad Reza Jahed-Motlagh, "Nonlinear Model Predictive Control of Chemical Processes with a Wiener Identification Approach", *IEEE Transactions on Automatic Control*, pp. 1735-1740, 2006.

[4] Monje, A, Vinagre BM, Feliu, V & Chen, YQ, “Tuning and auto-tuning of fractional order controller for industry applications”, *Journal of Control Engineering Practice*, vol. 16, pp. 798-812, 2007.

[5] Elarafi M., Hisham S.B., “Modeling and Control of pH Neutralization using Neural Network Controller”, *International Conference on Control, Automation and Systems*, pp. 1196-1199, 2008.

[6] Salam K. Al-dawery., Hameed aliomran al-anbari, “Nonlinear Adaptive Control of a pH Process”, *Iraqi Journal of Chemical and Petroleum Engineering*, Vol. 10, No. 01, pp. 9-16, 2009.

[7] Padula, F. & Visiol, A. 2011, “Tuning rule for optimal PID and fractional-order PID controllers”, *Journal of Process Control*, vol. 21, pp. 69-81.

[8] Meenakshipriya, B., Saravanan, K., Krishnamurthy, K. and Bhaba, P.K. “CDM based PI-P control strategy in pH neutralization system”, *Instrumentation Science and Technology*, Vol. 39, Issue. 3, pp. 273-287, 05/2011.

[9] Meenakshipriya, B., Saravanan, K., Krishnamurthy, K. and Bhaba, P. K. “Design and implementation of CDM-PI control strategy in pH neutralization system”, *Asian Journal of Scientific Research*, Vol. 5, No. 3, pp. 78-92, 2012.

[10] Ibrahim Al-Adwan, Mohammad Al-Khawaldan, ShebelAsad, Ayman Al-Rawashdeh, “Design of an Adaptive Fuzzy-Based Control System using Genetic Algoritham over a pH Process”, *IJRRAS*, Vol.17, Issue 2, pp. 177-184, 2013.

[11] Parikshit Kishore Singh, SurekhaBhanot, Hare Krishna Mohanta,”Optimized and Self-Organized Fuzzy Logic Controller for pH Neutralization Process”, *I.J. Intelligent Systems and Application,* Vol.12, pp. 99-112, 2013.

[12] Florance Mary M., Ananda Natarajan R., “Fuzzy Model for IMC Based PI Controller for a nonlinear pH Process”, *International Journal on Recent and Innovation Trends in Computing*.