Design procedure for anaerobic digestion controllers aimed at feasible full-scale application

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Abstract
This paper presents a methodological procedure to design a specific controller for anaerobic digestion reactors. Considerations concerning the appropriate definition of the control problem and its performance specifications in the context of full-scale plants are discussed. To effectively adjusting the controller's parameters a method based on an optimization tool is described and then validated by simulation. Results show a satisfactory response of the controller under stationary and dynamic conditions. With such a procedure, an optimal operation of the plant in terms of methane production and process stability is achieved despite the intrinsic limitations of the control problem.

Keywords
Anaerobic digestion; automatic control; optimization; methane production; whole plant modelling

INTRODUCTION

Nowadays, the treatment and the disposal of urban and industrial effluents in a way that is fulfilling environmental requirements is probably the major challenge that Wastewater Treatment Plants (WWTP) face. An optimal operation of WWTP implies to accomplish the effluent requirements with a cost effective operation. In the last years, the application of control strategies to biological processes has been revealed as being crucial to guarantee appropriate operation of WWTP, to reject disturbances and to reduce energy costs (Ingildsen, 2002; Beltrán et al., 2009). Recent developments in advanced on-line instrumentation, data acquisition systems and also in the modelling of biological processes have contributed to the gradual implementation of control systems in WWTP.

Concerning waste sludge treatment by anaerobic digestion (AD), the inherent characteristics of this biological process make it a special candidate to apply advanced control. Both to overcome operational problems such as process instability and high sensitivity to disturbances, and to fully exploit the AD potential to provide a renewable energy source are the main objectives to look at (Olsson et al., 2005). Control approaches reported in the literature have been validated essentially by simulation using simplified models of the process or lab/pilot plant platforms. Most of the control solutions for AD have been designed for the unit process, even if industrial treatment plants often include equalization tanks in their configurations to manage influent load hydraulics. Therefore, how to design control strategies for anaerobic digesters in the context of full-scale plants is a topic not dealt with yet. Practical applications require considering physical limitations, process variability and both available instrumentation and manipulated variables (Liu et al., 2004a; Spanjers and van Lier, 2006), making it difficult to define an realisable control objective and its performance specifications.

Using simulations and an optimization tool, this paper describes the design procedure of a control strategy for anaerobic digesters aimed to be applied in practice. Based on a specific case study, control objectives and performance specifications are defined, and a systematic method to appropriately tune the controller parameters in order to satisfy transient performance specifications is also presented and validated by simulation.

MATERIALS AND METHODS

Case study
The studied plant configuration (Figure 1) was made up of an equalization tank (ET) followed by an Anaerobic Hybrid Reactor (AHR). The ADM1 model (Batstone et al., 2002) was used to describe the anaerobic digestion process using default values for the model parameters. Only the hydraulic effect has been considered in the ET. Weekly profiles (Figure 2) of raw wastewater from a slaughterhouse factory were used to specify the influent characteristics in stationary and dynamic conditions and also to calculate the effective volume of both elements (ET = 171 m^3, AHR = 68 m^3). A realistic 168-day influent profile is provided for long-term evaluation. Since the desirable practical application, only cost-effective and reliable on-line instrumentation was considered. The influent flow rate to the digester (Q_{feed}) was the only considered manipulated variable. The plant-model was implemented in Matlab/Simulink.

