Design and Implementation of Intelligent Control Schemes for pH Neutralization Process

SYNOPSIS

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by

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SYNOPSIS

1. Introduction

To remain competitive in global economy, modern process plant automation demands increased productivity, better product quality, growing profit, and meeting obligation to laws concerning increased safety levels and reduction in environmental pollution. These requirements demand the advanced control system to be accurate, robust, reliable, efficient, optimal, adaptive, and intelligent. The design of control system is greatly influenced by amount of nonlinearity present within process. If nonlinearity encountered is very mild, a linear model can adequately represent the process and a classical controllers such as Proportional-Integral-Derivative (PID) or Proportional-Integral (PI) based on linear control theory provide satisfactory control over a wide operating range. To deal with severe nonlinearities and address concerns of varying operating conditions and parameter variations in modern process plant, development of rigorous dynamic plant model is required.

Highly nonlinear behavior and time varying parameters of pH process makes it a benchmark for modeling and control of nonlinear processes. Nonlinear processes can be modeled using two ways, namely mathematical modeling based on first principles approach and system identification based on experimental input-output data. First principle based dynamic models developed with idealistic assumptions such as perfect mixing and absence of measurement noise do not represent true and realistic behavior of process. Artificial Neural Network (ANN) based system identification technique is inspired by biological neural networks and it has an excellent ability to learn nonlinear dynamics of a complex process because of its inherent parallel and distributed configuration.

The focus of advanced control methodologies now a day is to develop intelligent control algorithm based on Computational Intelligence (CI) paradigms. The intelligent controllers have capability of self-organizing and take appropriate control actions in case of any change in process conditions, much like human nature of first think and then act. The recent focuses of CI paradigms are ANN, fuzzy logic, Evolutionary Computation such as Genetic Algorithm (GA) and Differential Evolution (DE), Swarm Intelligence such as Particle Swarm Optimization (PSO).

The research work describes, with extensive experimentation and simulation, three aspects of a pH neutralization process: (i) Dynamic modeling, (ii) Intelligent Control, and (iii) Optimization. The neutralization of strong acid (Hydrochloric acid, HCl) and strong base (Sodium Hydroxide, NaOH) streams for experimentation part is carried out in the multifunctional Process Control Teaching System (PCT40) with Process Vessel accessory (PCT41) and pH Probe accessory (PCT42) of Armfield® Ltd., United Kingdom. The pH neutralization system is interfaced with Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW®) for communication, control and display.

The main objectives of research work are as follows:

(a) Development and validation of dynamic modeling of Armfield pH neutralization system PCT40, PCT41, PCT42

    (i) To develop calibration equations for pH sensor and pump actuators.

    (ii) To develop first principle and ANN based dynamic models.

    (iii) To evaluate performances of dynamic models.

(b) Design and experimental implementation of optimized control of pH neutralization process for servo and regulatory operations

    (i) To design PID control and Fuzzy Logic Control (FLC) schemes.

    (ii) To optimize PID and FLC schemes using global optimization techniques namely GA, DE, and PSO.

    (iii) To evaluate performances of control schemes and optimization methods.

(c) Design and implementation of Self-tuned FLC scheme of pH neutralization process for servo and regulatory operations

    (i) To design Self-tuned FLC scheme.

    (ii) To evaluate performances of optimized FLC and Self-tuned FLC schemes.

2. Literature Review and Research Gaps

Literature review has been carried out around: first principles based modeling and adaptive control, nonlinear adaptive control, Internal Model Control (IMC), ANN based modeling and Model Predictive Control (MPC), nonlinear MPC, fuzzy logic based intelligent control, and evolutionary and swarm algorithms based optimization. Literature survey shows following challenges/gaps in dynamic modeling, control and optimization of pH neutralization process.

(i) Reported works in literature are mostly based on simulation studies only and their extensive experimental validations are often lacking.

