Performance Analysis of pH Neutralization Process for Conventional PI Controller and IMC Based PI Controller

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Abstract

The pH control process stays in center in a wide range of industries including wastewater treatment, biotechnology, pharmaceuticals and chemical processing. The general aim is to maintain the pH value within a liquid at a specific level. The objective of this process is to neutralize the fluid under test by regulating the reagent solution flow rate until the mixture stabilizes at set point. After analyzing the mathematical model of the process, Simulink model is developing. Neutralization process is controlling by PI controller and IMC-PI controller. The performance of the advanced controllers are comparing with that of conventional PI controller.

Keywords: FOPTD Process, IMC-PI Controller, Model Based Controllers, pH Neutralization Process, ZN –PI Controller

I. INTRODUCTION

The pH neutralization process plants are widely used in waste water treatment plants. It has applications in process industries such as bio technology, chemical processing, pharmaceutical, fermentation and food processing industries. It is one of the most difficult problems in process industries due to severe non linearity and time varying nature of titration curve. Even a small change in composition can affect titration curve, so modelling and control of pH neutralization plants are very difficult.

Studies on pH neutralization control in process industries have shown a dramatic increase in the last years. A perfect and simple mathematical modelling of pH process is introduced by McAvoy is a mile stone in the development of pH process [1]. Fuzzy and Neural network based models also performs well [2]. CDM –PI controllers are designed for the pH control in textile industries [3]. A comparative study of ZN PI, GA PI, BFO PI controllers are available [4]. IMC based PI, PID controllers are also used to control the neutralization reaction [5]. Fractional order PI controller is a good option for the pH neutralization process [6]. Most of the papers are based on fuzzy logic controller; FLC provides good performance for the system. In some studies the set point of process also given as input [7]. But in most cases the ordinary FLC with two inputs and one output is used [8]. Hybrid fuzzy PID controllers can be used for control strong acid–strong base neutralization [9]. Here the output of fuzzy logic controller used to adjust the PID parameters. Adaptive fuzzy sliding mode control also introduced in some papers [10]. Model based controller is a good attempt for the control of both strong acid–strong base and weak acid – strong base neutralization reaction. MRAC have shown excellent control of the process [11]. Most of the papers propose MIT rule to design MRAC. There are some papers which compare the performance of MRAC and AIMC on the process [12]. Some papers describes the use of model predictive controller (MPC) [13]. Adaptive non-linear control strategy also developed for the process. Studies are taking place to control the pH using robust loop shaping approach [14].

Here section 2 provides the detailed working of system and section 3 is mathematical modelling of the system. Section 4 deals with design of controllers and 5 is performance analysis of controllers. The last section is the conclusion.
II. NEUTRALIZATION PROCESS

The pH neutralization system The system consists of a CSTR with 2 input streams. One is influent stream (acidic) with the concentration (Conc.)a moles/L and flow rate of Fa L/min another is reagent stream with concentration (Conc.)b moles/L and flow rate of Fb L/min. The objective of this process is to neutralize the inlet fluid from the input stream by regulating the reagent solution flow rate Fb until the mixture stabilizes at pH equal to 7 or between the specified. The volume in the tank is constant and equal to V.

III. MATHEMATICAL MODELLING

pH is defined as the negative logarithm of hydronium ion\([H^+]\) (or hydrogen ion) concentration. It is given by:

\[
pH = -\log[H^+]
\]  
(1)

The chemical reaction between the two solutions (Strong Acid Strong Base system) taking place in the CSTR

\[
H^+ + Cl^- + Na^+ + OH^- = H_2O + Na^+ + Cl^-
\]  
(2)

Thus, the ionic concentration of \([Na^+]\) and \([Cl^-]\) in effluent stream would be related to the flows \(F_a\), \(F_b\) and feed concentration of HCl & NaOH entering the tank. Hence the mass balance equation is given by:

\[
\frac{d}{dt} [Cl^-] = [Cl^-] F_a - [Cl^-] (F_a + F_b)
\]  
(3)

\[
\frac{d}{dt} [Na^+] = [Na^+] F_b - [Na^+] (F_a + F_b)
\]  
(4)

The concentration must also satisfy the electro neutrality equation

\[
[Na^+] + [H^+] = [Cl^-] + [OH^-]
\]  
(5)

Dissociation equation for water at equilibrium at 25\(^0\)C

\[
[H^+] [OH^-] = K_w = 10^{-14}
\]  
(6)

From (3.5) we can write

\[
[H^+] - [OH^-] = [Cl^-] - [Na^+]
\]  
(7)

Let

\[
X = [H^+] - [OH^-]
\]  
(8)

Therefore from (6) and (8)

\[
[H^+] = \frac{X}{2} \left[ \frac{4K_w}{x^2} - 1 \right]
\]  
(9)

From equation (3) and (4)

\[
\frac{d}{dt} [Cl^-] - [Na^+] = [Cl^-] F_a - [Na^+] F_b - X F
\]  
(10)

Where \(F = F_a + F_b\)

From (7) and (8)

\[
\frac{d}{dt} X = [Cl^-] F_a - [Na^+] F_b - X F
\]  
(11)

The equations (1),(9),(11) corresponds to pH neutralization model. Using these equations we find out a first order plus time delay transfer function for the process.
IV. DESIGN OF CONTROLLERS

A. Design Of PI Controller

PI controller is a conventional controller used in industries. It will eliminate forced oscillations and steady state error resulting in operation of on-off controller and proportional controller respectively. It is generally used in the area where speed of the system is not an issue. The PI controller encapsulates two of the most important controller structures in a single package.

