

Fuzzy Gain Scheduling of PI Controller for an Anaerobic Digester

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Abstract. A cascaded controller for an anaerobic digester is presented. The upper-level controller is a Fuzzy Gain Scheduling of PI controller (FGS-PI) and the lower-level controller is a PI controller. The inner loop controller feeds the reactor pH back to the influent flow rate, and the outer loop controller measures the biogas flow rate and adjusts the pH set point. Simulation results of the proposed scheme show good performance during start-up operation of an anaerobic digester and also during rejection of disturbances. A comparison between FGS-PI controller and a Fuzzy Logic PI type controller is presented.

1 Introduction

The Anaerobic digestion processes are gaining an increasing interest in industrial waste treatments because of several advantages over other processes. The anaerobic digestion can reduce the influent Chemical Oxygen Demand (COD) producing valuable energy (a mixture of methane and carbon dioxide) and low sludge yield [1,4,9]. However, the interdependence of the different microbial groups involved in the degradation of organic matter may easily unstabilize the process and difficult the mathematical modeling of the anaerobic digestion [2,3,6,7].

In order to avoid the instability of anaerobic digestion processes, several techniques using monitoring and control has been used. The most widely used controller in industrial applications are PID-type controllers because of their simple structure and good performances in a wide range of operating conditions. But, these PID controllers can not always effectively control systems with strong nonlinearities. In recent years, fuzzy logic control (FLC) techniques have been applied to the control of anaerobic digesters [3,4,8,10]. However, the application of FLC has faced some disadvantages during hardware and software implementation due to its high computational burden. In order to overcome the disadvantages of PID controllers and FLC, a Fuzzy Gain Scheduling of PID controllers has been developed [13].

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In this paper a cascaded control strategy for an Upflow Anaerobic Sludge Blanket (UASB) digester is presented. The upper-level controller is a Fuzzy Gain Scheduling of PI controller (FGS-PI), and the lower-level controller is a PI controller. The goal is to achieve a good biogas production maintaining a stable process operation despite significant variations in the influent characteristics. The process and the control strategy has been simulated and tested in SIMULINK of MATLAB™.

2 Description of the process

Anaerobic digestion comprises basically two steps. In the first step, organic compounds are fermented into volatile fatty acids (VFA) and CO₂ by a group of acidogenic bacteria. In a second step, VFA are converted into CH₄ and CO₂ by a group of methanogenic bacteria. In order to design a cascaded controller for an UASB digester, a mathematical modeling of the process is necessary. The objective of the model is to simulate the process evolution and control the biogas production and pH.

In this paper, the control system was evaluated on a model of anaerobic digestion. Implementation depends on whether the liquid phase physico-chemical processes are implemented as kinetic rate equations. The mass balance for each state component in the liquid phase is as shown in Equation 1:

$$\frac{dS_{liq,i}}{dt} = \frac{q_{in}S_{in,i}}{V_{liq}} - \frac{S_{in,i}q_{out}}{V_{liq}} + \sum_{j=1-19} \rho_j v_{i,j} \quad (1)$$

where the term $\sum_{j=1-19} \rho_j v_{i,j}$ is the sum of the kinetic rates for process j multiplied by $v_{i,j}$

[2]. The model was developed using SIMULINK of MATLAB™. The simulated equipment was a 1.4 liters UASB digester with regulated temperature at 35°C. Synthetic wastewater with variable substrate concentration from 10 to 20 gCOD/L, was assumed.

3 Control structure

The control system depicted in Fig. 1 is a cascaded control. The Upper-level controller is a Fuzzy Gain Scheduling of PI Controller (FGS-PI) and the Lower-level controller is a PI controller. The inner loop controller feeds the reactor pH back to the influent flow rate Q_{in} . The outer loop controller measures the biogas flow rate Q_{gas} and adjusts the pH setpoint.

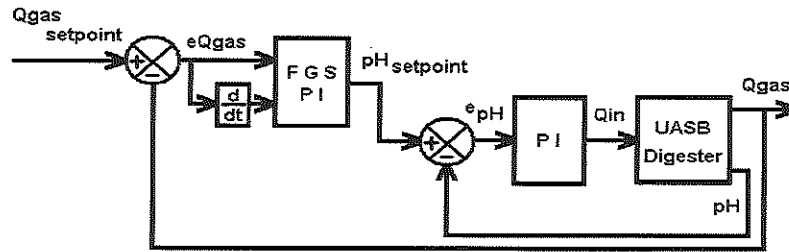


Fig. 1. Cascaded controller for an UASB digester. The upper level controller is a Fuzzy Gain Scheduling of PI controller (FGS-PI), and the lower level controller is a PI controller.

