COMPARATIVE ANALYSIS OF PH CONTROL METHODS

Liliana TOMA
Technical University of Cluj-Napoca, Romania
G. Baritiu Street, liliana.toma@bel.utcluj.ro

Abstract: The study of pH control is important for the environment as the effluent or wastewater has to be neutralized before being discharged. pH control is considered a challenge due to the highly nonlinear characteristics, time-varying nature and variations in the titration curve. This paper presents the main methods used to control the pH process. Also, it aims to provide a survey for pH control methods. This is achieved by a thorough comparison which highlights the main advantages and drawbacks for the control methods.

Keywords: *adaptive control, fuzzy logic, pH control, PID, process control, neural network*

I. INTRODUCTION

Control of pH is needed for a wide range of industries like wastewater treatment, food industry, chemical processing, textile industry, pharmaceuticals, biotechnology and beverage industry. There are significant research interests in the pH control problem because of its industrial importance [1].

In all these industries pH control is important not only for environment protection but also for process efficiency and product quality. The cost of low performance pH control associated with implications on equipment contamination and a compromised batch can be millions of dollars for high value-added pharmaceuticals [2].

The pH neutralization process is widely studied for two reasons. The first one is because of its importance for the environment, especially when the effluent or wastewater has to be neutralized before being discharged. The second reason is the fact that control of pH is considered to be one of the most difficult problems in process control [3]. This is because of the nonlinearity of the neutralization process, high sensitivity at or near the neutralization point and time-varying gains when uncertainties in flows and concentrations of neutralization agents are present [4].

The notion of pH (potential of hydrogen) is used to characterize the acidity or alkalinity of a solution on a scale from 0 to 14.

The logarithmic relationship between pH and hydrogen ion activity, as it can be seen in Equation 2, offers the ability to measure hydrogen ion concentration from 1 to 10^{-14} over the 0 to 14 scale range [2].

$$a_H = 10^{-pH} \quad (1)\ [2]$$

$$pH = -\log(a_H) \quad (2)\ [2]$$

$$a_H = \gamma * C_H \quad (3)\ [2]$$

where:
a_H = hydrogen ion activity (gm-moles per liter)
C_H = hydrogen concentration (gm-moles per liter)
γ = activity coefficient (1 for dilute solutions)
pH = negative base 10 power of hydrogen ion activity

The hydrogen ion activity is the effective concentration and is a measure of the ability of the hydrogen ion to move and combine with other ions [2].

Processes can be classified in three categories:
The first category are the *continuous processes* where the product flows out of the process on a continuous basis. The conditions within the production equipment are ideally constant, but in practice, minor adjustments to operating conditions are occasionally appropriate [5].
The second category are the *batch processes* where the product is manufactured in discrete quantities called batches. The conditions within the production equipment change as the product progresses through the manufacturing process [5].
The third category are the *semi-batch processes* where some parts of the process are continuous and other parts are batch [5].

The paper is structured as follows: Section II presents the general classification of pH control methods; Section III describes the traditional methods used in pH control, Section IV summarizes the methods based on computational intelligence, Section V describes the stages of implementing fuzzy control for pH, Section VI compares the pH control methods; Section VII lists the conclusions of this survey.

II. PH CONTROL METHODS

In the recent years, several control methods have been developed for the control of pH neutralization process. These methods can be organized in three categories.

The first category is the open loop control in which the opening of the control valve is kept at a specific position for specific time durations. This type of control is used for the start-up and shutdown of a process or in a neutralization process, done in multiple stages, where the pH will be maintained at a specific value by the later stages of the process [6].

The second category is the one based on feedback

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control principles. This type of control involves a direct relationship between the control valve opening and the pH value in the process. It is also called corrective control because the control action takes place when a discrepancy between the actual pH value in the process and the required set point occurs. The most used type of controller for this type of control is the Proportional, Integral and Derivative (PID) and variations on this algorithm involving Proportional control (P) or Proportional plus Integral Control (PI) [6].

The third category is represented by feedforward control. By using this approach, the controller will compensate for any measured disturbance before it affects the process. pH process disturbances can be caused by unexpected changes in concentration of both solutions or changes in the flowrates of reagent streams. This type of control is also called preventive control because the controller will react in case of a disturbance before the pH value in the vessel is affected. The preventive approach is much faster than the corrective control approach [6].

