Nonlinear Control of pH System for Change Over Titration Curve

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Original scientific paper
Received: January 21, 2005
Accepted: October 1, 2005

Wiener model based nonlinear controller for a pH process efficiently tackles the variations in gain. However, the controller performance deteriorates for significant change over titration curve (i.e. when the nature of the feed stream switches from a weak acid to a strong acid). To improve the performance of this controller, a nonlinear cascade controller is proposed. The nonlinear cascade structure consists of a Wiener model based nonlinear P controller in the inner loop and a linear PI controller in the outer loop. The proposed strategy is simulated for switch over titration curve from a weak acid – strong base system to strong acid – strong base system and then back to the weak acid – strong base system. The performance of the nonlinear cascade controller is compared with that of single loop Wiener model based PI controller and linear cascade (P-PI) controller.

Keywords:
pH, Wiener model, nonlinear cascade structure, strong acid, weak acid

Introduction

pH control is one of the most difficult problems encountered in process industries because of the severe non-linearity and time varying nature of the titration curve. Steady state gain varies drastically with the operating point. Even a small change in the composition can radically change the gain characteristics of the titration curve. Hence linear model-based controllers are not adequate to control pH. To tackle such nonlinearities Wiener model based controllers were proposed. The implementation of the controller is based on known titration curve and can handle mild variations in titration curve. However, the performance of the controller is not satisfactory for large variations in titration curves. To control the pH for significant variations in the titration curve, several model-based controllers were developed.

Wright and *Kravaris*[1] based on strong acid equivalent approach, developed a technique for on-line identification and control of an industrial pH process with unknown chemical composition. The technique is robust to modeling errors but fails when the titration curve undergoes large variations. *Pishvaie* and *Shahrokhi*[2] suggested multiple models, switching and tuning to overcome variations in the shape of the titration curve. This method works for large changes in titration curves but requires rigorous computations for model identification. *Lee* et al.[3] developed a relay feedback with hysterisis for tuning of nonlinear pH control systems where the pH process is parameterized with three parameters. But the controller performance is poor for setpoints far from where the model is evaluated. *William* et al.[4] (1990) suggested an in-line process model based control of wastewater pH using dual base injection. The method handles system response to changes in feed composition alone but fails when the titration curve varies significantly. *Lakshmi Narayanan* et al.[5] proposed an adaptive internal model control strategy for pH neutralization. The method gives good results when the titration curve undergoes large variations but employs a tuning factor whose tuning methodology has not yet been established. *Parekh* et al.[6] suggested in-line control of pH neutralization based on fuzzy logic. The method shows satisfactory performance over a wide operating range, but the design of fuzzy logic controller is difficult, since the fuzzy inference rules require a lot of insight and understanding of the problem. Very often, the rules can be derived heuristically rather than from closed-form mathematical formulae. Hence it is difficult to automate the design process. Recent studies on the applications of Wiener model based controller for pH system are reported by *Kalafatis* et. al.[7,8]. *Palancar* et. al.[9,10] considered measurement delay and proposed model reference adaptive control system for pH control and by neural network, respectively.

In the present work, to address the problem of maintaining pH at 7 when the titration curve undergoes large changes, a cascade structure is proposed. This structure consists of an inner loop (slave controller), which is a typical Wiener model with a nonlinear proportional controller. The outer loop

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(master controller) is a conventional feedback loop with a PI controller. This strategy also compares the performance of (i) linear cascade controller (P-PI) and (ii) single loop Wiener model-based PI controller. The nonlinear model equations are simulated with all three controllers. The change over of titration curves from Weak acid (CH_3COOH , 0.025 mol l^{-1}) – Strong base (NaOH, 0.025 mol l^{-1}) to Strong acid (H_2SO_4, 0.02 mol l^{-1}) – strong base (NaOH, 0.025 mol l^{-1}) and then back to weak acid system are considered. The effect of small time delay (3 s) on the response of the system for such change over of titration curves is studied separately.

Modeling of the pH process

The pH process is modeled by a set of differential equations followed by a nonlinear algebraic equation. Consider a CSTR of volume (V) 5.7l. Let Q_a , Q_b be the flow rates of acid and base streams, respectively. The concentrations of acid and base in the process and titrating streams are c_a, c_b, respectively. Let c_{x_a} , c_{x_b} be the state variable concentrations of acid and base at the outlet. The mathematical equations that represent the dynamic behaviour of the process are as follows:

$$V(\mathrm{d}c_{x_a}/\mathrm{d}t) = Q_a c_a - (Q_a + Q_b)c_{x_a} \tag{1}$$

$$V(\mathrm{d}c_{x_b}/\mathrm{d}t) = Q_b c_b - (Q_a + Q_b)c_{x_b} \tag{2}$$

$$-kc_{xa} + c_{xb} + 10^{-\mathrm{pH}} - 10^{\mathrm{pH}-14} = 0 \tag{3}$$

where,

k = 1 – for strong acid – strong base system (4)
= 1 /(1 + $10^{(pKa - pH)}$) for a weak acid – strong base system. (5)