3.1 Fuzzy Gain Scheduling of PI Controller (FGS-PI)

Fuzzy Gain Scheduling of PI Controller (FGS-PI) is a technique where PI controller parameters (k_p and k_i gains) are tuned during control of the system in a predefined way [13,14]. The structure of the control system is illustrated in Fig. 2. The fuzzy adapter adjusts the PI parameters to operating conditions, in this case based on the error and its first time derivative, during process control.

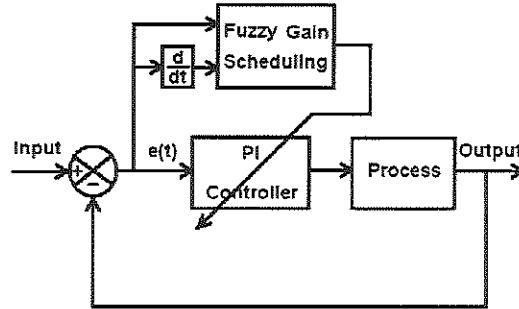


Fig. 2. Fuzzy Gain Scheduling of PI Controller.

3.2 Description of the Fuzzy Gain Scheduling of PI Controller

The parameters of the PI controller used in the direct chain, k_p and k_i , are normalized into the range between zero and one by using the following linear transformations [14]:

$$K'_p = (k_p - k_{p \min}) / (k_{p \max} - k_{p \min}) \quad (2)$$

$$K'_i = (k_i - k_{i \min}) / (k_{i \max} - k_{i \min}) \quad (3)$$

The inputs of the fuzzy adapter are the error (e) and the first time derivative of the error (Δe), normalized using a predefined maximum error and a maximum first time derivative. The outputs are the normalized value of the proportional action (k'_p) and of the in-

tegral action (k'_i). The parameters k'_p and k'_i are determined by a set of fuzzy rules of the form:

$$\text{If } e \text{ is } A_i \text{ and } \Delta e \text{ is } B_i \text{ then } k'_p \text{ is } C_i \text{ and } k'_i \text{ is } D_i \quad (4)$$

where A_i , B_i , C_i and D_i are fuzzy sets on corresponding supporting sets. The membership functions for the inputs e and Δe are defined in the range $[-1, 1]$, see figure 3(a), and for the outputs are defined in the range $[0, 1]$, see figure 3(b). The fuzzy subsets of the input variables are defined as follows: NL: Negative Large, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium, PL: Positive Large. The fuzzy subsets of the output variables are defined as: L: Large, S: Small.

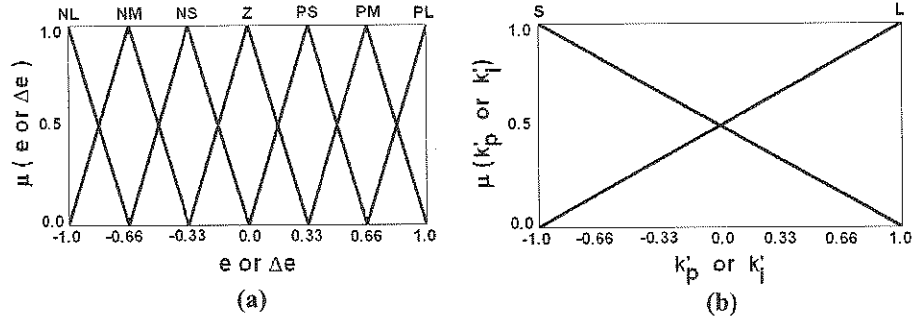


Fig. 3. (a) Membership functions for the inputs (e) and (Δe). (b) Membership functions for the outputs k'_p and k'_i .

The fuzzy rules in (4) are extracted from operator's expertise. The tuning rules for k'_p and k'_i are given in Tables 1 and 2 respectively.

Table 1. Fuzzy rules base for computing k'_p .

