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Design and Implementation of CDM-PI Control Strategy in a pH Neutralization System

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ABSTRACT

This study presents the design and implementation of a Coefficient Diagram Method (CDM) based PI controller in a pH neutralization system. By using the experimental step test method, the nonlinear pH system is approximated as First Order Plus Time Delay (FOPTD) transfer function. Based on the CDM, the tuning parameters of PI controller are designed and implemented in the laboratory scale strong acid-strong base pH neutralization system. The servo and regulatory performance of the proposed CDM-PI control strategy is compared with other conventional PI controllers at two different highly sensitive operating points. In addition, the robustness test is performed. The experimental results show that the proposed CDM-PI control strategy is effective and potential for severe non linear control problem.

Key words: CDM-PI, pH control, experimental, time delay process, performance measures

INTRODUCTION

Most of the process industries generate wastewater (effluent) as an offshoot of their production. The effluent discharged by these industries consist organic, inorganic chemicals and toxic metals. It is a major source of environmental pollution and also has a major impact on human health. In accordance with the environmental conservation act and environmental rules, it is mandatory to install Effluent Treatment Plants (ETPs) to treat the wastewater before it is disposed into the environment (Hanif *et al*., 2005).

An important and common technique used in wastewater treatment system is neutralization. The purpose of the neutralization is to adjust or control the pH value of the wastewater so that it does not have impact over the environment. However, it is very difficult to control pH process with adequate performance due to its severe nonlinearity, time varying properties and sensibility to small disturbance when working near the equivalence point. Therefore, more reliable, accurate, robust, efficient and flexible control systems are required for pH neutralization process.

In order to fulfill the above requirements, there is a continuing need for research on improved forms of control. Many research studies have been reported in the literature such as linear and nonlinear adaptive controller (Jutila, 1983; Gustafsson and Waller, 1992), self-tuning adaptive controller (Lin *et al.*, 2000), model based controller (Palancer *et al.*, 1996; Rivera *et al.*, 1986), neuro controller (Akesson *et al.*, 2005), fuzzy controller (Ahmed *et al.*, 2007), non-linear gain scheduling based on neuro-fuzzy controller (Zhang, 2001) and genetic based controller (Valarmathi *et al.*, 2009). Even though there are significant developments in the control systems, the chronic Proportional Integral (PI) controller is by far the most widely used control algorithm for pH neutralization process. The primary task of the controller is to maintain the process at desired operating conditions and to achieve the optimum performance when facing various types of disturbances. The typical transfer function models are used to represent the process and it can be easily controlled with PI controller (Nithya *et al.*, 2008). It also known that the improvements in the tuning of PI controller will have a significant practical impact. At this juncture, a simple and robust tuning is keenly needed. Hence, in the present study, a simple and robust control strategy based on polynomial approach, namely Coefficient Diagram Method (CDM) is considered as a candidate to design the PI controller.

OVERVIEW OF COEFFICIENT DIAGRAM METHOD (CDM)

CDM is a polynomial algebraic approach and proposed by Manabe in the year 1991. The algebraic approach (CDM) was then said to be an alternative for conventional and modern control theories and uses polynomial expression for the mathematical representation. The advantageous parts of these control theories are combined to form the principles of CDM and it is derived by using the previous experience and knowledge about the controller design. Without confronting with serious difficulties and necessitating much experience, CDM makes possible to design very good controllers with less effort and relative ease when compared with the other existing methods (Manabe, 1998). By comparing the existing method, it is very easy to design a controller under the conditions of stability, time domain performance and robustness. Also, CDM is less sensitive to disturbances and bounded uncertainties resulted from the parameter variations. The important property of CDM is that the designer can have complete control over the transient response by specifying the key parameters namely stability indices (γ_i) and equivalent time constant (τ) at the beginning of the design. The simultaneous design nature exists in CDM, gives advantages to designer to keep good balance between the rigor of the requirements and the complexity of the controller.

Mathematical model: The standard CDM block diagram for single input single output system is shown in Fig. 1, where, y is the output signal, r is the reference input, u is the controller signal and d is the external disturbance signal. N(s) and D(s) are numerator and denominator polynomials of the plant transfer function. A(s) is the forward denominator polynomial while F(s) and B(s) are the reference numerator and the feedback numerator polynomials of the controller transfer function. For the given system, the output of the CDM control system is given by:

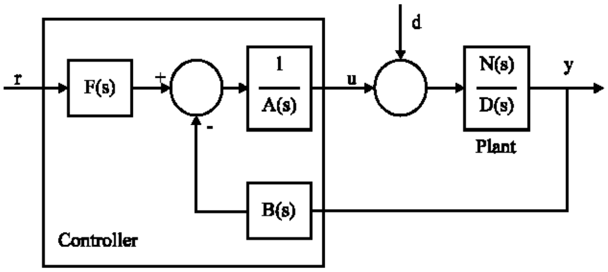

Fig. 1: Standard CDM block diagram

$$y = \frac{N(s)F(s)}{P(s)} r + \frac{A(s)N(s)}{P(s)} d \tag{1}$$

where, P(s) is the characteristic polynomial of the closed-loop system and defined by:

$$P(s) = A(s)D(s) + B(s)N(s) = \sum_{i=0}^{n} a_i s^i ,\ a_i > 0 \tag{2}$$

Here, the controller polynomials (A(s) and B(s)) are given as:

$$A(s) = \sum_{i=0}^{p} l_i s^i \text{ and } B(s) = \sum_{i=0}^{q} k_i s^i \tag{3}$$

When polynomial F(s) is chosen as:

$$F(s) = P(s) / N(s)\big|_{s=0} \tag{4}$$

the overall closed loop transfer function becomes Type-1 system. Therefore, a good closed-loop response can be achieved.

Design of CDM controller: The design parameters of CDM are the stability indices (γ_i) and equivalent time constant (τ). The stability indices determine the stability of the system and the transient behavior of the time domain response (with overshoot, without overshoot and oscillations etc.). In addition, they determine the robustness of the system to parameter variations. The equivalent time constant which is closely related to the bandwidth and it determines the rapidity of the time response. According to Manabe (1998), the design parameters are defined as follows:

$$t = t_s/(2.5 \gg 3) \tag{5}$$

where t_s is the user specified settling time:

$$\gamma_i = [2.5\ 2\ 2\ \dots], \tag{6}$$

where, $i = 1, \dots, n\text{-}1$, $\gamma_0 = \gamma_\infty = 0$

If necessary, the designer can modify the values of stability indices.

Using the design parameters defined in Eq. 5 and 6, a target characteristic polynomial ($P_{target}(s)$) is formulated as:

$$P_{target}(s) = a_0 \left[\{ \sum_{i=2}^{n} \left(\prod_{j=1}^{i-1} \frac{1}{\gamma_{i-j}^{j}} \right) (ts)^i \} + ts + 1 \right] \tag{7}$$

By substituting the controller polynomials in Eq. 3 into Eq. 2, the closed loop characteristic polynomial P(s) are obtained. This polynomial is compared with Eq. 7 to obtained the coefficients of CDM controller polynomials l_i, k_i and a_i.

DESIGN OF PROPOSED CDM-PI CONTROLLER

The design procedure for the proposed CDM-PI control strategy is summarized as follows:

- The given system is approximated as FOPTD model
- The equivalent transfer function of the above said FOPTD model is determined using first order Pade's approximation technique
- The standard CDM block diagram given in Fig. 1 is reduced as its equivalent block diagram as shown in Fig. 2 using block diagram reduction techniques (Hamamci *et al.*, 2007)

In Fig. 2, the CDM controller polynomials (A(s) and B(s)) and pre-filter element (F(s)) are chosen as:

$$A(s) = s \text{ and } B(s) = K_1 s + K_0 \tag{8}$$

$$F(s) = P(s)/N(s)\big|_{s=0} = P(0)/N(0) = 1/K = K_0 \tag{9}$$

The stability indices (γ_1 and γ_2) are selected from the Eq. 6 or the designer can change the value of stability indices, if required. However, the equivalent time constant (τ) is not specified and it is considered as another variable to be solved.

The closed loop characteristic polynomial (P(s)) and target characteristic polynomial ($P_{target}(s)$) are determined using Eq. 2 and 7. By equating P(s) and $P_{target}(s)$, the CDM controller parameters (k_1 and k_0) and the equivalent time constant (τ) are computed.

The proposed CDM-PI control system is displayed in Fig. 3 consisting of the main controller C(s) and feedforward controller $C_f(s)$. Imposing the conditions:

$$\lim_{s\to 0} C(s) = \infty \text{ and } \lim_{s\to 0} \frac{C_f(s)}{C(s)} = 0$$

on the control system, the steady state error to unit step change and unit step disturbance become zero (Hamamci *et al.*, 2007). To satisfy the above conditions, the C(s) must include an integrator. Hence, C(s) is chosen as:

$$C(s) = K_c\left(1 + \frac{1}{T_i s}\right) \tag{10}$$

in the conventional PI element and $C_f(s)$ is an appropriate element satisfying the condition.