(K_a is the dissociation constant of the weak acid, CH_3COOH = 1.83 × 10^{-5})

At the operating point of pH 7, the process is approximated as a first order transfer function [$K_p/(\tau_p s + 1)$]. The process parameters (K_p and τ_p) are evaluated from simulation results on the actual nonlinear system from the transient response for step change in base flow rate in increased and decreased base flow. The steady state gain for the strong acid system is about 350 times that of the weak acid system but the process time constants of the systems do not vary significantly. The calculated process parameters for the weak acid – strong base and strong acid – strong base systems are given in Table 1.

Table 1 – *Process model parameters at pH 7*

System	K_p / pH (l min^{-1})	τ_p / min
H_2SO_4 (0.02 mol l^{-1}) – NaOH (0.025 mol l^{-1})	30157	3.1667
CH_3COOH (0.025 mol l^{-1}) – NaOH (0.025 mol l^{-1})	78.76	2.865

Wiener model

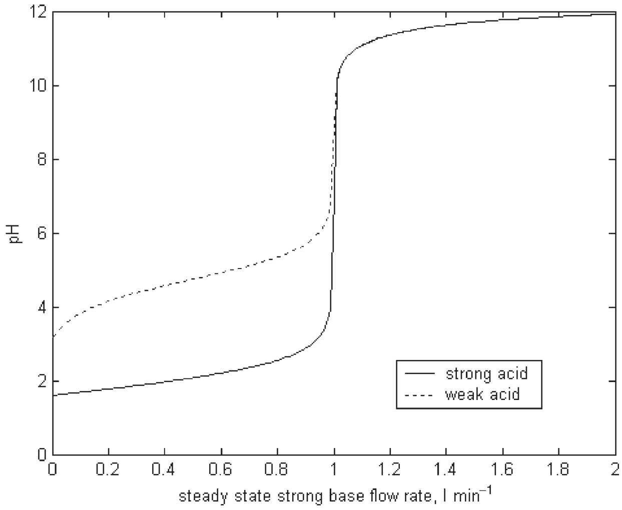
Wiener model consists of a linear dynamic element (LDE) followed in series by a nonlinear static element (NLE). The gain of the process is concentrated in the nonlinear element, so the linear dynamic element will be of unity gain. From equations (1), (2) and (3) it is seen that Wiener model (linear dynamic equations followed by nonlinear algebraic equation) suitably describes the pH process.

The choice of the nonlinear static element ranges from simple algebraic equations to complex neural networks. The choice is governed by the fact that, the model used for control purpose should have an inverse. Polynomial models are usually employed to represent the nonlinearities because they have an inverse by means of their roots. Odd degree polynomials are preferred because they have at least one real root. Here, third order piecewise continuous polynomials are used to represent the nonlinearity of the process. The linear dynamic element can be represented as an ARX (Auto Regressive exogenous input) or simple step change model. In the present case, a first order model with unity gain is chosen to represent the dynamic behaviour of the process.

Design of controllers

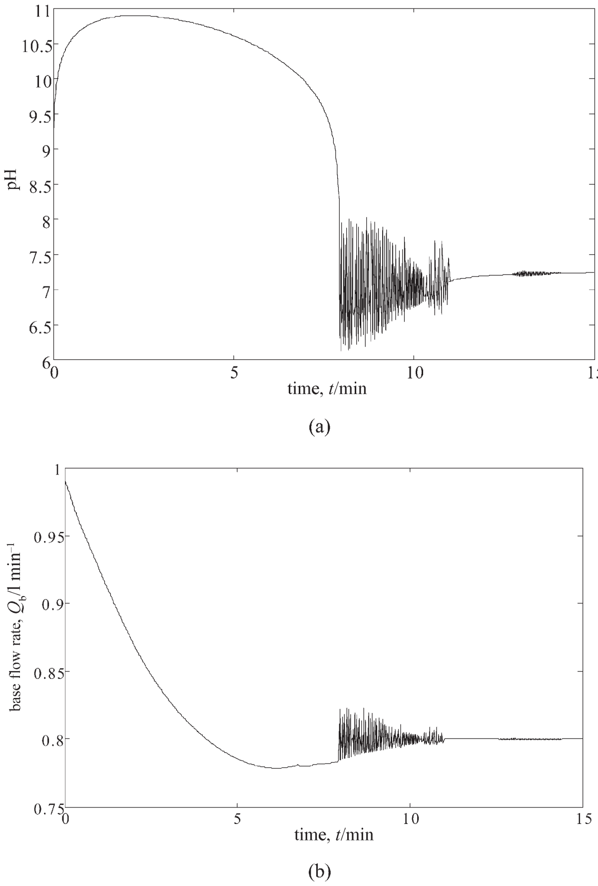
The steady state gain varies significantly when the system switches from weak acid to strong acid. Hence, linear model based single PI controllers cannot give satisfactory results. To account for these gain variations Wiener model based nonlinear controllers are used. As discussed earlier, the linear dynamic element of the Wiener model is a unity gain first order transfer function and the nonlinear static gain is represented by a set of third degree piecewise continuous polynomials (6 zones for weak acid – strong base system and 7 zones for strong acid – strong base system). Figure 1 shows the titration curve for strong acid-strong base and weak acid-strong base system.