The parallel form of PI controller has transfer function:

\[ C(s) = K_p + \frac{K_i}{s} = K_p \left(1 + \frac{1}{T_i s}\right) \]  

(12)

where: \(K_p\) = Proportional Gain, \(K_i\) = Integral Gain, \(T_i\) = Reset Time = \(K_i / K_i\)

The main propose of designing a PI controller is to determine the two gains, they are proportional gain \(K_p\), integral gain \(K_i\).

Different methods are used for the tuning of PI controllers. The two categories of PID tuning methods are

1) Open loop method
2) Closed loop method.

Ziegler Nichols open loop method is used to design the PI controller. Open loop testing is to make a step change to the final control element and record the results of the process output.

\[ \frac{c(t)}{U(s)} = \frac{K_0 - Ls}{Ts + 1} \]  

(13)

Then the obtained transfer function is

\[ g_p(s) = \frac{3.668e^{-1.5s}}{7.5s + 1} \]

PI controller is developed having \(K_p = 0.813076505\) and \(K_i = 0.162778079\).

B. Design Of IMC-PI Controller

Model based control systems are helpful to achieve desired set points and reject small external disturbances. The internal model control (IMC) design is based on the fact that control system contains some representation of the process to be controlled then a perfect control can be achieved.

Information produced by the open-loop test is the open-loop gain \(K\), the loop apparent dead time \(L\), and the loop time constant \(T\). They are determined by plotting a tangent to the S shaped curve at the inflection point. These constants are determined by intersections of tangent lines at time axis. The line \(c(t) = K\) as shown in figure. The transfer function of the plant may then approximated by a first-order system with a transport lag.

The FOPTD transfer function is given below

\[ \frac{C(s)}{U(s)} = \frac{K_0 - Ls}{Ts + 1} \]

(13)

Then the obtained transfer function is

\[ g_p(s) = \frac{3.668e^{-1.5s}}{7.5s + 1} \]

PI controller is developed having \(K_p = 0.813076505\) and \(K_i = 0.162778079\).
Here we have to develop a feedback equivalent to IMC from the above given block diagram using block diagram manipulation. $q(s)$ Represents the controller, $g_p(s)$ represents the actual process and the $\tilde{g}_p(s)$ represents model of the process.

![Block Diagram](image)

Fig. 4: Standard feedback Equivalent to IMC

The standard feedback controller which is equivalent to IMC is

$$g_c(s) = \frac{q(s)}{1 - \tilde{g}_p(s)q(s)}$$

(14)

In order to arrive at a PI equivalent form for processes with a time-delay, we must make some approximation to the dead time, using either a zeroth or a first-order Padé approximation for dead time. Here zero-order Padé approximation is used, that is

$$\tilde{g}_p(s) = \frac{k_p e^{-\theta s}}{\tau_p s + 1} \approx \frac{k_p}{\tau_p s + 1}$$

(15)

1) Find the IMC controller transfer function, $q(s)$, which includes a filter to make $q(s)$ semi proper

$$q(s) = \tilde{g}_p^{-1} f(s) = \frac{\tau_p s + 1}{k_p \lambda s + 1}$$

(16)

Note: Internal model controller is designed as inverse of the process model which is in series with the low pass filter i.e

$$G(s) = G_c(s)f(s)$$

Where $f(s) = \frac{1}{\lambda s + 1}$

(17)

$\lambda = $ Filter Tuning Parameter

2) Find the equivalent standard feedback controller using the transformation

$$g_c(s) = \frac{q(s)}{1 - \tilde{g}_p(s)q(s)} = \frac{\tau_p s + 1}{k_p \lambda s}$$

(18)

recall that the transfer function for a PI controller is

$$g_c(s) = k_c \frac{\tau_I}{\tau_p s + 1}$$

(19)

3) Rearrange (18) to fit the form of (20). Multiplying (18) by $\frac{\tau_p}{\tau_p}$

$$g_c(s) = \left( \frac{\tau_p}{k_p \lambda} \right) \frac{\tau_p s + 1}{\tau_p s}$$

(20)

Equating 19 and 20 we get PI tuning parameters

$$k_c = \frac{\tau_p}{k_p \lambda}$$

(21)

$$\tau_I = \tau_p$$

(22)

Since dead time has been neglected, creating quite a bit of model error, it is recommend that $\lambda = 1.70$

$k_c = 0.767821128$

$\tau_I = \tau_p = 7.5$

$k_I = 0.10237615$

V. PERFORMANCE ANALYSIS OF CONTROLLERS

The performance of the system for PI controller and IMC-PI controller can be analyzed easily from the simulation results. Both the regulatory and servo responses provided below.
The performance of the two controllers can be evaluated using performance indices namely Integral Square error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE). A control system is considered optimal when it minimizes the above integrals. Table 4 summarizes the integral error values for the two control schemes. IMC PI controller has the least ISE, ITAE and IAE values.

### Table 1

<table>
<thead>
<tr>
<th>Controller</th>
<th>Servo Response</th>
<th>Regulatory Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZN PI</td>
<td>521</td>
<td>170.4</td>
</tr>
<tr>
<td>IMC PI</td>
<td>415</td>
<td>118.6</td>
</tr>
<tr>
<td>IAE</td>
<td>38.09</td>
<td>31.9</td>
</tr>
<tr>
<td>IMC PI</td>
<td>32.56</td>
<td>27.33</td>
</tr>
<tr>
<td>ISE</td>
<td>145.8</td>
<td>121.5</td>
</tr>
<tr>
<td>IMC PI</td>
<td>141.3</td>
<td>127.1</td>
</tr>
</tbody>
</table>

### VI. CONCLUSION

Analysis of Simulation results and the comparison of performance indices reveal that IMC-PI controller performs well for the pH neutralization process compared to the ZN –PI controller
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