If the pH control methods are regarded from the perspective of the process type (continuous or batch) then many of the design techniques developed for continuous control are applicable also for batch. A continuous process can be thought of as a long batch that can benefit from the automation of its start-up and shut-down. One major difference between batch and continuous process is that during the reaction or formation of product, the vessel discharge flow is zero for the batch processes. Some specific advanced batch control methods have been developed that can be used to reduce the batch cycle time and improve consistency. These methods are [2]:
(1) automatic calculation of charge from temperature corrected titration curve;
(2) automatic partial correction of charge based on last best batch;
(3) automatic end-point prediction and shut-off based on rate of change of pH;
(4) pulse width and amplitude modulation of a proportional only controller output;
(5) cascade of batch pH to inline pH control of a high recirculation flow.
The best results are obtained when an initial charge is done based on (1) and (2) and after a trim adjustment is done by a combination of items (3) and (4) or (5) [4].

Another classification divides the pH control methods in traditional control methods and methods based on computational intelligence. The first category includes the PID controller and its variations, P or PI controller.

The second category includes the methods based on fuzzy logic, neural networks and combinations of the two (neuro-fuzzy control methods).

III. TRADITIONAL PH CONTROL METHODS

In process industries, PI and PID controllers are generally used for their simple design and tuning methods [7], [8]. Because of the presence of measurement noise, PI controllers are more preferable than PID controllers. The absence of the derivative action makes a PI controller simple and less sensitive to noise [6]. In practice, nearly 90% of all industrial PID controllers have their derivative action turned off [8].

An extensive survey on the controllers used in industries like refinery, chemical processes, pulp and paper shows that 97% of them are of PID structure; even the advanced control methods are based on PID algorithms at the lowest level [9]. Simplicity, applicability and the fact that is easy to implement has led to its wide acceptance [10].

In the case of PID controllers, the control signal is the sum of three terms: term P (Proportional) which is proportional with the error, term I (Integrative) which is proportional with the integral of error signal and term D (Derivative) which is proportional with the derivative of error signal. These three terms can be interpreted in terms of time, as follows: term P depends of the present error, term I depends of the accumulation of errors from the past and term D is a prediction of errors from the future relying on the current rate of change.

Since the pH process has a nonlinear dynamic, the standard PI or PID controllers are limited for controlling this type of process. Process nonlinearities influence the gain adjustment of the PID controller. On top of that, the sensors and actuators used in industrial processes are adding nonlinearities through dead times. To overcome this problem, linear control methods are used to control nonlinear processes, like the pH process. In the case of PID controllers, when changes or perturbations appear in the process, it is necessary to recalculate the control parameters. New approaches have been proposed to overcome this issue. These new approach include: adaptive linear control and methods that recalculate automatically the control parameters of the controller.

A self-tuning PI controller for the pH of a neutralization process is presented in [11]. Results show that controlling the pH of this type of process can be performed by a fixed parameter PI controller due to the reason that the self-tuning algorithm can easily find appropriate fixed parameter values for the controller. The task of tuning such a controller would be very difficult, if not impossible, for a human operator.

Another self-tuning PI regulator used to control the pH in a neutralization process is described in [12]. The difficulties in this type of control due to the variations in process sensitivity with pH and process nonlinearities were overcome with a self-tuning pH regulator. Results prove that even though the process is nonlinear, the implemented PI controller has satisfactory static and dynamic properties. It is also proven that the self-tuning algorithm can adapt to changes in process conditions.

Studies show that researches have been investigating for a long time to control the pH with a tuned traditional PID controller, but the solution is not working properly due to the changing of dynamics hence the transfer function when the PID is tuned for a certain characteristics, it becomes un-tuned for the next. In order to tackle this issue, intelligent pH control methods have been developed.

IV. INTELLIGENT PH CONTROL METHODS

With the emerging of new hardware technologies, the industry tends to move slowly and cautiously with regards to new approaches in control algorithms.

For example, in the industrial bioprocesses, the reluctance to implement these techniques is due to the uncertainty of how to validate them, a desire to keep things simple for operators who don't always have an engineering background and lack of published evidence that these techniques increase bioprocess productivity [13].

Controllers based on linear models are working properly for processes which are slowly nonlinear, but they are inadequate for highly nonlinear processes, like the pH. The solution for control of pH processes is to develop a process model that can identify the titration curve together with the implementation of a nonlinear controller that is using the model of the process.

The application of fuzzy logic for pH control was studied in [14]. The characteristics of the implemented method are: larger range for the control of nonlinear process, robustness for perturbations and a relatively simple implementation. The pH neutralization process is highly nonlinear, which is reflected in the titration curve (Figure 1), where the gain factor can vary between 10000 and 1, in a restricted area of the titration curve.