$e \backslash \Delta e$	NL	NM	NS	Z	PS	PM	PL
NL	L	L	L	L	L	L	L
NM	S	L	L	L	L	L	S
NS	S	S	L	L	L	S	S
Z	S	S	S	L	S	S	S
PS	S	S	L	L	L	S	S
PM	S	L	L	L	L	L	S
PL	L	L	L	L	L	L	L

By using the membership functions shown in Fig. 3, we satisfy the following condition:

$$\sum_{i=1}^m \mu_i = 1 \quad (5)$$

Table 2. Fuzzy rules base for computing k'_p .

$\Delta e \backslash E$	NL	NM	NS	Z	PS	PM	PL
NL	L	L	L	L	L	L	L
NM	L	S	S	S	S	S	L
NS	L	L	S	S	S	L	L
Z	L	L	L	S	L	L	L
PS	L	L	S	S	S	L	L
PM	L	S	S	S	S	S	L
PL	L	L	L	L	L	L	L

The defuzzification rule is chosen as:

$$k'_p = \sum_{i=1}^m \mu_i k'_{p,i} \quad (6)$$

$$k'_i = \sum_{i=1}^m \mu_i k'_{i,i} \quad (7)$$

where $k'_{p,i}$ is the value of k'_p corresponding to the grade μ_i for the i_{th} rule. $k'_{i,i}$ is similarly defined. Once the values of k'_p and k'_i are obtained, the new parameters of the PI controller are calculated by the following equations:

$$k_p = (k_{p\max} - k_{p\min})k'_p + k_{p\min} \quad (8)$$

$$k_i = (k_{i\max} - k_{i\min})k'_i + k_{i\min} \quad (9)$$

3.2 Description of the Fuzzy Logic PI type controller

The Fuzzy Logic PI type controller is essentially a low pass filter which attenuates high frequency signals, it is commonly used to design a robust controller for ensuring suppression of disturbances. In Fuzzy PI type controller (Fig. 4), which is the fuzzy equivalent of the conventional PI controller, its nonlinear mapping between the control rules and the fuzzy reasoning can be represented as a function of the error e and the first time derivative of the error Δe as follows:

$$\Delta u = FLC(e, \Delta e) \quad (10)$$

where Δu is the first time derivative of the output control action. Δu can be expressed approximately as follows:

$$\frac{\Delta u(t)}{S\Delta u} = \frac{\Delta e(t)}{S\Delta e} + \frac{e(t)}{Se} \quad (11)$$

where $-Se < e(t) < Se$, $-S\Delta e < \Delta e(t) < S\Delta e$, $-S\Delta u < \Delta u(t) < S\Delta u$.
or

$$u(t) = k_p e(t) + K_i \int e(t) dt \quad (12)$$

tegral action (k'_i). The parameters k'_p and k'_i are determined by a set of fuzzy rules of the form:

$$\text{If } e \text{ is } A_i \text{ and } \Delta e \text{ is } B_i \text{ then } k'_p \text{ is } C_i \text{ and } k'_i \text{ is } D_i \quad (4)$$

where A_i , B_i , C_i and D_i are fuzzy sets on corresponding supporting sets. The membership functions for the inputs e and Δe are defined in the range $[-1, 1]$, see figure 3(a), and for the outputs are defined in the range $[0, 1]$, see figure 3(b). The fuzzy subsets of the input variables are defined as follows: NL: Negative Large, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium, PL: Positive Large. The fuzzy subsets of the output variables are defined as: L: Large, S: Small.

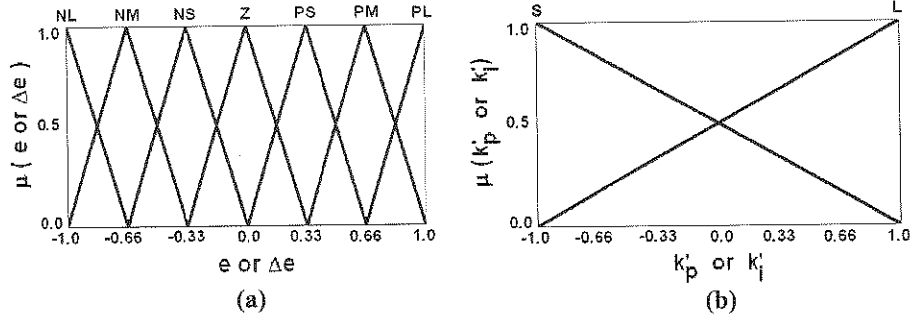


Fig. 3. (a) Membership functions for the inputs (e) and (Δe). (b) Membership functions for the outputs k'_p and k'_i .