The implementation of the Wiener model based controller is carried out in two stages and it is based



F i g . 1 – *Titration curves for strong acid-strong base system & weak acid – strong base system*

on known titration curve. In the first stage, the inverse of the set point and the output are obtained by inverting the polynomial gain relation [i.e. the polynomial is solved for its real root of Q_b]. In the second stage, the difference in these values is fed to the controller, for the necessary corrective action. Since the nonlinear gain is cancelled by its inverse, the controller is designed for the unity gain subsystem time delay. The combined root calculation followed by PI controller for the unity gain subsystem constitutes the nonlinear controller. The nonlinear model equations are simulated for change over titration curve from weak to strong acid system with this controller. Figure 2 shows that the system response is not satisfactory. Although, the offset is small (0.23), the manipulated variable fluctuates rapidly over a short period of time. Such a valve action is not possible in practice.



F i g . 2 – *Response with Wiener model based nonlinear controller, for switch over titration curve from weak to strong acid system. Six zone polynomial fit is used to represent the static nonlinear gain. (a) system response (b) response of the manipulated variable*

To handle this problem, a rigorous polynomial fit for the nonlinear gain is carried out (9 zones for weak acid – strong base system and 12 zones for strong acid – strong base system). Tables 2 and 3

T a b l e 2 – *Values of coefficients of the equation* $pH = A_0u^3 + A_1u^2 + A_2u + A_3$ *for* CH_3COOH *and NaOH system ('u' is the base flow rate (l min^{-1})) (rigorous fit)*

pH range	A_0	A_1	A_2	A_3
3.19 ≤ pH < 4.445	29.49	−23.625	8.37	3.187
4.445 ≤ pH < 5.4725	3.3598	−4.982	4.1593	3.4844
5.4725 ≤ pH < 6.49	0.4865×10^3	-1.288×10^3	1.4018×10^3	-0.3319×10^3
6.49 ≤ pH < 7.5205	0.564×10^6	-1.673×10^6	1.6538×10^6	-0.5448×10^6
7.5205 ≤ pH < 8.5635	0.8115×10^8	-1.068×10^8	2.4258×10^8	-0.807×10^8
8.5635 ≤ pH < 9.7224	0.355×10^8	-3.535×10^8	1.071×10^8	-0.3578×10^8
9.7224 ≤ pH < 10.638	0.342×10^5	-1.054×10^5	1.084×10^5	0.372×10^5
10.638≤ pH < 11.449	0.836×10^2	-3.014×10^2	3.643×10^2	-1.361×10^2
11.4492 ≤ pH < 11.85	0.7535	−4.3325	8.6339	5.9545

Table 3 – – *Values of coefficients of the equation* $pH = A_{0<I>}u^3 + A_{1<I>}u^2 + A_{2<I>}u + A_3$ *for* H_2SO_4 *and NaOH system where 'u' is the base flow rate* ($l\ min^{-1}$) *(rigorous fit)*

pH range	A_0	A_1	A_2	A_3
1.7 ≤ pH < 2.854	3.598	−2.335	1.506	1.676
2.854≤ pH < 3.947	3.329×10^3	-7.35×10^3	5.409×10^3	-1.325×10^3
3.947 ≤ pH < 5.01	0.549×10^7	-1.306×10^7	1.038×10^7	-0.275×10^7
5.01 ≤ pH < 5.91	0.534×10^{10}	-1.28×10^{10}	1.024×10^{10}	-0.272×10^{10}
5.91 ≤ pH < 6.696	1.518×10^{12}	-3.64×10^{12}	2.92×10^{12}	-0.777×10^{12}
6.696 ≤ pH < 7.358	-0.908×10^{13}	2.178×10^{13}	-1.743×10^{13}	0.485×10^{13}
7.538 ≤ pH < 8.095	1.475×10^{12}	-3.541×10^{12}	2.833×10^{12}	-0.755×10^{12}
8.095 ≤ pH < 8.935	0.760×10^{10}	-1.826×10^{10}	1.462×10^{10}	-0.39×10^{10}
8.935 ≤ pH < 9.816	1.748×10^7	-4.22×10^7	3.387×10^7	-0.91×10^7
9.816 ≤ pH < 10.69	3.863×10^4	-9.58×10^4	7.92×10^4	-2.18×10^4
10.69 ≤ pH < 11.542	0.708×10^2	-2.17×10^2	2.23×10^2	-0.655×10^2
11.542 ≤ pH < 12.00	0.2430	−1.5917	3.6249	9.1723

give the increased range polynomial fit for the weak and strong acid systems, respectively. Simulation result for switch over titration curve from weak to strong acid system with increased range of polynomial fit is shown in Figure 3. The figure shows the performance improvement of the controller with increased number of zones in the polynomial fit. The offset with this controller is zero. Nevertheless, the manipulated variable fluctuates highly and such a response is impractical.

