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Multivariable Adaptive Lyapunov Fuzzy Controller for pH Neutralisation Process

M.F. Zanil[a] and M.A. Hussain[b]

[a] *Chemical and Petroleum Engineering, Faculty of Engineering & Built Environment, UCSI University, 56000 Kuala Lumpur, Malaysia.*
[b] *Chemical Engineering Department, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.*

Abstract

A multivariable fuzzy logic controller with Lyapunov adaptive control scheme has been developed for a pH neutralisation process. In this study, the nominal neutralisation process condition exhibit nonlinear dynamics and multi-delayed-effects input variables. The proposed controller uses a Takagi-Sugeno fuzzy inference system and it has been optimised by genetic algorithm which minimizing the closed loop error in feedback control system. The optimised structure is used to predict three-difference control action simultaneously. The Lyapunov function is integrated in the fuzzy inference calculation at output membership function. The proposed controller has been tested and compared in several cases such as for set-point tracking, model plant mismatch and unknown disturbance. The adaptive fuzzy controller demonstrate better performance over the conventional PID controller in all the tested cases.

Keywords: Non-linear control; Fuzzy Controller; Adaptive control.

1. Introduction

The pH neutralisation is a typical process in chemical wastewater treatment plant. The effluent from the treatment plant must be neutralised before it can be safety discharged to the environment. Problem that occurs in pH neutralisation control are due to the process characteristics involved in such a process as strong nonlinear respond among acid, neutral, and base regions, wide-ranging time delay of the titration, and the complexity of inlet composition. The characteristic might vary from case to case and thus, the conventional controller can only work at a single desired point and could fail to compensate when the controlled region is changed. There are many solutions in the literature that has been reported, but an ideal solution still depend on the cases involve and it has not been totally solved due to vigour and complexity of the control and process. Thus, the need of an advanced control system is necessary for this situation.

The adaptive technique with a fuzzy logic system has been investigated in this case study is controlling the pH neutralisation for set point tracking and load disturbance. Previously, Salehi (2009) had used fuzzy as an estimator to the adaptive model based control framework , Min (2006) work on adaptive algorithm of universal learning network, and Menzl et al. (1996) had developed self-adapting mechanism inside fuzzy logic controller at neutralisation point. All of these work focus on utilising the fuzzy system for neutralisation control at nominal conditions with satisfactory performance. Related literatures are given in Goodwin (1982), Gustafsson (1984), Henson (1994), Narayanan (1997), Sung (1998), and Boling (2007). However, fuzzy controller incorporated with adaptive mechanism is not easy to build and furthermore an effective control performance

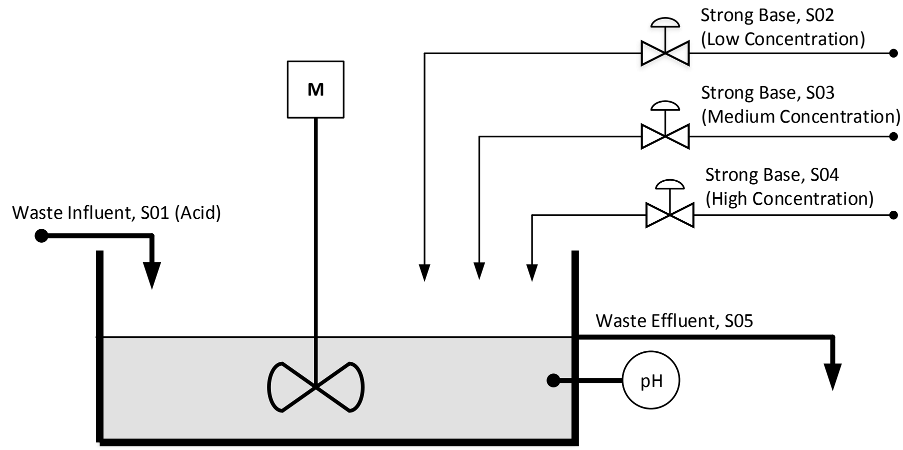

Figure 1: Scheme of pH neutralisation process

for multiple pH regions is very hard to generalize. Therefore, the need of robust controller performance in this field arise significantly.
The objective of this study is to investigate the multivariable controller for the control of nonlinear pH neutralisation process in continuous stirred tank reactor by using the Lyapunov based adaptive Fuzzy Logic approach. The process using the strong acid equivalent model (Zanil et al., 2014). The control system has been set to regulate the pH reactor at neutral point (pH = 7.0) by manipulating several acid flow rates.