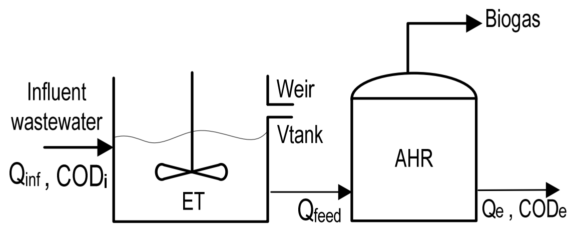

Figure 1. Plant layout

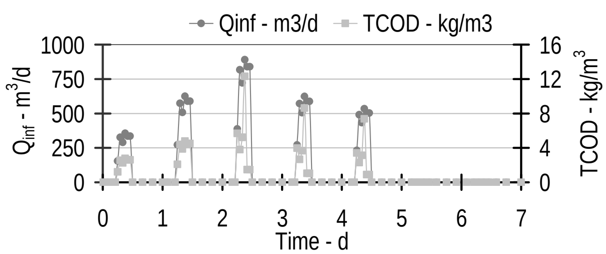

Figure 2. Weekly wastewater profile

Control problem
The control objective was defined as follows: (1) guarantee a stable operation of the plant and a good rejection of disturbances; and (2) maximize the methane production in the medium-long term. According the case study, the control problem has to face the following limitations: (1) high non-linearity of the AD that affects the dynamic behavior of the controlled variables and the validity of the control solution at different operational points; (2) manipulation of Q_{feed} is limited by the total volume of wastewater produced by the industry; (3) Even if Q_{feed} is the manipulated variable it is also a main perturbation for the process; and finally (4) physical limitations concerning the hydraulic capacity of the ET. As a result, to fulfil the control objective the control problem has been treated as a 'dynamic optimization problem' and not as a traditional set-point adjustment statement. Since Q_{feed} is the only manipulated variable, the optimization problem is reduced to properly manipulate Q_{feed} to fulfil the control objective taking into account the state of the AHR but also the hydraulic behaviour of the ET.

Control architecture: Design procedure
Figure 3 shows the control architecture used in this work. It corresponds to the two-layer scheme reported in Alferes and Irizar (2010). The bottom-layer is based on the extremum-seeking algorithm proposed by Liu et al. (2004b) aimed at maximising the instantaneous methane production. The top-layer (a fuzzy-based module) is in charge of guaranteeing appropriate water levels in equalization tanks. With such a structure, a satisfactory balance between methane production and process efficiency in the long-term can be achieved. Since the purpose of each layer is well defined, each layer can be considered as a particular system with its specifications. While a full realization of the top-layer was set out in Alferes and Irizar (2010), the design procedure described in this paper is focused on the bottom-layer as individual system. The design procedure for the bottom-layer is focused in to guarantee a fast and damped transient response of the methane production to efficiently reach its instantaneous maximum.

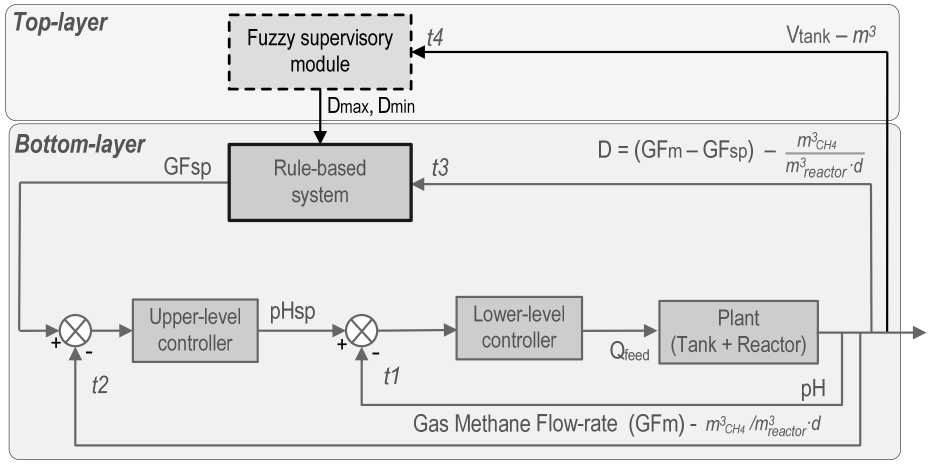

Figure 3. Scheme of the two layer control architecture for AD (Alferes and Irizar, 2010)