Instead of fitting higher order polynomial, we can use the exact equation for the pH versus base flow rate. At steady state condition, eqs (1) and (2) can be solved for c_{xa} and c_{xb} and substituting in Eq (3) we get:

$$-[k Q_a c_a/(Q_a + Q_b)] + [Q_b c_b/(Q_a + Q_b)] + \\ + 10^{-pH} - 10^{pH-14} = 0 \qquad (6)$$

Using this equation, for a given pH, the value of Q_b can be calculated numerically.

When the titration curve changes from weak to strong acid system, a mismatch arises between the actual nonlinear gain and the nonlinear inverse used for control calculations and hence the nonlinear Wiener model based PI controller fails to perform satisfactorily. To handle such mismatches, cascade controllers are proposed here.

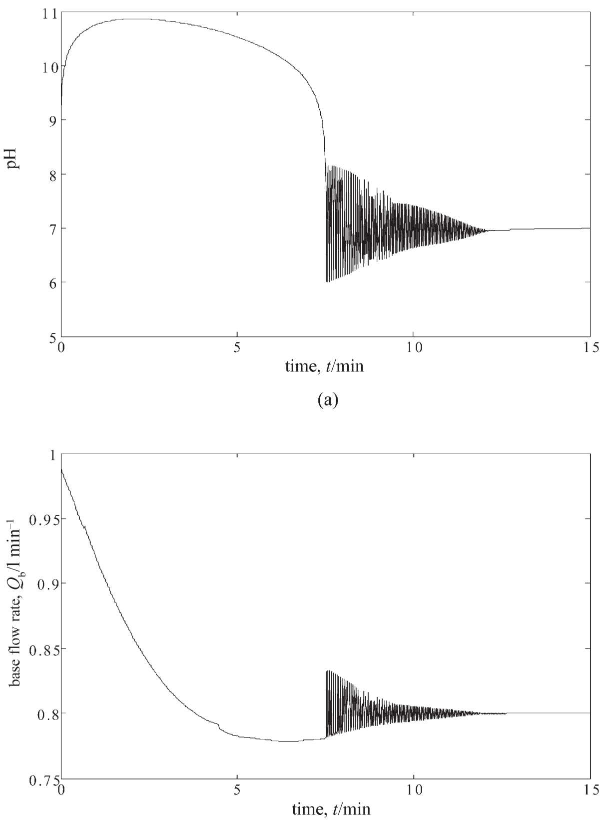
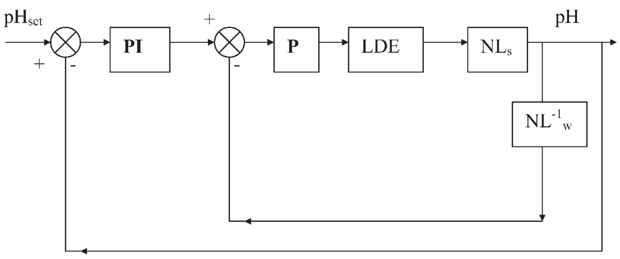


Fig. 3 – *Response with Wiener model based nonlinear controller, for switch over titration curve from weak to strong acid system. Nine zone polynomial fit is used to represent the static nonlinear gain. (a) system response (b) response of the manipulated variable.*

Nonlinear cascade controller

The nonlinear cascade controller (refer Figure 4) consists of an inner loop, which is a typical Wiener model with a nonlinear proportional (P) controller (slave or secondary controller). The outer loop is a conventional feedback loop with a linear PI controller. As discussed earlier, the implementation of the inner loop Wiener model based controller is in two stages and the controller is designed for the unity gain subsystem. When the titration curve switches from weak to strong acid system, the nonlinear inverse corresponds to the weak acid system, but the pH of the strong acid system is actually measured. Hence nonlinear gain does not cancel totally with the nonlinear inverse and thus leaves a residue. Hence a single loop Wiener model based controller designed for the unity gain subsystem fails to perform satisfactorily. This mismatch between the nonlinear gain and the nonlinear inverse is handled by the outer loop primary PI controller. The primary PI controller eliminates offset. The dynamics of the inner loop are much faster than those of the outer loop. Therefore, higher gains can be used in the secondary controller in order to efficiently reject the disturbances occurring in the inner loop without endangering the stability of the system.