2. pH Neutralisation

The potential of hydrogen, pH is mathematically defined the negative logarithm of concentration of ion hydrogen. In pH neutralisation modelling, the nonlinearity characteristic are from the logarithm term in the equation. The model (Eq.1) which follows the law of conservation of mass and chemical equilibrium (Gustafsson et al., 1995). The process is assumed isothermal with constant fluid density and no solid formation occurring during experiment. The schematic diagram (Figure 1) illustrate the multi titration streams with single influent and effluent stream.

The model used in the study is as follows:

$$V\frac{dx}{dt} = F_a C_{a0} - (F_a + \sum_{i=1}^{3} u_{b,i})x - \sum_{i=1}^{3} u_i(t-\theta_i)C_{b0,i} \quad (1)$$

Where x is the remaining acid concentration in the reactor, C_e , C_{p0} and $C_{b0,i}$ is the concentration of the component in the effluent stream, influent stream, and titrating stream, respectively. The input time-delay is used to approximate the dynamics of the pH sensor and non-ideal mixing condition (Sung et al., 1998). In an aqueous solution, the electro neutrality and water-equilibrium theories are used to express the electrolyte disassociations (Eq.2) at an isothermal temperature of 27 ^oC, and water equilibrium constant of K_w at 1×10^{-14}.

$$x = [H^+] - \frac{K_w}{[H^+]} \quad (2)$$

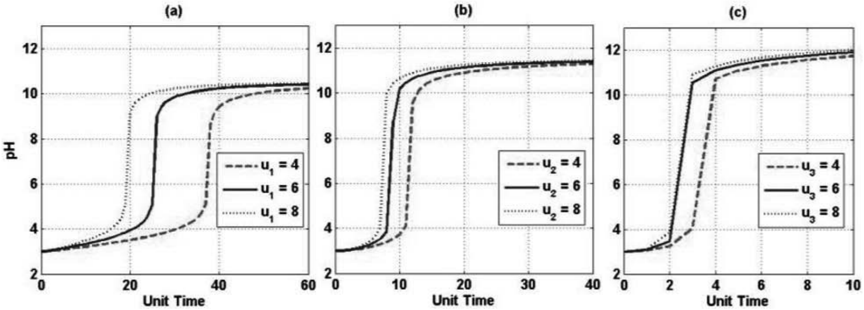

Figure 2: Open loop studies for variation of titration flow rate: (a) Low, (b) Medium, (c) High.

Thus, the hydrogen ion, $[H^+]$ as in Eq.3 can be used to simulate the dynamic profile of hydrogen concentration and pH value of the stirred tank reactor.

$$V\frac{d}{dt}\left([H^+] - \frac{K_w}{[H^+]}\right) = F_a C_{a0} - (F_a + \sum_{i=1}^{3} u_{b,i})\left([H^+] - \frac{K_w}{[H^+]}\right) - \sum_{i=1}^{3} u_i(t-\theta_i) C_{b0,i} \quad (3)$$

The pH value is calculated by taking the logarithm of hydrogen concentration. The simulated result for several titration flow rates has been demonstrate in Figure 2 and it is observed that the variation time response over the titration flow rates has significant effect. The pH value inside the reactor shows several dynamic responses over time. The nominal condition that shows in Table 1 has been used for the simulation study.

3. Control Mechanism

Fuzzy logic consist a set of fuzzy inference that works on approximate reasoning that give a consequence action as the outcome. The structure has been set to receive three inputs and three outputs. The fuzzy logic inference mechanism were computed from the product of input membership function (e, ce and AV) and the fulfilment of fuzzy rules (R_i). i.e.;

R_i : $IF\ e\ is\ A_i\ AND\ ce\ is\ A_i\ AND\ AV\ is\ A_i THEN\ u_1$is $U_{1,i}\ AND\ u_2 is\ U_{2,i}\ AND\ u_3\ is\ U_{3,i}$

Every output membership function can be written as

$$U_{j,i}(k) = A_{1,i}\,e + A_{2,i}\,ce + A_{3,i}\,AV + A_{4,i}\ ; j = 1,2,3\ and\ i = 1,2..N \quad (4)$$