Finally, the PI controller parameters (K_c and T_i) in terms of CDM controller polynomials are found by relating the Fig. 2 and 3. Figure 2 and 3 indicate that the C(s) and $C_f(s)$ are expressed as:

$$C(s) = \frac{B(s)}{A(s)} \tag{11}$$

$$C_f(s) = \frac{F(s)}{B(s)} \tag{12}$$

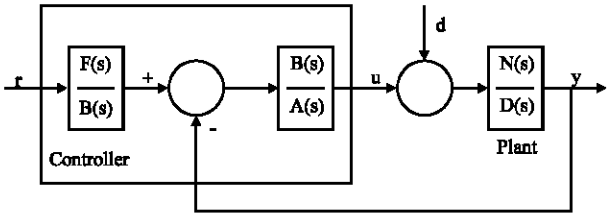

Fig. 2: Equivalent CDM block diagram

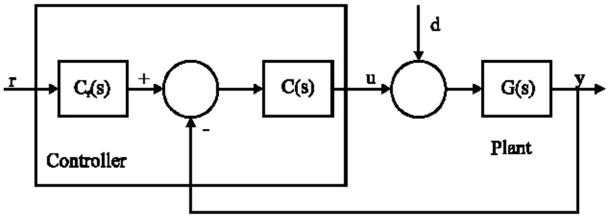

Fig. 3: Proposed CDM-PI control system

Substitute the Eq. 8 and 10 in Eq. 11, derives:

$$\frac{K_1 s + K_0}{s} = K_c\left(1 + \frac{1}{T_i s}\right) \tag{13}$$

By equating the coefficients of like power terms, the CDM-PI controller parameters (K_c and T_i) are obtained as follows:

$$K_c = K_1 \text{ and } T_i = K_1/K_0 \tag{14}$$

Substitute the Eq. 8 and 9 in Eq. 12, the parameter of feedforward controller is found to be:

$$C_f(s) = \frac{F(s)}{B(s)} = \frac{K_0}{K_1 s + K_0} = \frac{1}{T_i s + 1} \tag{15}$$

Since the parameter of $C_f(s)$ depends on the CDM-PI controller parameters directly, the designer need not perform extra calculation for the feedforward controller.

EXPERIMENTS AND ANALYSIS

System description: The details pertaining to experimental work carried out in the laboratory scale pH neutralization system are described in this section and shown in Fig. 4. The experimental setup consists of four transparent perspex glass tanks (acid, base, water and process) with a maximum storage capacity of 5.3 L each. To maintain constant head in the system, level sensors have been employed. The strong acid (Hydrochloric acid HCl, 0.1 N) and strong base (Sodium hydroxide NaOH, 0.1 N) solutions are prepared in feed tanks having a storage capacity of 100 L, from which the solution is pumped to the respective tanks using fractional submersible pump. The

Fig. 4: Photographic view of pH neutralization experimental setup

flow rate of both the streams is controlled individually using equal percentage control valves which normally open with Cv of 0.16. To introduce a disturbance, a ¼" needle valve is provided in the buffer (water) stream to increase the buffer flow rate.

The process stream of strong base enters as an inlet feed into a CSTR. It is being neutralized by HCl of 0.1 N through the control valve, which is controlled by PI controller. To avoid overflow in CSTR, constant volume of liquid (3.5 liters) is maintained by means of overflow line. A motorized agitator with a constant speed of 200 rpm is used to maintain uniform degree of homogenization in CSTR. The pH value of the solution in the process tank is measured by pH sensor located in the CSTR. The output of the pH sensor is converted into current signal (4-20 mA) by means of a transmitter powered by a 24 V DC power supply.

The current signal 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. The pH system is interfaced with the PC through specially designed microcontroller based VDPID-03 unit. It helps in implementing real time control algorithm written in MATLAB/SIMULINK platform. The output current signal (4-20 mA) from the PC based controller is converted into a pneumatic signal (3-15 psig) using I/P converter. This pneumatic signal is directed to actuate the control valve which acts as a final control element for manipulating the load of acid flow rate. In this way, it brings the system to its desired pH value.

Model identification: The pH system is modeled as FOPTD transfer function:

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

around two nominal operating points of pH 11 and 2 which are close to the inflection point. In the open loop scheme, the operating point of pH 11 is maintained by regulating the acid flow rate. Then, a step change with a magnitude of ±08 and ±10% DAC output is given to the control valve

Table 1: Identified model parameters at different operating points

Operating points (pH value)	Step magnitude (DAC output) (%)	K_p (%/%)	τ_p (min)
11	+08	6.9985	13.93
	-08	0.4053	09.31
	+10	7.0861	09.74
	-10	0.3606	14.48
2	+08	0.2336	10.23
	-08	6.9143	09.27
	+10	0.1559	09.56
	-10	7.0921	08.54

of acid stream. As a consequence, the value of pH varies and this variation is recorded (through pH probe) against time until a new steady state is attained. The recorded data are plotted against time to obtain reaction curve by which first order model parameters (process gain K_p and process time constant τ_p) of the pH system are determined (Gobal, 2002). The same procedure is repeated for another operating point of pH 2. The identified model parameters are tabulated in Table 1.