NL_s – Nonlinear gain of strong acid system
NL_w^{-1} – Nonlinear inverse of weak acid system

Fig. 4 – *Nonlinear cascade controller*

The secondary nonlinear P controller gain, K_{cs} is tuned (trial and error) to a value of 0.1956. The time constant of the weak acid system (τ_p = 2.865 min) is considered as the time constant of the unity gain subsystem. Assuming that the nonlinear gain and the nonlinear inverse cancel out, the closed loop transfer function of the inner loop is $[k^*/(\tau^* s + 1)]$ where $k^* = \{K_{cs}/(1 + K_{cs})\}$ and $\tau^* = \{\tau/(1 + K_{cs})\}$. The primary, linear PI controller is designed for the closed loop transfer function of the inner loop using pole placement technique (*Chidambaram*[11]) with $\zeta = 0.707$ and $t_s/\tau = 5$. The primary controller settings are obtained as: K_c = 6.0845 (l min^{-1}) /pH, τ_I = 1.1978 min.

For the purpose of comparison, the switch over of titration curves is simulated using linear cascade controller (P-PI) and regulatory single loop Wiener model based PI controller. The inner loop P controller of the linear cascade structure is designed based on the linear process parameters of the weak acid system. The secondary P controller gain, K_{cs} is 0.00248 (This value of K_{cs} is obtained by dividing the K_{cs} tuned for the unity gain transfer function i.e. the K_{cs} of the nonlinear cascade controller by the gain, K_p of the weak acid system). The closed loop transfer function of the inner loop is $[k^*/(\tau^* s + 1)]$, where $k^* = \{K_{cs} K_p/(1 + K_{cs})\}$ and $\tau^* = \{\tau/(1 + K_{cs})\}$. The outer loop PI controller is designed for the closed loop transfer function of the inner loop. The outer loop PI of the linear cascade controller and single loop Wiener model based PI controller are designed using pole placement method (ζ = 0.707 and $t_s/\tau = 5$). The primary controller settings of the linear cascade controller are calculated as: K_c = 6.0845, τ_I = 1.1978 min. The controller settings for the single loop Wiener model based nonlinear PI controller along with the nonlinear gain inverse are calculated as: K_c = 1.0, τ_I =1.4321 min.

Simulation results

The titration curve switches from weak acid system (CH_3COOH) to strong acid system (H_2SO_4) and then back to the weak acid system. The simulation results demonstrate the superior performance of the nonlinear cascade controller in comparison to linear cascade and single loop Wiener model based PI controllers. The nine zone polynomial fit (Table 2) shows no offset and hence it is used in the simulation studies. Figure 5 shows the system response using nonlinear cascade and linear cascade controllers. The response of pH using single loop Wiener

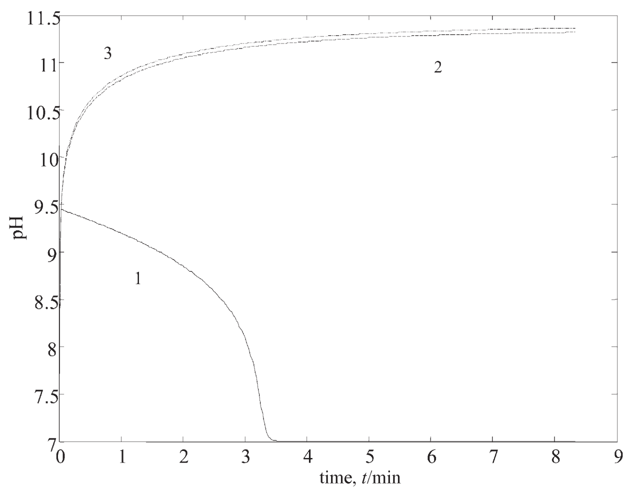


Fig. 5 – *Response of the system for switch over titration curve from weak to strong acid system. 1 – Nonlinear cascade controller, 2 – Linear cascade controller, 3 – Open loop response.*

model based nonlinear PI controller is shown earlier in Figure 3. Due to the mismatch in actual measured pH and the nonlinear inverse, the system response using single loop Wiener model based controller is not satisfactory. The response fluctuates rapidly over a short period of time and then settles. Further, the system takes a longer time to settle (12.5 min) whereas, the linear cascade controller fails to account for the gain variations and hence the system moves to a different operating pH resulting in large offset, and shows a response similar to that of the open loop response. The mismatch which results from partial cancellation of nonlinear gain equation and its inverse, is efficiently handled by the outer loop linear PI controller of the nonlinear cascade controller. The nonlinear cascade controller eliminates offset and gives a fast (settling time = 3.5 min) and stable response. The comparative performance of these controllers is shown in Table 4.

