pH Control of industrial effluent using CDM based PI controllers

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Coefficient Diagram Method (CDM) based PI controllers (CDM-PI and CDM-PI-P) has been implemented in a pH neutralization system to control the pH value of industrial effluent. The proposed techniques are tested with collected effluent in lab-scale pH neutralization system. Experimental runs are carried out at the operating point of pH 8 as per the requirement of PCETP and the regulatory performance in terms of Error Indices (ISE and IAE) and Total variations (TV) are reported. The results of the proposed control techniques are compared with conventional control techniques such as Ziegler Nichols PI controller (ZN-PI) and Internal Model Control based PI controller (IMC-PI). The experimental results show that the proposed CDM based PI controllers had impeccable performance with industrial effluent in pH neutralization system.

Keywords: CDM-PI, CDM-PI-P, Industrial effluents, pH control

Textile industry is one of the main pillars of Indian economy constituting approximately 14% of industrial production, 4% of Gross Domestic Product (GDP) and 11% to the country’s export earnings according to the Annual Report 2012-13 of the Ministry of Textiles. It is the second largest employment generator after agriculture. Even though textile industry plays an important role in the Indian economy in multiple ways, it also causes major environmental impact. This industry continuously threatens the livelihood by discharging the effluent into the rivers and nearby canals. Hence, the proper treatment is essential for a healthy and eco-friendly atmosphere. 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 discharged. An important and common technique used in wastewater treatment system is neutralization. The purpose of 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.

Several control strategies are reported in the literature to control pH problem such as adaptive control¹, self-tuning adaptive controller², model reference adaptive control³, internal model control⁴, model predictive control⁵, neural network⁶, fuzzy logic⁷, non-linear gain scheduling based on neuro-fuzzy controller⁸ and genetic algorithm⁹. The above methods are quite complex and difficult to implement in the existing distributed control systems. Though there have been significant developments in control systems for the past two decades, the chronic PI controllers are still popular for pH neutralization process due to its structural simplicity and reliability. Many research studies on controller tuning have reported that the control loops are not properly tuned when they are implemented, while other loops are not updated sufficiently¹⁰.

Classical control and Modern control approaches have well performed for simple control applications, but not for complex systems. Coefficient Diagram Method (CDM) is an algebraic approach which has paved way for such systems. CDM, established by
Prof. S. Manabe in the year 1991, is a polynomial based approach and so no crises arise as a result of pole zero cancellation. Though CDM is a recent and unfamiliar design approach, its essential idea has been used in control community for more than 30 years with successful implementation in several applications such as steel mill control, gas turbine control, control of robotic manipulators, space craft control, control of DC motor, and control of chemical processes such as temperature control, heat exchanger system and level control.

From the literature, it is clear that the CDM is an efficient and fertile control tool which makes the designer to design a controller under the conditions of stability, robustness and time domain performance. Hence, a simple and efficient control strategy, CDM based PI controllers, namely CDM-PI and CDM-PI-P are proposed for the pH neutralization system. These control strategies are already implemented and validated in lab-scale pH neutralization system with synthetic effluents consist of strong base (NaOH, 0.1N) and strong acid (HCl, 0.1N). As the continuation of previous work, this work is carried out to investigate the performance of the proposed CDM-PI and CDM-PI-P controllers with real industrial effluents in lab-scale pH neutralization system.

Experimental Section
The first stage of this work describes the sample collection of industrial effluents at Perundurai Common Effluent Treatment Plant (PCETP) in detail. In the second stage, the development of pH system model and tuning parameters of CDM-PI, CDM-PI-P, ZN-PI and IMC-PI controllers are presented. In the third stage, the proposed control strategies are tested with collected industrial effluents in lab-scale pH neutralization system and the performance are compared with conventional PI control techniques.