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Table 1. Fuzzy rules base for computing k'_p .

$e \backslash \Delta e$	NL	NM	NS	Z	PS	PM	PL
NL	L	L	L	L	L	L	L
NM	S	L	L	L	L	L	S
NS	S	S	L	L	L	S	S
Z	S	S	S	L	S	S	S
PS	S	S	L	L	L	S	S
PM	S	L	L	L	L	L	S
PL	L	L	L	L	L	L	L

By using the membership functions shown in Fig. 3, we satisfy the following condition:

$$\sum_{i=1}^m \mu_i = 1 \quad (5)$$

The model and the experimentation allowed the rule table to be built up (Mamdani, 1975) [11]. The fuzzy rules are given in Table 3. In order to convert the fuzzy information into a numerical value to be applied to the process, the center of gravity method was used.

Table 3. Fuzzy rules base for computing Δu .

$e \backslash \Delta e$	NL	N	Z	P	PL
NL	NL	NM	NS	Z	PS
NM	NM	NS	Z	PS	PM
NS	NS	Z	PS	PM	PL

3.3 Description of the PI controller

The conventional PI controller for the proposed lower-level controller was designed with Ziegler-Nichols tuning formulas. In order to apply the Ziegler-Nichols tuning formulas based on frequency response [12], there are only two parameters which are necessary: the critical gain K_c , and the critical period T_c . To determine them, a delay is introduced in the control closed-loop, to force the system oscillates in a controlled limit cycle [5]. The tool box SIMULINK of MATLAB™ was used to obtain K_c and T_c . With those values, the proportional gain K_p and integral gain K_i were calculated.

4 Results

In order to test the ability of the developed control scheme to handle start-up condition, we apply the proposed scheme to the control of start-up operation of UASB digester. Fig. 7 shows a biogas flow rate comparison between the start-up period of the FGS-PI controller and FLC-PI controller, each one operating in the proposed cascaded controller of an UASB digester at constant influent substrate equal to 3 gCOD/L and $Q_{gas_setpoint} = 1$ Lgas/d. The settling time is 17 hours with the FGS-PI controller and 25 hours for the FLC-PI. For the same conditions, a comparison of the influent flow rate (i.e. the control action) between FGS-PI controller and FLC controller is presented in Fig. 8. When the influent flow rate (Q_{in}) is increased at time=10.5h, for the control action of the FGS-PI controller, the pH decreases from 7 to 6.9 (Fig. 9), due to the increased Organic Load Rate (OLR) but, at time=15h, the pH increases up to 6.92 for the control action of the lower level controller. On the other hand, when the influent flow rate (Q_{in}) is increased at time=13h (Fig. 8), for the control action of the FLC-PI controller, the pH decreases from 7 to 6.9, following the $pH_setpoint$.

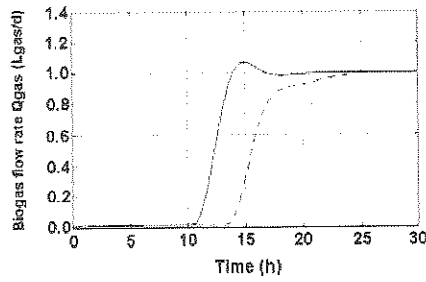


Fig. 7. Simulation of the biogas flow rate (Q_{gas}) during a start-up procedure at constant influent substrate at 3 gCOD/L and $Q_{gas_setpoint}=1\text{Lgas/d}$, with FGS-PI controller (*solid line*) or FLC-PI controller (*dotted line*), each one operating in the developed cascaded controller.

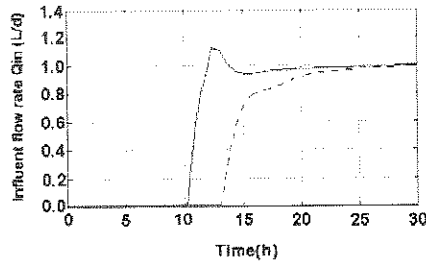


Fig. 8. Simulation of the influent flow rate (Q_{in}) during a start-up procedure at constant influent substrate at 3 gCOD/L and $Q_{gas_setpoint}=1\text{Lgas/d}$, with FGS-PI controller (*solid line*) or FLC-PI controller (*dotted line*), each one operating in the developed cascaded controller.