Table 4 – *Controller performance for the regulatory problem of change over titration curve from weak acid to strong acid system*

Controller	ISE	IAE	peak error	offset
Nonlinear cascade	731.10	370.10	2.5	0
Linear cascade	8495.36	2055.6	4.32	4.32
Single loop Wiener PI	5597.73	1680.67	3.9	0

ISE and IAE calculated from $t = 0$ to $t = 900$ s with a step size = 1 s.

Figure 6 shows the response of pH using the above cascade controllers and single loop Wiener model based PI controller, when the titration curve shifts from strong acid (high gain) back to the weak acid (low gain) system. The results demonstrate the superior performance of nonlinear cascade controller in terms of undershoot and settling time. The settling time and undershoot with nonlinear cascade controller are 5 min and 0.03, respectively. The steady state gain changes from a very high value (30157) to a low value (78.76) and hence linear cascade structure, and single loop Wiener model based nonlinear PI controller eliminate offset and bring back the pH 7. Due to the ability of single loop Wiener model based nonlinear controller to tackle gain variations, its performance is superior to that of linear cascade controller. The settling time and undershoot using single loop Wiener PI is 18.5 min and 1.1 and that of linear cascade controller is 22.5 min and 1.4, respectively. However, the system response is very sluggish in comparison to the nonlinear cascade controller. The performance of the controllers evaluated in terms of ISE and IAE values is shown in Table 5. Figure 7 shows the response of the manipulated variable for switch over titration curve from strong acid system back to the weak acid system.

Table 5 – *Controller performance for the regulatory problem of change over titration curve from strong acid to weak acid system*

Controller	ISE	IAE	Undershoot	t_s / min
Nonlinear cascade	1.3895	14.038	0.22	5.5
Linear cascade	1117.93	1023.4	1.36	23
Single loop Wiener PI	394.73	505.67	1.13	18.5

ISE and IAE calculated from $t = 0$ to $t = 900$ s (step size = 1 s). t_s – settling time

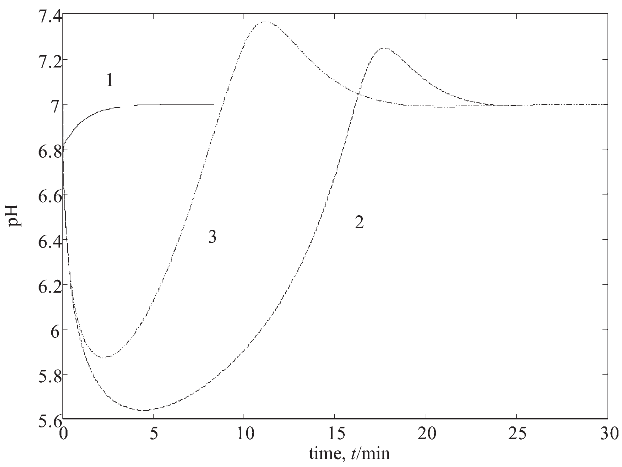


Fig. 6 – *Response of the system for change over titration curve from strong acid to weak acid syste. 1 – Nonlinear cascade controller; 2 – Linear cascade controller; 3 – Single loop Wiener PI (open loop settles at pH 5.3).*

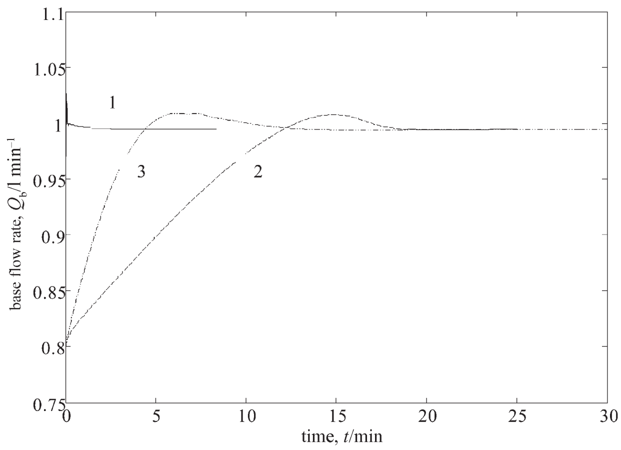


Fig. 7 – *Response of manipulated variable for change over titration curve from strong to weak acid system. 1 – Nonlinear cascade controller; 2 – Linear cascade controller; 3 – Single loop Wiener PI.*