Among all these models, larger process gain and smaller time constant are chosen as model parameters. Hence, the parameters for DAC output of -10% change at the operating point of pH 2 is selected to represent the pH system for the design of controllers. The identified model is represented as:

$$G(s)=\frac{7.0921}{8.54s+1}e^{-1.71s} \tag{16}$$

Here, the process delay (θ = 1.71 min) is approximately considered as 20% of the process time constant (Swati *et al.*, 2008).

Experimental works: The experimental works carried out in the pH neutralization system is described in this section. The experiments are carried out in three folds. In the first fold, the performance of the newly developed CDM-PI control strategy is tested for the set point tracking. Next, the robustness of the controller is tested. In the last and third fold, the regulatory performance of the CDM-PI controller is analyzed. In all the three folds, the performance of the CDM-PI controller is compared with conventional PI control techniques such as Ziegler-Nichols (Bhaba *et al.*, 2007; Abbas, 1997) and Saeed Tavakoli (Tavakoli and Fleming, 2003). For convenience, these techniques are abbreviated as ZN-PI, AB-PI and ST-PI, respectively.

The PI controller settings for the above said controllers are worked out based on the FOPTD model given in Eq. 16. Taking the model parameters into account and choosing the stability indices values γ_1 = 2.5, γ_2 = 2, the CDM-PI settings are determined as:

$$C(s)=0.6176\left(1+\frac{1}{4.3544s}\right) \text{ and } C_f(s)=\frac{1}{4.3544s+1} \tag{17}$$

The controller parameters for ZN-PI: K_c = 0.6338, T_i = 5.69, AB-PI: K_c = 0.3253, T_i = 9.4 and ST-PI: K_c = 0.3844, T_i = 8.91, are also determined.

PERFORMANCE EVALUATION AND COMPARISON

First fold-Set point tracking: In this section, the set point tracking performance of the CDM-PI controller is evaluated and compared with ZN-PI, AB-PI and ST-PI controllers. Experimental runs for the set point tracking of ±05% and ±10% with CDM-PI, ZN-PI, AB-PI and ST-PI control system are carried out at the operating point of pH 6. The tracking responses are plotted in Fig. 5 to 8.

From the Fig. 5 to 8, it can be seen that, the servo responses obtained by other conventional PI controller are highly oscillatory and never settled at the tracking period. At the same time, the servo response made by CDM-PI controller is forced to follow the set point and yields a fair transient response when compared to others. CDM responses are found to have low percent or no overshoot and smallest settling time with little oscillations. This is not the case with responses of other control techniques. To analyze the performance of the controllers, the different performance measures such as Errors indices (Integral Squared Error (ISE), Integral Absolute Error (IAE)), Quality indices (rise time t_r, settling time t_s, peak overshoot %Mp) are used. In addition, the Total Variation (TV) of the output (y) is calculated using the expression.

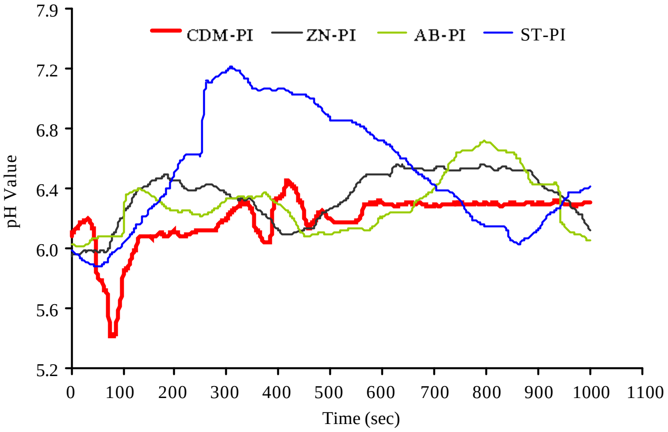

Fig. 5: Servo responses for set point tracking of +05% at the operating point of pH 6