Overview of Perundurai Common Effluent Treatment Plant (PCETP)
PCETP has been established in the industrial area (SIPCOT), Perundurai, Erode District, Tamilnadu, India. The maximum operating volume of PCETP is 3600 m$^3$/day to treat the wash water with TDS range of < 2100 mg/L. The present work has been formulated based on the field study conducted at the primary treatment plant of PCETP. The sequence of operation adopted in the primary treatment plant of PCETP is shown in Fig. 1 and plant specifications are given in Table 1.

The effluent first passes through the bar screen (1) which is placed in the influent of the receiving sump. It is used to take care of rags and large objects in the effluent, so that these objects do not destroy the forthcoming units. To maintain the uniform flow in the treatment plant, the receiving sump (2) is used. From the receiving sump, the effluent is pumped to the equalization tank (3), where three floating aerators are used to obtain the homogeneity in the effluent.

![Fig. 1 — Layout of the primary treatment plant-PCETP](image-url)
The outlet from the equalization tank is pumped to the flash mixing tank (4) with the help of a centrifugal pump. To enhance the settling process, the effluent is mixed with lime, iron sulphate and polyelectrolyte in the flash mixing tank.

The effluent from flash mixing tank is fed into the clariflocculator (5) where both flocculation and sedimentation take place. During sedimentation, the pH value should be maintained approximately at 11 to ensure that none of the metal hydroxides re-dissolve and become soluble in the effluent. The outlet from the clariflocculator led to the clarified effluent sump (6) which is used to maintain a constant flow for the next unit. Then, the effluent is pumped to the Automatic Valveless Gravity Filter (AVGF) (7).

Hydrochloric acid (HCl) is added and mixed with the effluent in a static mixer (8) from AVGF to reduce the pH around 8. The effluent then is led to the stabilization sump (9) to stabilize the pH of the effluent. The effluent from stabilization sump is distributed into two parallel Activated Carbon Filters (ACFs) (10). The clean effluent from ACF flows through magnetic flow meter (11) which records TDS and pH. Finally, the effluent is pumped by a booster pump to the biological treatment plant.

The sludge from the bottom of the clariflocculator is collected in the sludge sump (12) which is essential to maintain the constant flow for the next unit. Further, the sludge is fed to the sludge thickener (13) where the solid content of the sludge is increased by removing a portion of the liquid fraction. From the sludge thickener, the sludge can flow in two different ways. Most of the sludge is fed to the centrifuge (14) which separates liquids from solids by increasing the gravity power. The remaining sludge is fed to the drying beds (15) which are used to dewater digested sludge. In the final stage of operation, the sludge is packed in sacks and stored under a roof (16) until further notice from the concerned authority.

### Collection of Industrial effluent

Collection of samples always presents serious difficulties because of large variations in flow and composition. It is very important that a sample collected should be truly representative of the whole of the effluent that passed in the given time. Thus the raw effluent samples are collected at the outlet of equalization tank and a sample of effluent before HCl dosing is collected at the outlet of the Automatic Valveless Gravity Filter (AVGF) at a regular interval of 1 hour to analyze the effluent characteristics. From the sludge thickener, the sludge is used to conduct the experiments in pH system within 2 hour. The

<table>
<thead>
<tr>
<th>Description</th>
<th>Capacity m³/hr</th>
<th>Retention time min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving sump</td>
<td>132-150</td>
<td>45</td>
</tr>
<tr>
<td>Equalization tank</td>
<td>150</td>
<td>1440</td>
</tr>
<tr>
<td>Flash mixing tank</td>
<td>3-4</td>
<td>2</td>
</tr>
<tr>
<td>Clariflocculator</td>
<td>450-350</td>
<td>240</td>
</tr>
<tr>
<td>Clarified effluent sump</td>
<td>145-150</td>
<td>30</td>
</tr>
<tr>
<td>Automatic valveless gravity filter</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Stabilization sump</td>
<td>130-135</td>
<td>30</td>
</tr>
<tr>
<td>Activated carbon filter</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 1 — PCETP specifications**