(ii) Strong acid-strong base neutralization has not been investigated extensively and existing dynamic pH models and subsequent control schemes are based on weak acid-strong base neutralization process.

(iii) Reported works in literature do not provide a comprehensive performance comparison of controller parameter optimization using GA, DE and PSO for PID and fuzzy logic based pH control techniques of strong acid-strong base neutralization process.

(iv) Performance of self-tuning based fuzzy control for strong acid-strong base neutralization process needs to be compared with optimized fuzzy logic controller.

3. Description of pH Neutralization Process

A brief overview has been presented for pH neutralization system i.e. Armfield Process Control Teaching System (PCT40) with Process Vessel Accessory (PCT41) and pH Sensor Accessory (PCT42). PCT41 with volume 2000 mL acts as Continuous-Stirred Tank Reactor (CSTR). PCT40 has peristaltic pumps A and B which carries strong acid (HCl) and strong base (NaOH) streams with concentrations as 0.01778 mol/L and 0.01259 mol/L respectively, minimum flowrates of 0 mL/s of pumps corresponds to pumps speed of 18% or less, and maximum flowrates of 5.1139 mL/s and 5.8749 mL/s of pump A and pump B correspond to maximum pumps speed of 100%, respectively. Using Dynamic Link Library (DLL) file, LabVIEW installed on personal computer communicates with the Armfield pH neutralization system by accessing following analog/digital input/output data: Analog Inputs (from PCT40 to computer), Analog Outputs (from computer to PCT40), Digital Inputs (from PCT40 to computer), Digital Outputs (from computer to PCT40). Also, linear calibration equations for pumps flowrates and pH sensor have been developed, which are used for dynamic modeling, identification, and control of pH neutralization system.

4. Dynamic Modeling of pH Neutralization Process

For development of dynamic models for Armfield pH neutralization system, two approaches have been used: (i) first principles method proposed by [1]McAvoy et al. (1972), and (ii) feedforward Artificial Neural Network (ANN). The specifications of Armfield pH neutralization system are comparable with those of [2]McAvoy (1972) experimental set up except that Armfield pH neutralization system involves reaction of strong acid-strong base with reduced concentration whereas McAvoy (1972) experimental set up involves weak acid-strong base reaction with relatively higher concentration. The first principles method for Armfield pH neutralization system uses material balances on sodium and chloride ions, water equilibrium relationships, and electroneutrality equations. The performance of first principles based dynamic pH model is compared with experimental response of Armfield pH neutralization system for various step tests conducted at pH = 7 described as follows: For initial acid and base pump speeds as 35% and 38.5% respectively, when the base pump speed is given step changes of 41.5%, 31.5%, 21.5%, 11.5%, 1.5%, -3.5%, -8.5%, and -18.5% for 300 seconds, keeping the acid pump speed fixed at 35%, the experimental responses of pH neutralization system indicate an average dead time of 3 seconds. The dead time incorporated first principles based dynamic pH model gives performance function i.e. Mean Squared Error (MSE) values as 0.121, 0.349, 0.440, 0.746, 1.535, 4.277, 1.364, and 0.547 respectively for above base pump speed changes. Therefore McAvoy et al. (1972) based dynamic pH model response does not obey the experimental results, especially in the dynamic pH range of 4 to 10.

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[1] *McAvoy T.J., Hsu E., Lowenthals S., 1972, 'Dynamics of pH in Controlled Stirred Tank Reactor', Ind. Eng. Chem. Process Des. Develop., 11, pp. 68-70.*

[2] *McAvoy T.J., 1972, 'Time Optimal and Ziegler-Nichols Control', Ind. Eng. Chem. Process Des. Develop., 11, pp. 71-78.*