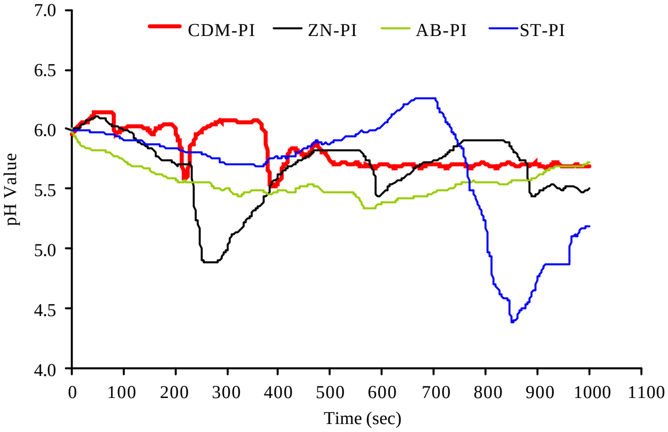

Fig. 6: Servo responses for set point tracking of −05% at the operating point of pH 6

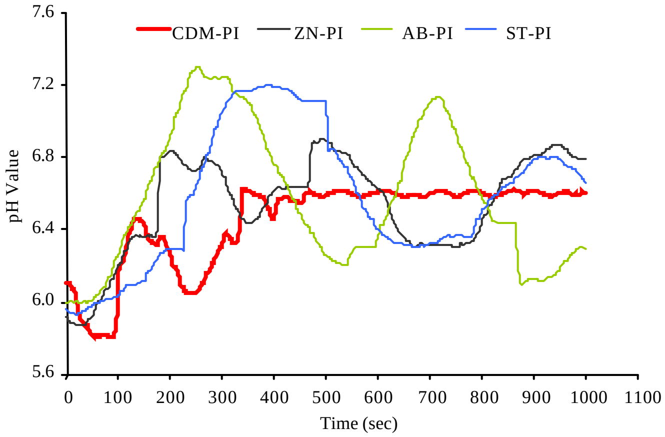

Fig. 7: Servo responses for set point tracking of +10% at the operating point of pH 6

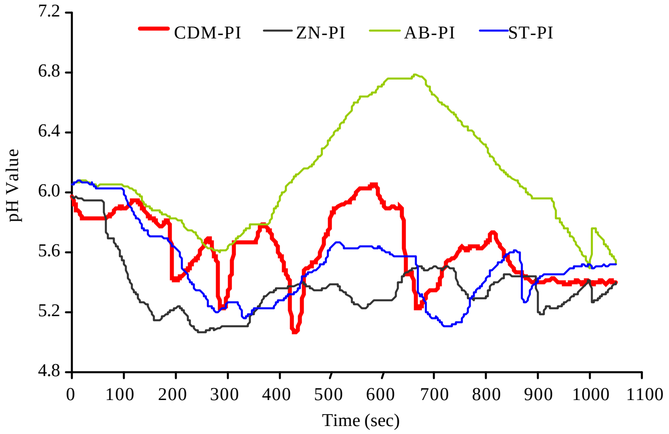

Fig. 8: Servo responses for set point tracking of –10% at the operating point of pH 6

$$TV = \sum_{k=1}^{\infty} \left| y(k+1) - y(k) \right|$$

to evaluate the controller effort. The minimum TV value represents the smoothness and consistency of the output signal (Chen and Seborg, 2002). The output derived from the above figures is presented in Table 2. From this table, it is cleared that the CDM-PI controller gives minimum error indices, good quality indices and minimum TV when compared to the other conventional PI controllers.

Second fold-Robustness test: The study of controller performance without robustness test will be incomplete. In this study, the robustness of the CDM-PI controller is tested by conducting an experimental run at another operating point of pH 9. The robustness metrics obtained using CDM-PI, ZN-PI, AB-PI and ST-PI control system for ±05% and ±10% change at the operating point of pH 9 is shown in Fig. 9 to 12. The performance measures are tabulated in Table 3. From the Fig. 9-12 and Table 2, it is observed that the CDM-PI controller provides better performance with the

Table 2: Servo performance of the controllers at the operating point of pH 6

Performance	+05%				-05%				+10%				-10%			
measures	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB- PI	ST-PI
ISE	8.00	6.72	7.10	41.66	8.79	16.40	7.04	46.58	16.45	15.47	30.88	29.40	21.39	8.82	131.18	15.88
IAE	23.06	32.26	30.69	73.70	28.06	43.27	33.15	71.41	32.17	45	69.02	65.69	53	31.87	147.74	45.33
t_r (sec)	575	115	175	165	415	205	115	305	360	315	430	245	420	630	Nil	795
t_s (sec)	575	**	**	**	515	990	**	**	460	**	**	**	890	**	**	**
%M_p	0.02	0.04	0.07	0.14	0.02	0.14	0.06	0.23	0.003	0.05	0.12	0.09	0.06	0.06	Nil	0.06
TV	3.89	2.24	2.49	3.08	3.6	3.93	1.48	3.75	3.15	3.39	4.64	2.91	5.91	3.33	3.49	3.44