**Table 2 — Characterization of industrial effluent and effluent samples**

<table>
<thead>
<tr>
<th>S No</th>
<th>Parameter</th>
<th>Range of value after</th>
<th>Value (Effluent before HCl dosing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>pH</td>
<td>8.0-9.0</td>
<td>10.5</td>
</tr>
<tr>
<td>2</td>
<td>Total Dissolved Solids (TDS, mg/L)</td>
<td>1800-2000</td>
<td>1850</td>
</tr>
<tr>
<td>3</td>
<td>Turbidity (Nephelometric Turbidity Units, NTU)</td>
<td>20-40</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Chemical Oxygen Demand (COD, mg/L)</td>
<td>40-125</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>Biological Oxygen Demand (BOD, mg/L)</td>
<td>250-350</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>Total Hardness (mg/L)</td>
<td>250-350</td>
<td>150</td>
</tr>
<tr>
<td>7</td>
<td>Total Alkalinity (mg/L)</td>
<td>250-350</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>Chlorides (mg/L)</td>
<td>20-40</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Sulphates (mg/L)</td>
<td>50-150</td>
<td>150</td>
</tr>
</tbody>
</table>
primary characteristics of collected samples 1 and 2 are shown in Table 2 and it interprets that the pH value of these samples are within the specified range as given in the same table.

**Computation of PI controller parameters**

The pH system is approximated as first order plus time delay (FOPTD) model to compute the PI controller parameters. For model identification, the experiments are carried out in lab-scale pH neutralization system by considering 0.1N of HCl and 0.1N of NaOH as reactants and it is discussed in[19,20]. The reactants are selected based on the field study conducted at PCETP. From the field study, it is observed that the effluent is mostly alkali waste (10-12 pH) and it is being neutralized by HCl to maintain the pH around 8 for the survival of bacteria in the biological treatment. However, as per the environmental legislation, it is necessary to maintain the pH value of the effluent between 5.5 and 9 before it is being discharged into the environment. Therefore, for the present study, 0.1N of NaOH is used since its maximum alkalinity is also around 12 pH. For the strong-acid and strong-base neutralization process, the normality of both reactants is to be considered as same to reduce the complexity in model identification. Hence, 0.1 N of HCl is taken as a neutralizing agent. The identified FOPTD model for computing the PI controller parameters are as follows:

\[
G(s) = \frac{K_p}{\tau_p s + 1} e^{-\theta s} = \frac{7.0921 e^{-1.71 s}}{8.54 s + 1} \quad \ldots(1)
\]

where \(K_p\) = Process gain (%/%); \(\tau_p\) = Process time constant (Min); \(\theta\) = Process delay (min).

**Conventional PI controllers**

The PI controller parameters are computed based on the FOPTD model given in Eq (1). To analyze the performance of the proposed CDM based PI controllers, the existing conventional PI control techniques such as such as Ziegler Nichols\(^22\) and Internal Model Control (IMC)\(^23\) based PI tuning rules are considered for comparative studies. For convenience, these techniques are abbreviated as ZN-PI and IMC-PI respectively. The conventional PI controller tuning rules and the value of computed parameters are given in Table 3.

**CDM based PI controllers**

The CDM-PI and CDM-PI-P controller settings are worked out based on the design procedure given in\(^{19,20}\). The design calculations are as follows:

**Step 1:** FOPTD Model of pH system represented in Eq (1) is:

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

**Step 2:** Equivalent transfer function of the above said FOPTD model using first order Padé’s approximation technique is:

\[
G(s) = \frac{-12.1275 s + 14.1842}{14.6034 s^2 + 18.79 s + 2}
\]

**Step 3:** First degree CDM controller polynomials \((A(s)\) and \(B(s))\) are chosen as \(A(s) = s\) and \(B(s) = k_0 s + k_s\)