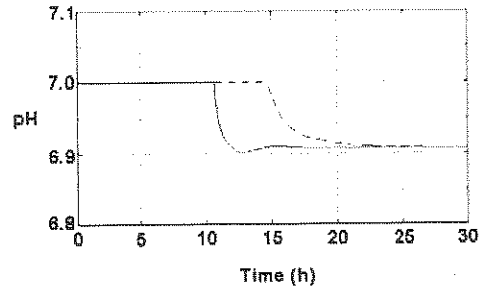


Fig. 9. Simulation of the behavior of pH during a start-up procedure at constant influent substrate at 3 gCOD/L and $Q_{gas_setpoint}=1\text{Lgas/d}$, with FGS-PI controller (*solid line*) or FLC-PI controller (*dotted line*), each one operating in the developed cascaded controller.

In order to test the characteristics of the developed cascade controller, different disturbances are applied to the influent COD substrate concentration. The influent COD was increased by 33%, from 3 to 4 gCOD/L, at time=40h, with $Q_{gas_setpoint} = 1$

Lgas/d. Fig. 10 shows a comparison of biogas flow rate between the FGS-PI controller and FLC-PI controller, at the same conditions. The FGS-PI controller rejects the disturbance more rapidly than the FLC-PI controller. To compare the performance of both controllers, the criterion of Integral Square Error (IAE), from 35 to 60 hours, was used. The obtained value when using the FGS-PI controller is IAE = 58950 versus 62280 when using the FLC-PI controller.

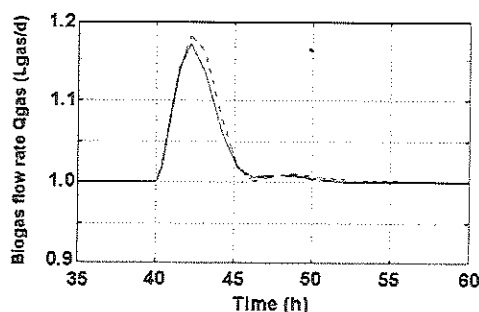


Fig. 10. Simulation of the biogas flow rate (Q_{gas}) under influent COD variation from 3 gCOD/L to 4gCOD/L, at $Q_{gas_setpoint}=1\text{Lgas/d}$, with FGS-PI controller (*solid line*) or FLC-PI controller (*dotted line*), each one operating in the developed cascaded controller.

4 Conclusion and directions for further research

A Fuzzy Gain Scheduling of PI (FGS-PI) controller operating in a cascaded controller was designed and simulated to operate an UASB digester. Good control performances were achieved during the start-up operations and during rejection of disturbances. The FGS-PI controller starts-up the process and rejects disturbances more rapidly than FLC-PI controller. A comparison between the developed FGS-PI controller and a Fuzzy Logic PI type (FLC-PI) controller was presented.

Through simulation we have shown the ability of the developed control scheme to handle start-up condition of an UASB digester at constant influent substrate equal to 3 gCOD/L and $Q_{gas_setpoint} = 1\text{ Lgas/d}$ (Fig. 7). The FGS-PI controller had a better performance than the FLC-PI controller, because the settling time using the FGS-PI controller was 17 hours against 25 hours using the FLC-PI controller. However, the fact that the influent flow rate (Q_{in}) grow faster when using the FGS-PI controller (Fig. 8), at time 10 hours, causes the pH reaches a lower value compared with the FLC-PI controller (Fig. 9), at time 12.5 hours, due to increased of the organic load rate.

Moreover, we have shown the performance of FGS-PI controller versus FLC-PI controller (Fig. 10), under influent COD variation from 3 gCOD/L to 4gCOD/L, at $Q_{gas_setpoint}=1\text{Lgas/d}$. We have compared the performance of both controllers using the criterion of integral absolute error (IAE), from 35 to 60 hours. The FGS-PI controller had a better performance than the FLC-PI controller, because its IAE=58950 was lower than the IAE=62280 for the other controller.

Nowadays, we are working on the physical verification of the simulations presented in this paper.

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