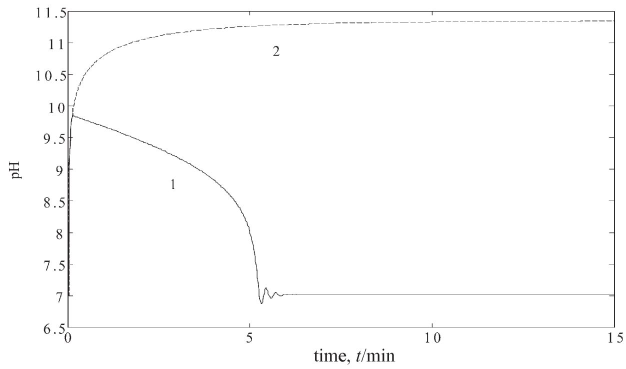
Effect of time delay

pH processes are characterized by time delays. The time delays may arise due to flow variations, measurement, and actuator dynamics. However, in the present study a small measurement time delay (L) of 3 s (*Parekh* et al.[4]) is considered. The three controllers are designed, simulated, and compared for change over titration curves from weak to strong acid system, and then back to the weak acid system. As discussed in the previous section, the nonlinear cascade controller consists of an inner loop with a nonlinear P controller and an outer loop with a linear PI controller. The control system is similar to that given in the block diagram in Figure 4. The nonlinear P controller is designed for the unity gain transfer function with time delay. The outer loop linear PI controller handles the mismatch that arises from change over titration curve. The secondary nonlinear P controller, K_{cs} is tuned to a value of 0.19575. Assuming that the nonlinear gain cancels with the nonlinear inverse, the closed loop transfer function of the inner loop is $[k^*/(\tau^* s + 1)]$ where, $k^* = \{K_{cs}e^{-Ls}/(1 + K_{cs})\}$ and $\tau^* = \{(\tau - K_{cs} L)/(1 + K_{cs})\}$ [time delay, e^{-Ls} in the denominator is approximated as $(1 - Ls)$]. The outer loop PI controller is designed for the closed loop transfer function of the inner loop. The primary PI controller settings are obtained by pole-placement technique with $\zeta = 0.707$ and $t_s = 8\tau$. The controller settings for primary PI controller are: $K_c = 1.5861$, $\tau_I = 0.7976$ min.

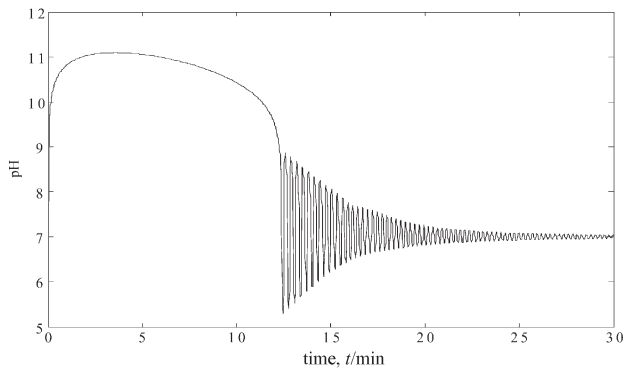
The design of linear cascade controller is based on the process parameters of the weak acid system at pH 7. The inner secondary controller (P) gain for the first order transfer function is, $K_{cs} = 0.002485$ (This value of K_{cs} is obtained by dividing the K_{cs} tuned for the unity gain transfer function i.e. the K_{cs} of the nonlinear cascade controller by the gain, K_p of the weak acid system). The outer loop PI is then designed for the closed loop transfer function of the inner loop. The closed loop transfer function of the inner loop is $[k^*/(\tau^* s + 1)]$ where, $k^* = \{K_{cs}K_p e^{-Ls}/(1 + K_{cs})\}$ and $\tau^* = \{(\tau - K_{cs} L)/(1 + K_{cs})\}$ (time delay, e^{-Ls} in the denominator is approximated as $(1-Ls)$). The design of outer loop PI of the linear cascade and single loop Wiener model based PI controllers is based on pole placement method with $\zeta = 0.707$ and $t_s = 8\tau$. The controller settings obtained for outer loop PI of the linear cascade controller and single loop Wiener model based nonlinear PI controller are $K_c = 1.5861$, $\tau_I = 0.7976$ min and $K_c = 0.258$, $\tau_I = 0.950$ min, respectively.

Simulation results

The nonlinear equations with a measurement time delay of 3 s are simulated for change over titration curves, using (i) nonlinear cascade controller, (ii) linear cascade controller, and (iii) single loop Wiener model based nonlinear PI controller. Figure 8 shows the response of pH for switch over of titration curve from weak to strong acid system using nonlinear cascade controller, linear cascade controller and Figure 9 shows the response using single loop nonlinear Wiener PI controller. The results show the superior performance of the nonlinear cascade controller. The response using the nonlinear cascade controller is fast and stable. The linear controller fails to tackle the gain variations and hence gives large offset, while the response with single loop Wiener model based PI controller oscillates about the pH 7.