** Not settled

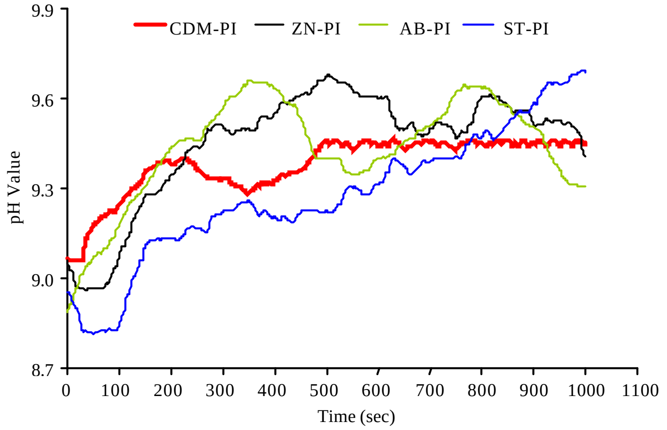

Fig. 9: Servo responses for set point tracking of +05% at the operating point of pH 9

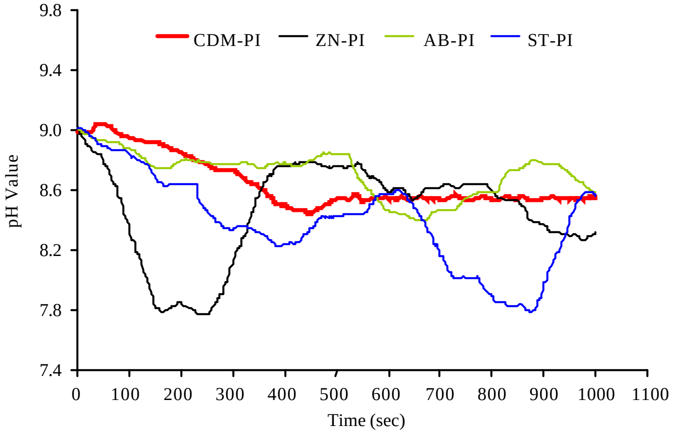

Fig. 10: Servo responses for set point tracking of -05% at the operating point of pH 9

same settings for different operating point. Among the four controller tuning rules, CDM-PI tolerates the perturbations in the model parameters when the operating point changes and provides the most consistent and robust response.

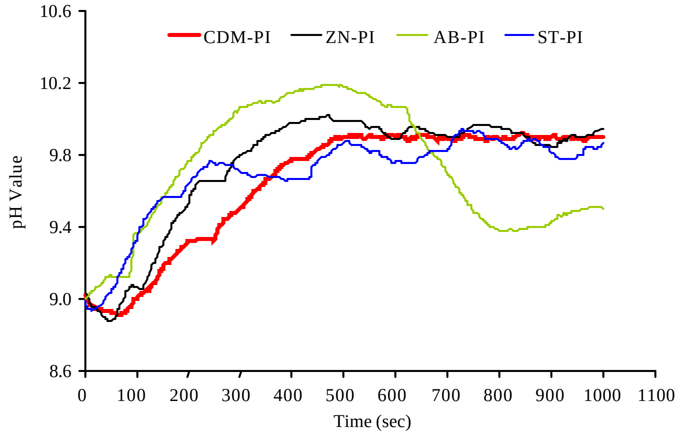

Fig. 11: Servo responses for set point tracking of +10% at the operating point of pH 9

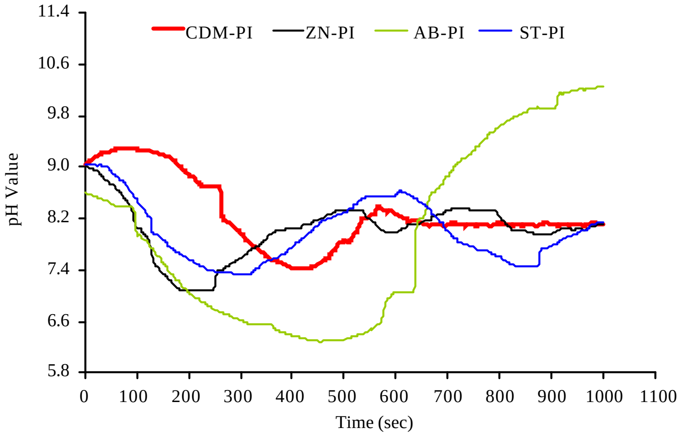

Fig. 12: Servo responses for set point tracking of −10% at the operating point of pH 9