Dynamic feedforward ANN structure using Tapped Delay Line (TDL) approach to model Armfield pH neutralization system uses total 32740 data samples covering pH range from 4 to 10 for training, validation, and testing of the network. For various number of delayed input-output samples of the nonlinear pH neutralization process, offline performance of training functions namely Gradient-Descent method with constant learning rate (GD), Gradient-Descent method with constant learning rate and Momentum (GDM), Gradient-Descent method with Adaptive learning rate (GDA), Gradient-Descent with Adaptive learning rate and Momentum (GDAM), and Levenberg-Marquardt algorithm (LM) are compared based on MSE values for training, validation and testing data sets using MATLAB®. It is found that LM gives best performance values for all test cases. Further it is found that for three delayed input-output samples, dynamic ANN model using LM training function gives reasonably acceptable performance values of MSE as 5.175×10^{-4}, 4.535×10^{-4}, and 4.671×10^{-4} for training, validation, and testing respectively.

5. Optimized Fuzzy Logic based pH Control Schemes

The feedback control of Armfield pH neutralization process for servo and regulatory operations has been done using optimized conventional Proportional-Integral-Derivative (PID), and optimized intelligent Mamdani Fuzzy Inference System (FIS) based Fuzzy Logic Control (FLC). The servo and regulatory (SR) operations in pH neutralization process for 3600 seconds are defined as follows: starting with pH setpoint as 6, pH setpoint is changed to 7, 8, 9, 8, 7, and 6 at interval of 600 seconds, keeping acid flow rate at 35%; 200 seconds after every change of pH setpoint, acid flow rate is changed from 35% to 30%, 30% to 35%, 35% to 40%, and 40% to 35%, consecutively after every 100 seconds. Thus, SR operations consist of six cases, of equal duration, namely SRi where i = 1, 2, 3, 4, 5, and 6, each part involves servo operation of 200 seconds followed by total regulatory operations of 400 seconds. In order to tune pH controller parameters i.e. proportional, integral and derivative gains K_P, K_I and K_D respectively for PID, and scaling factors K_1, K_2 and K_3 for error, change in error and change in output respectively for FLC, either offline using ANN based dynamic pH model or online using Armfield pH neutralization process, global optimization techniques namely GA, DE, and PSO have been used. The objective function for global optimization techniques is ISE. Offline simulations of GA optimization, DE optimization, and PSO based PID controller gives total ISE for SR operations as 80.6441, 80.6644, and 80.7496, whereas experimental validation of same gives total ISE for

SR operations as 411.7163, 577.2561, and 126.1982, respectively. Offline simulations of GA optimization, DE optimization, and PSO based fuzzy logic controller gives total ISE for SR operations as 73.8843, 71.9779, and 72.2608, whereas experimental validations gives total ISE for SR operations as 80.3776, 67.9637, and 67.9266, respectively. These results demonstrate that nonlinear Mamdani based fuzzy controller is better than linear PID controller, for pH control of SR1, SR5, and SR6 operations.

To address nonlinearity of pH neutralization process, fuzzy logic controllers are also designed for six different regions of dynamic pH range from 6 to 9 in piecewise manner. Offline simulations of GA optimization, DE optimization, and PSO based piecewise fuzzy logic controller gives total ISE for SR operations as 64.7311, 64.3618, and 64.4981, whereas experimental validations gives total ISE for SR operations as 66.1221, 64.3561, and 64.8058, respectively. Use of offline optimized piecewise fuzzy logic controller of SR brings ISE values down by amount 14.2555 for GA, 3.6076 for DE, and 3.1208 for PSO. The offline optimization results show that pH control for SR1 and SR5 operations are most challenging task.

Online optimization of piecewise fuzzy logic controller gives ISE values for SR1 and SR5 operations as follows: 8.7858 and 10.8342 for GA, 9.7916 and 11.3888 for DE, and 9.3424 and 9.4614 for PSO, respectively. From the above results it is clear that all three global optimization techniques give approximately similar solutions, but final population members from DE optimization have better convergence than PSO followed by GA optimization.