**Step 4:** For CDM-PI controller:-Selected stability indices values are \(\gamma_1 = 2.5\) and \(\gamma_2 = 2\)

**Step 5:** Calculated \(P(s)\) = \(s (14.6 s^2 + 18.79 s + 2) + (k_s + k_0) (-12.13 s + 14.18)\)

**Table 3 — Conventional PI controllers**

<table>
<thead>
<tr>
<th>Conventional PI controllers</th>
<th>PI controllers tuning rule</th>
<th>PI controller parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZN-PI</td>
<td>(K_c = \frac{0.9 \tau_p}{\theta K_p})</td>
<td>(K_c = 0.6338)</td>
</tr>
<tr>
<td></td>
<td>(T_i = 3.33 \theta)</td>
<td>(T_i = 5.69 \text{ min})</td>
</tr>
<tr>
<td>IMC-PI</td>
<td>(K_c = \frac{K_p}{K_p (\lambda) + 0.5 \theta})</td>
<td>(K_c = 0.4557)</td>
</tr>
<tr>
<td></td>
<td>(T_i = \tau_p + 0.5 \theta)</td>
<td>(T_i = 9.395 \text{ min})</td>
</tr>
</tbody>
</table>

where, \(K_c\) — Controller gain; \(K_p\) — Process gain; \(\tau_p\) — Process time constant;
\(T_i\) — Integral time constant; \(\lambda\) — Tuning factor (Recommended value \(1.7 \theta\)); \(\theta\) — Process delay.
Step 6: Computed coefficients of CDM controller polynomials
For CDM-PI controller: \( k_1 = 0.6176 \) and \( k_0 = 0.1418 \)
For CDM-PI-P controller: \( k_1 = 0.7556 \) and \( k_0 = 0.1418 \)

Step 7: Selected PI controller transfer function is:

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

Step 8: Comparing the CDM controller polynomials with PI controller transfer function, the CDM based PI controller parameters are computed and shown in Table 4.

### Results and Discussions

Investigation of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers with industrial effluent in laboratory scale pH neutralization system is described in this section. For this investigation, the collected industrial effluent is fed to the mixing tank at a constant flow rate of 0.5 lpm and HCl of 0.1 N is added to the mixing tank through the control valve which is controlled by the PI controller as shown in Fig. 2.

As per the requirement of PCETP, the pH value of effluent is to be maintained around 8. Hence the experimental runs are carried out at the operating point of pH 8 to analyze the performance of above said controllers. The behavior of the feed flow rate of acid and pH response of the process with load disturbance using above said controllers was studied. It is seen that the pH response is measured without load disturbance for the first 3000 sec and it is measured with load disturbance for the next 3330 sec.
Here the load disturbance is introduced by increasing the water flow rate from 0 to 1 lpm. The performance measures such as error indices and total variations are calculated for the period of \( t = 0 \) to 6330 sec with a step size of 5 sec and it is given in Table 5. The performance of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers at the operating point of \( p_H = 8 \) was studied with industrial effluents (sample 1).

The ZN-PI controller maintains the \( p_H \) value in the range of 5 to 9.5 without load disturbance since the % of acid flow rate varies from 10 to 27%. After introducing the load disturbance at \( t = 3000 \) sec, the \( p_H \) value varies from 5.5 to 10 till \( t = 4650 \) sec while the % of acid flow rate increases upto 30%. Then the \( p_H \) value brought to its previous range. It is observed that the ZN-PI controllers provide rapid changes in the control action. Thus, it could not maintain the \( p_H \) value in the required range since the process gain of the operating point (\( p_H = 8 \)) is high. The performance IMC-PI controller is quite better than the ZN-PI controller. This controller provides the output in the range of 6.0 to 9.0 \( p_H \) without load disturbance with the variation of 17 to 27% of acid flow rate respectively. Similarly with load disturbance, the \( p_H \) value varies from 6.0 to 9.6 till \( t = 4900 \) sec while increase the % of acid flow rate upto 29%. It is clear that the controller provides slight deviation in the controller actions before and after load disturbance. Though they offer smooth and consistent action, it could not able to maintain the \( p_H \) value in the required range.