Table 3: Servo Performance of the controllers at the operating point of pH 9

Performance measures	+05%				−05%				+5%				−5%			
	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB-PI	ST-PI	CDM-PI	ZN-PI	AB- PI	ST-PI
ISE	2.98	7.40	6.03	16.24	8.16	22.90	9.99	23.98	36.59	27.32	31.1	20	65.01	38.09	394.15	47.69
IAE	15.05	29.09	26.45	46.42	24.62	50.91	39.72	55.13	51.67	42.14	66.74	42.33	77.47	61.23	256.05	85.05
t_r (sec)	505	265	215	770	505	80	750	575	510	935	240	715	655	640	640	980
t_s (sec)	505	**	**	**	505	**	**	**	510	**	**	**	655	**	**	**
%M_p	Nil	0.024	0.022	0.025	0.01	0.088	0.013	0.088	Nil	0.01	0.028	0.004	0.083	0.121	0.221	0.094
TV	1.37	1.81	1.83	1.72	1.43	3.46	1.76	2.99	1.85	2.01	2.27	2.05	4.28	4.66	6.35	4.89

**Not settled

Third fold-Regulatory performance: The disturbance rejection property of CDM-PI, ZN-PI, AB-PI and ST-PI control systems are investigated. A step disturbance is introduced into the system by the way of increasing the buffer (water) flow rate from 0 to 1 Lpm at the operating point of pH 9. The response to this disturbance is shown in Fig. 13. Figure 13 indicates that CDM-PI controller

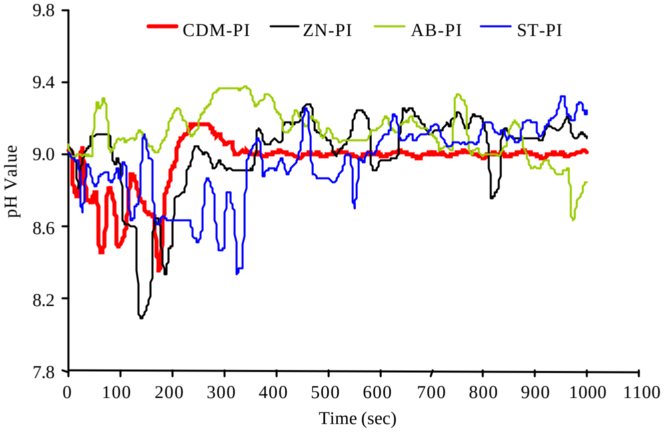

Fig. 13: Regulatory response at the operating point of pH 9

Table 4: Regulatory performance of the controllers at the operating point of pH 9

Performance measures	CDM-PI	ZN-PI	AB-PI	ST-PI
ISE	4.54	10.65	6.80	8.95
IAE	15.1	32.89	29.84	33.23
t_r (sec)	25	35	20	140
t_s (sec)	320	**	**	**
%M_p	0.07	0.1	0.04	0.07
TV	4.78	7.09	5.04	8.60

**Not settled

is the one to damp the disturbance in a shorter time. The error indices, quality indices and TV of output signal are used to evaluate the disturbance rejection performance of the controllers are tabulated in Table 4. The ZN-PI, AB-PI and ST-PI control systems in this regard is affected by the nonlinear (gain variations) behavior of the system. As far the CDM-PI controller, its disturbance rejection performance is not affected by the nonlinearity. The performance measures confirm that CDM-PI control strategy is successful in disturbance rejection.

CONCLUSION

In this study, a CDM based PI control strategy is designed for a strong acid-strong base pH neutralization process. The designed control strategy is implemented in real time operations. The performance of the CDM-PI control system in the set point tracking and load disturbance rejection are evaluated and compared with other conventional PI control techniques. The results put forward CDM-PI control strategy. In addition, the robustness of the control systems is also tested. It concludes that the CDM based PI controller works well against the uncertainties of the nonlinear pH system.

NOMENCLATURE

y : Output signal
r : Reference input

u : Controller signal
d : External disturbance signal
$N(s)$: Numerator polynomial of the plant transfer function
$D(s)$: Denominator polynomials of the plant transfer function
$A(s)$: Forward denominator polynomial of the controller transfer function
$F(s)$: Reference numerator polynomial of the controller transfer function
$B(s)$: Feedback numerator polynomial of the controller transfer function
$P(s)$: Characteristic polynomial of the closed-loop system
$P_{target}(s)$: Target characteristic polynomial of the closed-loop system
l_i, k_i and a_i : Coefficients of CDM controller polynomials
$C(s)$: Main controller
$C_f(s)$: Feed forward controller
K_1 and K_0 : CDM controller parameters
K_c and T_i : CDM-PI controller parameters
HCl : Hydrochloric acid
NaOH : Sodium hydroxide
Kp : Process gain
t_r : Rise time
t_s : Settling time
%Mp : Peak overshoot