6. Self-Tuned Fuzzy Logic based pH Control

To overcome the problem of random variations in process operating condition, Mamdani FIS based self-tuned FLC scheme has been implemented on Armfield pH neutralization process. The self-tuned FLC has input scaling factors K_1 and K_2, and output scaling factor K_3. Keeping K_1 and K_2 constant, self-tuning mechanism determines value of K_3 which consist of two components: (i) K_{3A} which has discrete values 2, 4, 6, and 8 based on present error and change in error values, (ii) K_{3M} which is magnifier that can take integer values from 1 to 4. First performance of self-tuned fuzzy logic controller has been evaluated for servo operation by introducing step change in pH setpoint from 6 to 7, and from 8 to 7 at acid flowrate of 35%. It is noted that in almost all test results, pH response finally settles within 7±0.2 pH band. In some cases, when pH response occasionally overshoots and undershoots the above band, controller adjusts its output universe of discourse and again brings the pH response back within the desired band. Also self-tuned fuzzy controller gives better performance in terms of ISE for magnified K_3. In addition, self-tuned fuzzy logic controller is used for SR operations, and its performance index ISE comes as 96.0062 for $K_{3M} = 3$, and 79.8271 for $K_{3M} = 4$. In comparison, experimental validation of GA, DE, and PSO based optimized FLC for SR operations gives total ISE as 80.3776, 67.9637, and 67.9266 respectively. Also experimental validation of GA, DE, and PSO based optimized piecewise FLC for SR operations gives total ISE as 66.1221, 64.3561, and 64.8051 respectively. Though ISE of self-tuned FLC for SR operations is somewhat greater than optimized FLC and optimized piecewise FLC, however, self-tuned FLC has reduced design complexity and execution time.

7. Summary of Contributions

The main contributions of the author in this thesis work are briefly listed below:

(i) Performed experimental validation of dynamic model of Armfield pH neutralization system based on first principles technique proposed by McAvoy et al. (1972), and demonstrated that first principles based dynamic model is not suitable for pH range from 4 to 10.

(ii) Developed dynamic feedforward Artificial Neural Network (ANN) architecture using Tapped Delay Line (TDL) approach, and proposed that three delayed input-output samples with Levenberg-Marquardt algorithm (LM) for training gives reasonably acceptable performance values which are close enough to best performance values obtained using six delayed samples.

(iii) Proposed tuning of pH controller parameters based on Proportional-Integral-Derivative (PID) and Fuzzy Logic Control (FLC) schemes using global optimization techniques namely Genetic Algorithm (GA), Differential Evolution (DE), and Particle Swarm Optimization (PSO).

(iv) Performed comparative study of GA, DE, and PSO based PID controller performances through simulations on ANN model and experimental validations on Armfield system for servo and regulatory operations in dynamic pH region of 6 to 9. Based on experimental validation results it is concluded that PID controller is not suitable for pH control around highly nonlinear region of pH equals 7.

(v) Performed comparative study of GA, DE, and PSO based fuzzy logic controller performances through simulations and experimental validations for servo and regulatory operations in dynamic pH region of 6 to 9. Based on final population convergence result for offline optimization with moderate number of generations it is concluded that DE is best followed successively by PSO and GA. Based on ease of implementation for online optimization with small number of generations it is concluded that DE has most simple algorithm followed successively by PSO and DE.

(vi) Performed comparative study of piecewise tuning of fuzzy logic controller using offline GA, DE, and PSO by dividing dynamic pH region of 6 to 9 into smaller segments, for servo and regulatory operations. Based on experimental responses of fuzzy logic controller it is concluded that piecewise optimization using GA, DE and PSO results in improved performance.

(vii) Proposed self-tuned FLC scheme, and a comparative performance study of optimized FLC and self-tuned FLC schemes through experimental validations for servo and regulatory operations in dynamic pH region of 6 to 9 is done. Based on experimental validation results it is concluded self-tuned fuzzy controller gives satisfactory and comparable performance compared to offline GA, DE and PSO based optimized fuzzy controller.