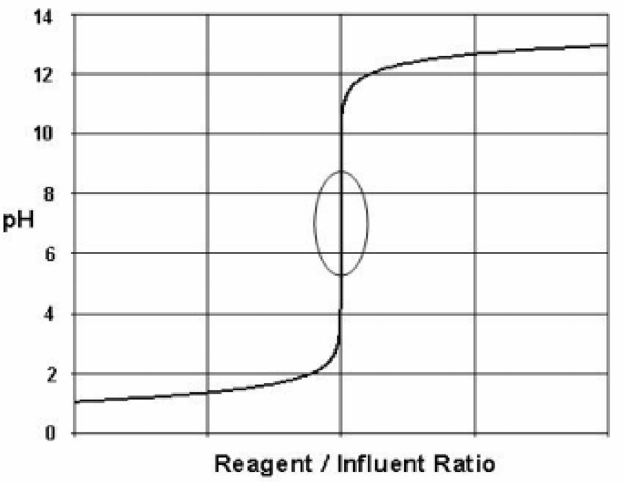

Figure 1. Titration curve [15]

The most severe changes are observed around the value pH=7, where the typical neutralization value usually resides. The implemented method uses the titration curve to characterize the system behavior. Based on the process characteristic, a fuzzy controller was designed; this controller overcomes process time variations, perturbations and process nonlinearities. Experimental results show that the fuzzy controller has a better performance than a simple feedforward controller.

Fuzzy control systems can mimic the behavior of human operators. Hence, they can be very flexible for highly nonlinear processes.

The development of a pH control system for the fermentation process of a reactor and for waste neutralization based on fuzzy logic is mentioned in [16]. The fuzzy logic controller is based on specific process knowledge and also on experimental data. The results of the study show that by using a fuzzy controller the adjustment of pH level was done faster than with a PID controller.

A study for the impact of different fuzzy rules on the pH neutralization process is done in [17]. The value of pH is controlled by adding acid reagent to decrease the pH value and by adding alkaline reagent to increase the pH level. Three rule bases were implemented and compared, for the cases of high and low frequency input signal. Based on the simulations, the conclusion was that a fuzzy controller with 9 rules is enough to obtain a good pH control. On the other hand, the fuzzy controller with 15 rules was capable of controlling the pH, but the best results were obtained with the fuzzy control which had 21 rules. This last controller was capable of maintaining the pH level at 7±1.

Another approach [18] uses fuzzy control together with sliding mode control and data related to state of the system in order to simplify the fuzzy set rules. The authors of this study present the design of a control system for pH neutralization in the chemical industry. The method of sliding mode control can be used for nonlinear system control due to its sturdiness. While it depends on the mathematical model of the system, the fuzzy control method does not depend on the mathematical model but rather on the number of system inputs and control rules. Therefore, by combining the two, the number of inputs for fuzzy control can be reduced thus facilitating the creation of the fuzzy rule set. The fuzzy system rule set used is based on the Lyapunov principle. The results prove that the system presents strong robustness and good anti-disturbance even in the case of a major change in operating point.

Fuzzy relational models (FRMs) for the nonlinear control of a pH process are used in [19]. The study focuses on the pH control with a model predictive controller (MPG) in a simulated and a laboratory continuously stirred tank reactor (CSTR). The implemented MPG controller has a fuzzy model created by using FRM identification. By comparing the MPG controller with that of a fuzzy relational model-based control, that of a PID controller and that of a linear MPG can be proven that the fuzzy relational model-based control is superior in terms of performance for highly nonlinear processes.

In [20] a fuzzy controller for a pH process at laboratory scale is presented. Based on previous knowledge about the process the pH neutralization process is split in several fuzzy regions such as: high-gain, medium-gain and low-gain. In this case the fuzzy controller uses three inputs: the control error, the change of the control error and an auxiliary variable that indicates different nonlinear regions of pH neutralization process. Compared to a usual fuzzy controller which does not have the auxiliary variable input signal, the designed controller has better control performance. The results show that this fuzzy controller with auxiliary variable signal is suited for highly nonlinear systems without the need of a complex mathematical model of the system. Taking in account that this is a laboratory scale system, this method would become more difficult to implement at a real scale process. This is due to the scaling factors for each variable, the membership functions and rules when they are applied to a real process.