Using on-line pH and methane flow rate (GF_m) measurements, the bottom layer consists of a cascaded structure embedded into a rule-based system (based on an extremum-seeking algorithm) aimed at maximizing the instantaneous production of methane gas. Both upper-level and lower-level controllers in the cascade structure are implemented as simple P controllers as follows:

$$u(k) = u_0 - K_p \cdot e(k); \quad \text{with} \quad k = k \cdot t_1 \quad \text{and} \quad k = 1,2,3... \tag{1}$$

where u is the output of the controller, e the error between the set-point and the controlled variable, u_0 a bias, K_p the proportional constant and k the sample time. The rule-based system monitors the value of the variable D (defined as the difference between GF_m and its set-point value, GF_{sp}) and then applies incremental steps ΔGF to GF_{sp} according to pre-set rules. Q_{feed} (output of the inner loop), the pH set-point in the digester (pH_{sp}; output of the outer loop) and the set-point of methane production (GF_{sp}; output of the rule-based system) are automatically adjusted at regular intervals t_1, t_2 and t_3 respectively (with $t_1<t_2<t_3$), to guide the process to its maximum methane production preserving the process stability. Two parameters in the rule-based system (D_{max}, D_{min}) delimit the operating regions of the variable D. Concepts behind the extremum-seeking controller lead to a continuous variation of pH_{sp} and GF_{sp}. It is translated in a permanent transient and dynamical behaviour of pH and GF_m. For that reason, the performance specifications of the bottom-layer cannot be given in a traditional way. Additionally, due to the non-linear characteristics of the control problem such specifications could not be valid for the whole operational range.

In this work, performance specifications have been defined in terms of the convergence of the extremum-seeking algorithm to the operational point considered as ‘optimum’. Since the bottom-layer is in charge of maximizing the instantaneous methane production, the design procedure was focused on guaranteeing both a fast and damped transient response of GF_m towards that maximum. Previous simulation results have shown that when only the lower-controller is closed and a change in pH_{sp} is applied, the response of the pH follows a second order system trajectory. Similar behaviour is observed for GF_m when the upper-level controller is closed and a change is applied to GF_{sp}. Additionally, when all control loops of the bottom-layer are closed, under constant input concentrations of the digester, the response of the methane production towards its maximum can be adjusted also to a second order system trajectory. Figure 4 shows an example of the dynamic behaviour of GF_m and GF_{sp} from an initial operating state until the maximum methane production is reached. According to the extremum-seeking algorithm GF_{sp} is updated at each sample time t_3 and GF_m follows the set-point value. A second order curve that describes the transient behaviour of GF_m (GF_m_fitted in Figure 4) can then be obtained. These facts allow defining the desirable behaviour of the transient response for each controller and to adjust the controller's parameters to fulfil those requirements.

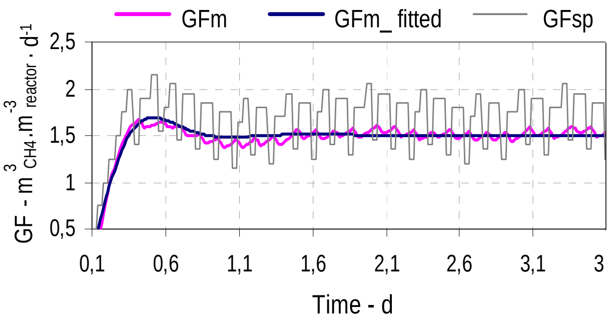

Figure 4. Convergence of GFm towards its maximum

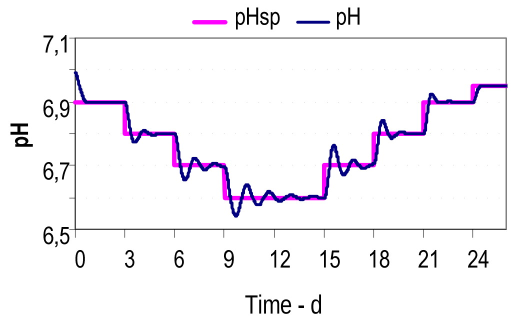

Figure 5. Lower-controller response for different pH_{sp} values

To solve the optimization problem, the Excel Solver optimization tool was linked to the dynamic plant simulator and the controller's parameters were tuned following a sequential and iterative process:

1- A set of initial performance specifications about the transient response is given for each controller.