The output parameter, $A_{j,i}$ has been optimised by genetic algorithm depending on the close loop error analysis; Integral Square Error (ISE). The controller output can be formulated as the summation of average weighted inference value for the active rule, R_i.

$$u_i = \frac{\sum_i^n w_i(e,ce,AV) U_{j,i}}{\sum_i^n w_i(e,ce,AV)} \quad (5)$$

$$w_i(e,ce,AV) = min[\mu_i(e), \mu_i(ce), \mu_i(AV)] \quad (6)$$

Table 1: Parameters and value for nominal

Parameter	Value	Unit
Reactor Volume, V_r	100	Litre
Influent flow rate, F_b	2.5	Litre/Min

Inlet Influent Concentration, C_{b0}	3E-3	Mole/Litre
Inlet Base Concentration (Low) , $C_{a0,1}$	3E-4	Mole/Litre
Inlet Base Concentration (Medium) , $C_{a0,2}$	3E-3	Mole/Litre
Inlet Base Concentration (High) $C_{a0,3}$	3E-2	Mole/Litre

Where w_i is degree of input membership function as Eq. 6 and $\mu_i(e), \mu_i(ce)$, and $\mu_i(AV)$ are the input membership function (triangular types) of error, change of error, and acidic region respectively.

3.1. Adaptive Mechanism

The used of adaptive mechanism is to improve the fuzzy controller performance during the model-mismatch operation in the plant. Let the model identifier approximate the nominal plant response and thus the model error, $\varepsilon = y_m - y$ which detect the existing of model-mismatch condition. So, the adjustable parameter, γ is introduced to minimise Eq. 7 in the negative gradient;

$$\frac{d\theta_i}{dt} = -\gamma_i\left(\frac{1}{2}\varepsilon^2\right) \quad (7)$$

The adaptation law is formulated as in Eq. 8

$$U_i = \frac{d\theta_i}{dt}u_i = -\gamma_i\left(\frac{1}{2}\varepsilon^2\right)u_i \quad (8)$$

3.2. Control System

The study use a conventional closed loop control strategy as in Figure 3 and the neutralisation models as stated in Section 2 has been used for the plant block. Measured disturbance is the signal from influent flow rate (base) and the manipulated variable signal at different concentrations. The fuzzy controller send three-output signals to every individual control valve before the change of titration effect takes place.

In the study, unmeasured disturbance and limited-band white noise has been introduced. A servo and regulator case study has been performed throughout the simulation. Several analysis for servo cases has been carried out; acid/base region at the neutral point and within neutral region. Beside, regulator case analysis has been conducted for ± 5% variation in the measured disturbance flow rate. Plant mismatch of ± 10% from nominal volume reactor has been carried out to test the control performance robustness.