Expert knowledge can be used to define the fuzzy rules which describe the titration curve. In [21] the static part of pH process is modeled with fuzzy and not the dynamic part. By doing this the computational load is reduced. The performance of the controller is improved when only one titration curve is used for fuzzy modeling. Once the titration curve is identified any model based control scheme can be used for control purposes.

Artificial neural networks [22] are trying to imitate the functionality of the human brain. Neural networks are often used to control nonlinear processes. Among the types of neural networks described in the literature the most used is the multilayer feedforward network because is capable to approximate any nonlinear function with the wanted accuracy on a compact dataset.

The use of neural network to control the pH level is proposed in [23]. Network training is done offline, based on the process input-output data. The neural network is a back propagation, feedforward one, with a hidden layer and sigmoid activation function. Results show a stable response and faster response time, compared with the traditional PID. The major advantage of this method comes from the fact that the network can be easily trained in a few hours.

Several authors [24-28] have studied the combination of fuzzy logic and neural networks.

By combining the formalism of fuzzy logic with the learning capabilities of the neural networks, a promising solution for modeling nonlinear processes can be obtained. Neural networks and neuro-fuzzy networks have to keep in mind the process dynamic. There are two methods used to add dynamism to a static neural network: the insertion of an external memory in the network or the use of a dynamic neural unit. These dynamic neural units have proven good approximation capabilities through functions and have been successfully used in the identification of nonlinear processes [29].

An architecture which combines dynamic neural networks with fuzzy logic techniques to model the pH of a chemical reactor is described in [29]. The mathematical model used to model the pH has two components: one component is the dynamic one which is modeled using dynamic neural units and the other one is a static component which was modeled using fuzzy logic. Results obtained with dynamic neural units are compared against the ones obtained from recurrent neural networks and fuzzy modeling. The comparison proves that the use of a fuzzy model with dynamic neural units is more suitable for pH modeling.

Among all different types of neuro-fuzzy models, Takagi-Sugeno fuzzy recurrent neural network (T-S FRNN) stands out due to its internal dynamic structure and has been employed in the modeling of the complex nonlinear systems [30]. Based on the success of DNA (Deoxyribonucleic acid) genetic algorithms, a DNA Non-Dominated Sorting Genetic Algorithm (NSGA-II) is proposed in [30] trying to optimize the parameters of a Takagi-Sugeno fuzzy recurrent neural network (T-S FRNN) for the modeling of the pH neutralization process. For the implementation every individual in the DNA based NSGA-II represents a premise part of one network whose corresponding consequent part is obtained by the recursive least square algorithm. The individual is evaluated on the base of Pareto-dominance relation and crowding measure. After modified genetic operators are applied to improve the global search ability of the algorithm. Elitism is also implemented in the algorithm based on the dominance relation and the crowding measure. Comparison between the DNA based NSGA-II and NSGA-II shows that the proposed algorithm is better than NSGA-II regarding the convergence speed and the quality of the final Pareto-optimum.

In [31] a method of pH identifier using neural network is proposed to increase the performance of pH control system. The pH control system is designed with a linear filter neural network and the learning algorithm that uses back propagation through time. Learning process of the network was done in on-line and also off-line. Results show that the model by means of data collection over a wide range of pH improves the accuracy, reduces the complexity, increases the immunity to noise and fewer controllers are needed. From the presented results it can be noted that neural systems are an appropriate solution for pH control systems.

There are some researchers interested in studying pH control using predictive control techniques [20]. For example [32] proposes the study of the in-line pH process with the use of neural predictive strategy. Authors use a nonlinear autoregressive exogenous model structure which is used to predict on-line the future process responses. In [33] is also studied the use of static nonlinear elements and the linear dynamic elements of the SISO Wiener Model. In the study several methods are uses to calculate the predicted response: polynomial methods, autoregressive models with exogenous inputs and step-response models to represent the linear dynamic element. Although these predictive control techniques have proven to be efficient for real plants, the difficulty of being necessary to develop a model that represents with high fidelity the pH process in any operating condition still remains. This problem can be solved by the implementing a fuzzy pH controller without the need of any plant model [20].

V. IMPLEMENTATION OF FUZZY CONTROL FOR pH

Fuzzy control is considered to be a good solution for the pH control. A fuzzy controller has four main parts as illustrated in Figure 2 [21]: fuzzification, knowledge base, inference and defuzzification.

Fuzzification phase converts numeric variables in the corresponding fuzzy sets.

First step in implementing the fuzzy controller is to determine the input values and the desired output.