2- A proper operational range for the pH in the digester is selected to avoid instability situations. That range will uniquely determine the applicable Q_{feed} range to the digester.

3- A proper operational point in the digester is selected and the corresponding stationary state is obtained.

4- <u>Lower-level controller</u>: the optimization problem is set to minimize the rise time in the pH response when an increment in pH_{sp} is applied, with as constraint the maximum allowed overshoot in Q_{feed}. Due to the non-linear nature of the pH system (as shown in Figure 5 by the overshoot variation as function of pH set-point), this procedure is carried out for different values of pH within its operational range.

5- <u>Upper-level and rule-based controller</u>: their parameters are adjusted to achieve the desirable trajectory of GF_m. Parameters of the rule-based system (D_{max}, D_{min}) are fixed to values that promote high instantaneous methane production. The optimization problem is then set to minimize the rise time in the GF_m response with all control loops closed. A maximum allowed overshoot in Q_{feed} and GF_m are established as constraints.

6- If the initial specifications are not accomplished satisfactorily, a new set of specifications should be provided and the design procedure applied again.

Table 1 summarises the performance specifications set for all controllers of the bottom-layer. Values have been chosen according to the observed dynamic response of pH, GF_m and Q_{feed} in preliminary simulations. Concerning the lower-level controller, higher maximum overshoot values at Q_{feed} lead to an excessive total overshoot in Q_{feed} when all loops are closed due to the continuous variation in pH_{sp} and GF_{sp}. Tuning of this loop entails the adjustment of the proportional constant K_{p1} and the sample time t_1. Although it could be convenient to restrict the maximum overshoot in pH_{sp}, it has been preferred for the upper-level and rule-based controllers to set the maximum overshoot in the final manipulated variable Q_{feed} as constraint, since that determines the behaviour of GF_m. Parameters to be tuned in this case are the correspondent proportional constant K_{p2}, the sample times t_2 and t_3 and finally the increment ΔGF to be applied to GF_{sp}. To facilitate the practical implementation of the controllers it is assumed that t_2 and t_3 are multiple integers of t_1.

Table 1. Performance specifications for controllers of the bottom layer

Lower-level controller	Unit	Value
Rise time (t_r)	d	minimum
Maximum overshoot in Q_{feed} (M_p)	%	<5
Upper-level and rule-based controller		
Rise time (t_r)	d	minimum
Maximum overshoot in Q_{feed} (M_p)	%	<20
Maximum overshoot in GF_m (M_{p_GF})	%	<4

Design of the bottom layer controller is done under constant conditions considering a constant influent obtained from the average values of the dynamic influent profile (Figure 2). Only the AHR is considered so as to isolate the effect and the physical limitations associated to the ET. If the bottom-layer is correctly designed to fulfil the performance specifications, that design will be valid for the whole system once proper restrictions in the manipulated variable, Q_{feed}, are established.

RESULTS AND DISCUSSION

Following the design procedure, pH was limited to values in the range [6.7; 7.05] to guarantee the stability in the digester. For the wastewater characteristics used in this study, values below this range result in oscillatory responses and lead the digester close to instability operating regions. Values above this range also result in undesirable slow or oscillatory responses. The following operational point has been selected: pH=6.86, Q_{feed} =196.5 m^3/d, GFm = 2.44 $m^3_{CH4}\cdot m^{-3}_{reactor}\cdot d^{-1}$.