Greek symbols

γ_i : Stability indices
τ : Equivalent time constant
τ_p : Process time constant
θ : Process delay

Abbreviation

CDM : Coefficient diagram method
FOPTD : First order plus time delay
PI : Proportional integral
ETP : Effluent treatment plant
CSTR : Continuous stirred tank reactor
DC : Direct current
PC : Personal computer
DAC : Digital to analog converter
ISE : Integral squared error
IAE : Integral absolute error
TV : Total variation
Lpm : Liter per minute
CDM-PI : Coefficient diagram method-proportional integral
ZN-PI : Ziegler Nichols-proportional integral
AB-PI : Abbas-proportional integral
ST-PI : Saeed Tavakoli-proportional integral

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REFERENCES

Abbas, A., 1997. A new set of controller tuning relations. ISA transactions, 36: 183-187.

Ahmed, D.F., S.K.H. Al-Dawery and H.A.O. Al-Anbari, 2007. On-line control of the neutralization process based on fuzzy logic. Emirates J. Eng. Res., 12: 89-97.

Akesson, B., T. Hannu, J. Waller and R. Nystrom, 2005. Neural network approximation of a nonlinear model predictive controller applied to a pH neutralization process. J. Comput. Chem. Eng., 29: 323-335.

Bhaba, P.K., S. Sathishbabu, A. Asokan and T. Karunanithi, 2007. Real time implementation of Wiener Model PI (WMPI) controller in a conical tank liquid level process. J. Applied Sci., 7: 2194-2197.

Chen, D. and D.E. Seborg, 2002. PI/PID controller design based on direct synthesis and disturbance rejection. Ind. Eng. Chem. Res., 41: 4807-4822.

Gobal, M., 2002. Control Systems Principles and Design. 2nd Edn. TATA McGraw Hill, New Delhi, pp: 755-761.

Gustafsson, T.K. and K.V. Waller, 1992. Nonlinear and adaptive control of pH. Ind. Eng. Chem. Res., 31: 2681-2693.

Hamamci, S.E., P.K. Bhaba, S. Somasundaram and T. Karunanith, 2007. Two degree of freedom transient response control for unstable. Proceedings of the 5th International Conference on Trends in Industrial Measurements and Automation, NIT, January 4-7, 2007, Tiruchirapalli, India, pp: 145-150.

Hanif, M.A., R. Nadeem, U. Rashid and M.N. Zafar, 2005. Assessing pollution levels in effluents of industries in city zone of Faisalabad, Pakistan. J. Applied Sci., 5: 1713-1717.

Jutila, P., 1983. An application of adaptive pH-control algorithms based on physicochemical in a chemical waste-water treatment plant. Int. J. Control, 38: 639-655.

Lin, F., R.D. Brandt and G. Saikalis, 2000. Self-tuning of PID controllers by adaptive interaction. Proceedings of the American Control Conference, 2000, June 28-30, 2000, Chicago, IL, USA, pp: 3676-3681.

Manabe, S., 1998. Coefficient diagram method. Proceedings of the 14th IFAC Symposium on Automatic Control in Aerospace, August 24-28, 1998, Seoul, Korea, pp: 199-210.

Nithya, S., A.S. Gour, N. Sivakumaran, T.K. Radhakrishnan, T. Balasubramanian and N. Anantharaman, 2008. Design of intelligent controller for non-linear processes. Asian J. Applied Sci., 1: 33-45.

Palancer, M.C., Aragon, J.M., Miguens, J.A. and J.S. Torrecilla, 1996. Application of a model reference adaptive control system to pH control. Effects of lag and delay time. Ind. Eng. Chem. Res., 35: 4100-4110.

Rivera, D.E., M. Morari and S. Skogestad, 1986. Internal model control for PID controller design. Ind. Eng. Chem. Proc. Des. Devel., 25: 252-265.

Swati, D., V.S.R. Rao, R. Pickhardi and M. Chidambaram, 2008. Nonlinear PI controller for time delayed pH system. Indian Chem. Eng., 50: 93-105.

Tavakoli, S. and P. Fleming, 2003. Optimal tuning of PI controllers for first order plus dead time/long dead time models using dimensional analysis. Proceedings of the 7th European Control Conference, September 1-4, 2003, Cambridge, UK.

Valarmathi, K., D. Devaraj and T.K. Radhakrishnan, 2009. Intelligent techniques for system identification and controller tuning in pH process. Brazilian J. Chem. Eng., 26: 99-111.

Zhang, J., 2001. A nonlinear gain scheduling control strategy based on neuro-fuzzy networks. Ind. Eng. Chem. Res., 40: 3164-3170.