In the case of the fuzzy pH controller the input values will be the pH value read from the process through a pH-meter and the desired set point. The output will be the control signal. After the input data is transformed in linguistic variables.

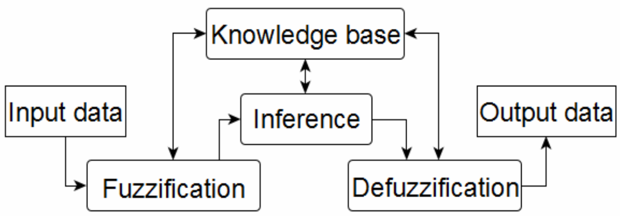

Figure 2. Structure of a fuzzy controller

For each linguistic variable is needed to determine the membership function and the operation range. In order to choose the operation points for the linguistic variables the flows of the reagents needs to be taken in account.

In the *knowledge base* phase rules of type IF <condition> THEN <conclusion> will be defined [34]. The phase of rules definition can be difficult if there is no knowledge about the dynamic behavior of the pH neutralization process. When there is no previous knowledge about the process the heuristic rules are obtained by running the system in manual mode. Another option is to study the existing pH systems and try to understand how they work so the rules can be defined as good as possible.

Accuracy can be increased by adding more fuzzy rules but this comes at the expense of higher computational load.

The *inference* stage emulates the expert's decision making on how to interpret data and apply knowledge about how it is best to control the pH process. The inference mechanism used in the case of pH control is based on individual rule firing. So the contribution of each rule is evaluated and overall decision is derived. During inference process each rule that is triggered by a crisp pH value is summed up after giving the weightages decided by the fuzzification unit [35].

After evaluation of rules the *defuzzification* phase will start. At this stage the linguistic variables from the output of the fuzzy system are converted in numeric values [34].

VI. COMPARISON OF PH CONTROL METHODS

Table 1 presents a summary of advantages and drawbacks of traditional and intelligent pH control methods.

Table 1. Advantages and drawbacks of pH control methods

Method	Ref.	Advantages	Drawbacks
PI	[7] [8],[11]	- simple design - self-tuning algorithm available	- less sensitive to noise than PID
PID	[7] [10] [25]	- simple design - easy to implement - automatic tuning methods available	- action in the system not satisfactory for pH control - tuning parameters need to be recalculated if changes in the process occur - sensitive to measurement noise
Fuzzy logic	[35] [16]	- good results for the control of pH - is possible to bring any waste pH to neutrality smoothly in an acceptable time - pH adjustment is faster than in the case of traditional PID	- expertise required to tune the controller - heuristic information needs to be available in order to define the fuzzy rules set
Neural networks	[23] [25] [31]	- neural network can be trained in a few hours - stable response and faster than a PID - don't require any tuning of the control parameters (unlike PID) - if modeled by means of data collection over a wide range of pH it can approve accuracy, reduce the complexity, increase the immunity to noise	- requires a large amount of data - data preprocessing may be required
Neuro-fuzzy	[24] [21]	- combines the advantages of fuzzy and neural methods - more suitable for pH modeling	- requires a lot of computational resources - can become impractical and ineffective if the number of parameters is moderately large

VII. CONCLUSIONS

Recently, process control using fuzzy logic and neural networks has gained a lot of attention from scientists and professionals from the process control world.

Traditional control methods present limitations when applied to a complex process like pH neutralization, where nonlinearities and a complex dynamic occur. These methods often require a process model.

Intelligent control methods (fuzzy logic, neural networks and neuro-fuzzy) provide an alternative approach, which allows the design of a controller by using a high level of abstraction, without knowing the process model.

Controllers based on linear models are working pretty well for processes which are slightly nonlinear, but they are unsuitable for processes such as pH control. The solution for pH control is the development of process models capable of identifying the titration curve (and which can adapt to process changes) together with nonlinear controllers that are using explicitly the process model.

Results proven by references listed in this paper recommend the use of intelligent methods for the control of pH, since they are faster, they can change the value of the control signal before the process value of the pH is affected and no process model needs to be known.

Control based on fuzzy logic can be efficient because it can incorporate expert knowledge regarding the pH control. The neural networks have the advantage of being able to identify patterns, but no explanation is given on how the conclusion was made. On the other hand, fuzzy methods can explain the reasoning process, but the rules for decision making have to be defined before a decision needs to be taken. To overcome the drawbacks of individual methods, the use the neuro-fuzzy methods is recommended.

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