Concerning the lower-level controller, the optimization problem has been expressed as follows:

$$\text{Min } t_r=f(t_1,K_{p1}); \quad \text{such that} \quad M_p<5\% \tag{2}$$

Different combinations of t_1 and K_{p1} allow accommodating the constraint. For a given specification set (t_r, M_p), high t_1 values necessarily lead to high K_{p1} values to reach the desirable response. In the present application, small K_{p1} values are preferred to avoid abrupt changes in the control action. Finally, t_1 is fixed to 10 minutes, according as well with the usual sensitivity of on-line pH sensors. Once t_1 is fixed, the optimization problem is reduced to properly adjust K_{p1} to fulfil the specifications. Figure 6 shows the transient response obtained when different maximum overshoot values were considered, resulting in Q_{feed} responses with rise times ranging from 0.15 to 0.5d. Logically, faster responses are associated with more oscillatory behaviours. Since a fast but stable dynamic response in the lower-level controller is desirable so as to avoid excessive oscillations in Q_{feed}, the maximum allowed overshoot was fixed to 1.5%. Based on that, the optimization problem was solved for different values of pH within its operational range. Some results are shown in Table 2. Less satisfactory responses are associated with operational points closer to the high organic loads or saturation zones. For high pH values higher K_{p1} values are needed to quickly lead the pH towards the maximum methane production. Finally, to cover the whole operational pH range, K_{p1} was limited to values in the range [10; 101].

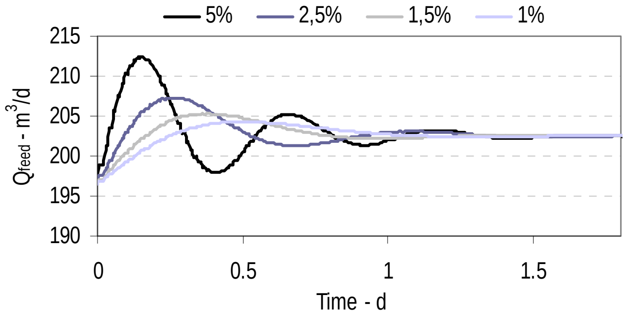

Figure 6. Q_{feed} response for different M_p values

Table 2. K_{p1} values for different operational points

pH	pH_{sp}	K_{p1}	t_r (d)
6.76	6.75	17.30	0.74
6.86	6.85	59.3	0.36
6.96	6.95	101	0.20

In relation to the upper-level and rule-based controllers, the optimization problem has been expressed as follows:

$$\text{Min } t_r = f(K_{p2}, \Delta GF); \quad \text{such that} \quad M_P < 20\% \quad \text{and} \quad M_{p\_GF} < 4\% \tag{3}$$

Based on preliminary simulations, sample times t_2 and t_3 were fixed to 20 and 60 minutes respectively. Parameters of the rule-based controller, D_{max} and D_{min}, were set to 0.1 and -0.3 $m^3_{ch4}/m^3_{reactor}.d^{-1}$ respectively, values that promote high methane production. Different combinations of K_{p2} and ΔGF fulfil the constraints resulting in GF_m responses with rise times ranging from 0.2 to 0.53 d. Some results are given in Table 3. The selection of suitable parameters is a trade-off between stability and fast convergence to the maximum methane production. In this implementation the parameters of the optimization nº3 in Table 3 were chosen at the expense of accepting a moderate overshoot in Q_{feed}.

Table 3. Optimization results for the upper-level and rule-based controllers

Optimization	K_{p2}	ΔGF	M_p (%)	M_{p_GF} (%)	t_r (d)
1	0.0690	0.49	20	4.3	0.37
2	0.0472	0.2929	14.9	3.03	0.47
3	0.988	0.3546	17.7	2.91	0.2013

Table 4 summarises the values obtained for the bottom-layer controller parameters after applying the design procedure and Figure 7 shows the response of GF_m towards the maximum methane production under stationary influent conditions for that design. The extremum-seeking controller that is part of the bottom-layer controller steers the digester to its maximum methane production by means of a continuous variation of Q_{feed}, pH_{sp} and GF_{sp}. Both a satisfactory convergence rate around 0.5 d and a stable pseudo-stationary response of GF_m are achieved.