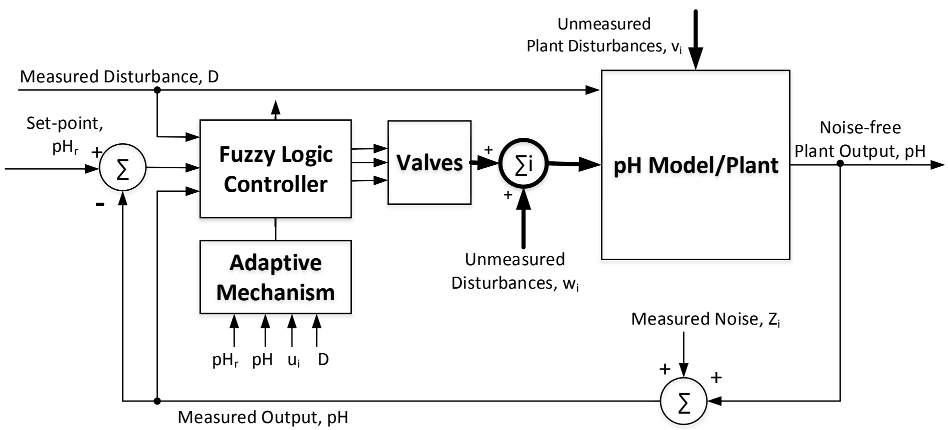

Figure 3: Adaptive Multiple Output Fuzzy Control Scheme for pH Neutralisation

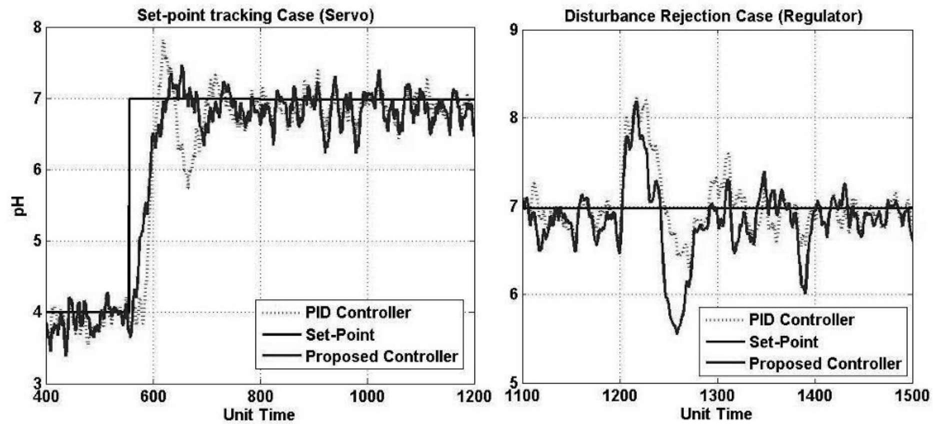

Figure 4: Comparison of control performance for set-point and disturbance rejection cases.

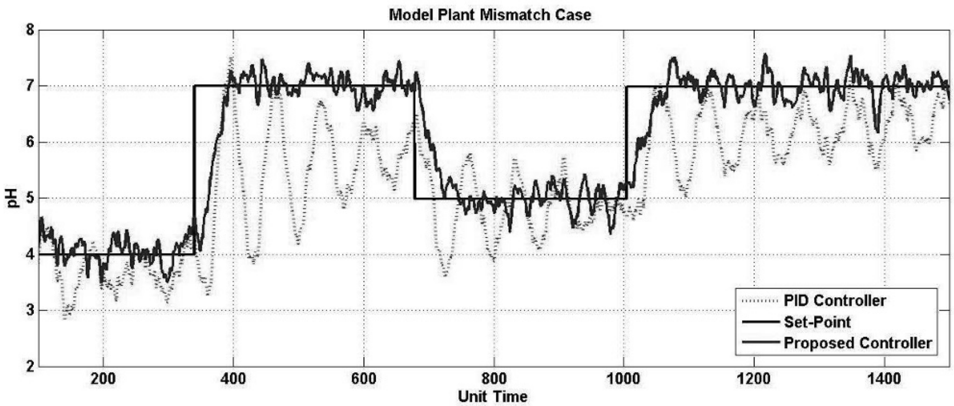

Figure 5: Comparison of control performance for plant mismatch case.

4. Result and Discussion

Simulation result for set point tracking, load rejection of proposed adaptive controller responses are shown in Figures 4 and 5 respectively. Considering the adaptive fuzzy logic controller, its set point and load changes show smoother response over the entire nonlinear region. Furthermore, there is no oscillation or overshoot in proposed control responses. PID controller has showed slightly overshoot and the settling time is more compared to propose controller. This is due to the sluggish control action at the neutralisation region.

The controller performance based on Integral Square Error (ISE), Integral Absolute Error (IAE), and Integral Total Absolute Error (ITAE) as shown in Table 2.

Table 2. Error analysis of control performance according to the case.

Case	Controller Type	ISE	IAE	ITAE
Disturbance Rejection	PID	224,92	367.21	2.57E5
	Proposed Controller	203.95	322.60	2.19E5
Set-point tracking	PID	681.93	582.83	3.64E5
	Proposed Controller	576.07	533.23	3.15E5
Plant mismatch	PID	1.94E3	1.29E3	9.16E5
	Proposed Controller	597.16	624.46	3.90E5

The result shows that the proposed controller gives best performance, which indicate less error analysis compared to conventional controller for all cases. The conventional controller unable to adapt with the plant mismatch case and therefore the error analysis give large value compare to the proposed controller.

5. Conclusions

A multivariable adaptive fuzzy logic controller has been proposed for the nonlinear pH neutralisation control system. It is the integration of empirical optimisation fuzzy logic controller with Lyapunov adaptive law. The results has shown superior performance for the proposed controller compared to conventional controller in all studied cases. The proposed controller has a promising potential for other nonlinear control applications.

Acknowledgement

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