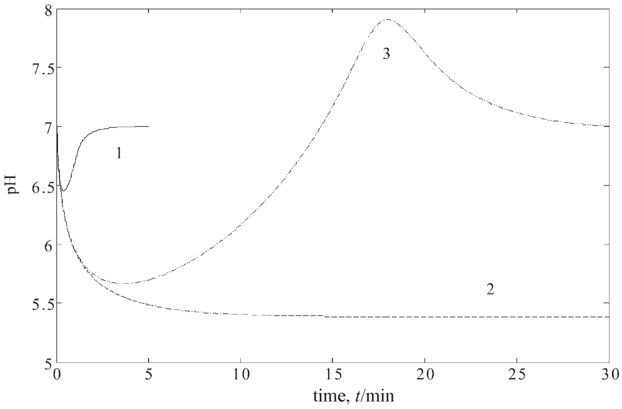


F i g . 8 – *Response of the system for change over titration curve from weak to strong acid system. Time delay is 3 sec. 1 - Nonlinear cascade controller, 2 - Linear cascade controller.*



F i g . 9 – *Response of the system for switch over titration curve from weak to strong acid system using single loop Wiener PI. Time delay is 3 s.*

Figure 10 shows that for switch over titration curve from strong to weak acid system, nonlinear cascade controller gives stable and faster response in comparison to single loop Wiener PI controller and the linear cascade controller gives large offset. The settling of the system with nonlinear cascade



F i g . 1 0 – *Response of the system for change over from strong to weak acid system. Time delay is 3 s. 1 – Nonlinear cascade controller, 2 – Linear cascade controller, 3 – Single loop Wiener PI.*

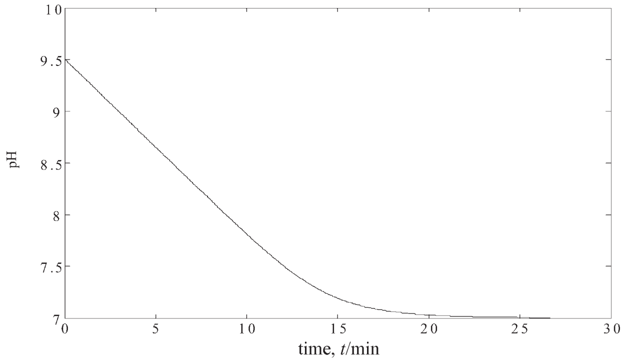
controller is 3.8 min and that with single loop Wiener PI is 28.5 min. The performance of the controllers in terms of ISE and IAE is tabulated in Table 6. Hence, it can be concluded that the performance of the nonlinear cascade controller is superior to that of the linear cascade controller and single loop Wiener model based nonlinear PI controller.

T a b l e 6 – *Controller performance for switch over titration curve (time delay = 3 s).*

Controller	Weak to strong acid system			Strong to weak acid system		
	ISE	IAE	offset	ISE	IAE	offset
Nonlinear cascade	1539.26	676.92	0	13.61	35.83	0
Linear cascade	32986.8	7698.18	4.34	4348.6	2779.5	1.16
Single loop Wiener PI	10483.5	3028.19	0.04	1062.2	1115.6	0

ISE and IAE calculated from t = 0 to t = 1800 s., step size = 1 s

The above simulation studies of nonlinear cascade and single loop Wiener PI controllers are based on the nonlinear inverse of the weak acid. The nonlinear inverse of the strong acid system in the feedback loop is also considered. Figure 11 shows the simulation result for switch over titration curve from weak to strong acid system with nonlinear cascade controller using the nonlinear inverse of the strong acid system. The figure shows the sluggish response of the system. The settling time with the nonlinear inverse of the strong acid system is 23 min and that with the weak acid inverse is 3.5 min.



F i g . 1 1 – *Regulatory response of the system with nonlinear cascade controller, for switch over titration curve from weak to strong acid system using the nonlinear inverse of the strong acid system. (disturbance introduced at t = 0 at pH 7)*

Conclusions

The implementation of the single loop Wiener model based nonlinear PI controller is based on known titration curve. For significant change over titration curve, there exists a mismatch between the nonlinear gain of the actual process and the one used in the controller calculations and, hence the single loop nonlinear controller fails to perform satisfactorily. A linear cascade controller with a linear P in the inner loop and a linear PI in the outer loop fails to handle the gain variations. A nonlinear cascade controller is proposed to control the pH for significant change over titration curve.

Nomenclature

c_a – concentration of acid in the feed, mol l^{-1}
c_b – concentration of base in the feed, mol l^{-1}
Q_a – flow rate of acid stream, l min^{-1}
Q_b – flow rate of base stream, l min^{-1}
K_c – controller gain
K_{cs} – secondary controller gain
K_p – process gain
NL – nonlinear element
NL^{-1} – nonlinear inverse
pK_a – –log (K_a)
PI – proportional – Integral
PID – proportional – Integral – Derivative
u – manipulated variable, Q_b, l min^{-1}
c_{xa} – concentration of acid in the exit stream
c_{xb} – concentration of base in the exit stream
τ_p – process time constant
$\tau_{p,ave}$ – average time constant of the process
t_s – settling time
τ_I – integral time
γ – controller weighting
ζ – damping coefficient

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