Table 4. Bottom-layer parameters

Parameter	Value	Unit
t_1	10	min
t_2	20	min
t_3	60	min
K_{p1}	[10 -101]	m^3/d
K_{p2}	0.988	$d{\cdot}m^3_{reactor}{\cdot}m^{-3}_{ch4}$
ΔGF	0.3546	$m^3_{ch4}/m^3_{reactor}.d^{-1}$

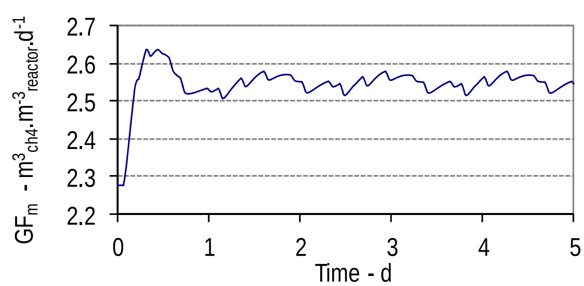

Figure 7. Response of GF_m under stationary influent conditions

For a short simulation period Figure 8a shows the response of Q_{feed} and the volume in the equalization tank (V_{tank}) under dynamic influent conditions (Figure 2) and the overall control architecture. Figure 8b shows the dynamic response of GF_m and GF_{sp}. The bottom-layer controller guarantees a good disturbance rejection and an efficient methane production with the continuous variation of Q_{feed}, pH_{sp} and GF_{sp}. The top-layer controller is able to minimize the occurrence of complete ET emptying and ET overflow events by continuously adjusting the parameters of the rule-based system (D_{max} and D_{min}), based on the state of the equalization tank reaching an optimal operation of the plant.

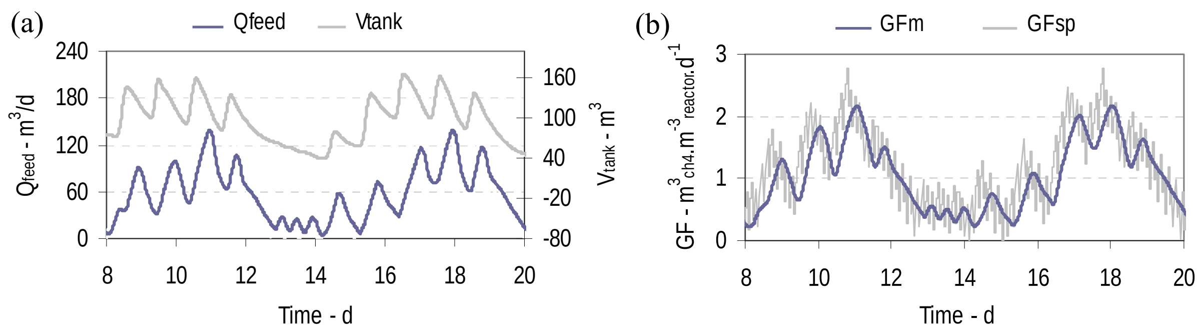

Figure 8. Performance of the controller under dynamical influent conditions: (a) Q_{feed} and V_{tank}; (b) GF_m and GF_{sp}

CONCLUSIONS

A methodological procedure to properly design a controller for anaerobic digesters has been defined and satisfactorily implemented for stationary and dynamic conditions. The control problem has been defined considering the intrinsic limitations of a full-scale scenario that include plant configuration, influent characteristics and available instrumentation in full-scale plants. The control objective has been treated as a dynamical optimization problem of the plant searching for a suitable trade-off between methane production and efficiency, while preserving the stability of the degradation process. A combination of the extremum-seeking algorithm within the bottom-layer controller with an effective handling of the equalization tank by the top-layer controller provides a good balance between optimum treatment efficiency and prevention of process failures. The systematic procedure presented here has been defined and implemented so as to facilitate future applications of the controller for different full-scale scenarios and operational conditions.

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