The performance of the CDM-PI and CDM-PI-P controllers with industrial effluent reveal that the controller maintains the \( p_H \) value in the range of 7.5 to 8.7 and 7.6 to 8.4 without load disturbance since the % of acid flow rate varies from 13 to 18% and 15 to 17% respectively. Similarly, with load disturbance, they maintain the \( p_H \) value from 7.1 to 9.1 till \( t = 4900 \) sec and 7.0 to 8.5 till \( t = 3300 \) sec while the % of acid flow rate decreases upto 7 and 13% respectively. It is observed that the CDM based controllers provide better result with the industrial effluent at the required operating point of \( p_H = 8 \) than the other control techniques.

Similar to the previous experimental analysis, the performance of ZN-PI, IMC-PI, CDM-PI and CDM-PI-P controllers at the operating point of \( p_H = 8 \) with the industrial effluent (sample 2) are also investigated. The performance of sample 2 is similar to that of sample 1. Without load disturbances, the \( p_H \) value varies from 5.0 to 9.5 with the acid flow rate of 10 to 30%, 6.0 to 9.5 with the acid flow rate of 17 to 28%, 7.4 to 8.6 with the acid flow rate of 15 to 18% and 7.5 to 8.5 with the acid flow rate of 13 to 18% for the controllers ZN-PI, IMC-PI, CDM-PI and CDM-PI-P respectively. Similarly, after introducing the load disturbance, the \( p_H \) value varies from 5.0 to 10.0 till \( t = 5675 \) sec, 6.3 to 9.9 till \( t = 4345 \) sec, 7.0 to 8.8 till \( t = 3685 \) sec and 6.7 to 8.5 till \( t = 3245 \) sec for the controllers ZN-PI, IMC-PI, CDM-PI and CDM-PI-P respectively because of variation in the acid flow rate. The comparative performance of the above said controllers in terms of ISE, IAE and $TV = \sum_{k=1}^{\infty} |y(k+1) - y(k)|$ at the operating point of \( p_H = 8 \) with the industrial effluent (sample 1 and sample 2) is shown in Table 5.

The numerical values interpret that the CDM based controllers exhibit minimum error indices and provide smooth and consistent (lowest TV value) response when compared to other conventional PI controllers. From the results, it is proved that the other conventional PI controllers could not able to offer the satisfied results at the required operating point instead the CDM based PI controllers provide the sustained oscillation about the operating point of \( p_H = 8 \) with \( \pm 5\% \) tolerance error and met the necessary range of \( p_H \) (around 8) as per the requirement of PCETP.

<table>
<thead>
<tr>
<th>Controllers</th>
<th>Sample 1</th>
<th>Performance Measures</th>
<th>Sample 2</th>
<th>Performance Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISE</td>
<td>IAE</td>
<td>TV</td>
<td>ISE</td>
<td>IAE</td>
</tr>
<tr>
<td>ZN-PI</td>
<td>1116.15</td>
<td>948.29</td>
<td>466.10</td>
<td>1186.27</td>
</tr>
<tr>
<td>IMC-PI</td>
<td>836.63</td>
<td>863.62</td>
<td>154.87</td>
<td>1092.37</td>
</tr>
<tr>
<td>CDM-PI</td>
<td>198.42</td>
<td>421.53</td>
<td>62.94</td>
<td>131.80</td>
</tr>
<tr>
<td>CDM-PI-P</td>
<td>49.37</td>
<td>202.96</td>
<td>75.58</td>
<td>65.99</td>
</tr>
</tbody>
</table>
Conclusion
The performance of CDM-PI and CDM-PI-P controllers are tested with industrial effluent in lab-scale pH neutralization system which is collected at PCETP. The performance measure substantiates that the CDM-PI and CDM-PI-P controllers exhibit minimum error indices and provide smooth and consistent response. CDM furnishes a convenient and flexible design under the conditions of stability and robustness which provides excellent performance in terms of disturbance rejection. The proposed control strategy works well against the uncertainties of the nonlinear pH system and also, it is found that the CDM based PI controllers have impeccable performance with the industrial effluent in laboratory scale pH neutralization system. Thus it is hoped that the favourable outcome of this research work may contribute in the process control field to reduce the gap between theoretical and practical approach.

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