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Generic Model Control of Biomethanation Process

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Abstract: ***This paper focuses on the design of Generic Model Control (GMC) algorithm for the control of the acetate concentration in a biomethanation process with production of methane gas. A nonlinear dynamic model for the biomethanation process is used in the derivation of the control law of Generic Model Control scheme. The controller parameters are estimated using the Trial and Error method. The effectiveness and performance of the proposed control strategy is illustrated by a MATLAB program under various operation conditions and disturbances. The simulation results obtained confirmed the good quality of the control.***

Keyword: Generic model control; process control; biomethanation process

I. Introduction

The control of biotechnological processes has been an important problem attracting wide attention. The main engineering motivation in applying advanced control methods to such processes is to improve operational stability and production efficiency. But, the use of modern control for these bioprocesses is still low. The nonlinearity of the bioprocesses and the uncertainty of kinetics impose the advanced control strategy as a suitable approach. So, the difficulties encountered in the measurement of the state variables of the bioprocesses impose the use of the so-called "software sensors". Note that these software sensors are used not only for the estimation of the concentrations of some components but also for the estimation of the kinetic parameters or even kinetic reactions. The dynamics of this biotechnological process are described by a set of nonlinear differential equations obtained from the reaction scheme and the unknown reaction rates are estimated. For the estimation of unknown parameters of the process, the distribution approach is used. The parameter identification of deterministic nonlinear continuous-time systems (NCTS), modeled by polynomial type differential equation has been considered by numerous authors [1], [2]. The generic model control scheme used in this paper is based on a control law that uses the nonlinear dynamic model of the process to calculate the effect of sequences of control steps on the controlled variables.

The paper is organized as follows. Section II is devoted to description and modeling of a biomethanation process. The generic model control strategy is presented in Section III. The generic model control law design is derived in Section IV. Simulations results presented in Section V illustrate the performance of the proposed control algorithms and, finally, Section VI conclusion of the paper.

II. Modeling of a Biomethanation Process Description

Anaerobic digestion is a multi-stage biological wastewater treatment process whereby bacteria, in the absence of oxygen, decompose organic matter to carbon dioxide, methane and water.

In the first phase, the glucose from the wastewater is decomposed in fat volatile acids (acetates, propionic acid), hydrogen and the second phase; the ionized hydrogen decomposes the propionic acid CH3CH2COOH in acetates, H2 and carbon dioxide CO2. In the first methanogenic phase, the acetate is transformed into methane and CO2, and finally, in the second methanogenic phase, the methane gas CH4 is obtained from H2 and CO2, [5]. The following simplified reaction scheme is considered [1],

$$S_1 \xrightarrow{\emptyset_1} X_1 + S_2$$
$$S_2 \xrightarrow{\emptyset_1} X_2 + P$$

In this paper, we consider a biomethanation process wastewater biodegradation with production of methane gas that takes place inside a Continuous Stirred Tank Bioreactor whose reduced model is presented in [1], [2].

The dynamic equations of the biomethanation process wastewater biodegradation are derived using material balance relations regarding, S_1 represents the glucose substrate, S_2 the acetate substrate, X_1 is the acidogenic bacteria, X_2 the acetoclastic methanogenic bacteria and P represents the product, i.e. the methane gas. The reaction rates are denoted by $\emptyset_1$, $\emptyset_2$ and Q is the methane gas outflow rate. D represents the dilution rate and S_{i} represents the concentration of the influent substrate – glucose. This process is evidently highly non-linear due to the inter-relationships of the states [1], [2]. According to the general material balance equation, the mass balance equations are represented by equations (1-5).

$$\frac{dX_1}{dt} = \emptyset_1 - DX_1 \quad (1)$$
$$\frac{dS_1}{dt} = -K_1\emptyset_1 - DS_1 + DS_{in} \quad (2)$$
$$\frac{dX_2}{dt} = \emptyset_2 - DX_2 \quad (3)$$
$$\frac{dS_2}{dt} = K_2\emptyset_1 - K_3\emptyset_2 - DS_2 \quad (4)$$
$$\frac{dP}{dt} = K_4\emptyset_2 - DP - Q \quad (5)$$

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III. Strategy of Generic Model Control (GMC)

GMC is an advanced model-based control strategy which uses linear/nonlinear models of a system to compute the control action. Since the GMC can directly use nonlinear models of a process to determine a control action, the nonlinear models do not need linearization. Generally the GMC controller design is based on the following nonlinear state space [3-5]

$$\frac{dx}{dt} = \dot{x} = f(x) + g(x)u \quad (6)$$

$$y = h(x) \quad (7)$$

Where $f(x)$ and $g(x)$ are vector fields, i.e. they are vector valued functions of a vector and $h(x)$ is a scalar field, i.e. a scalar valued function of a vector x. Generic Model Control (GMC) uses a model of the process in formulating the control law. However, rather than adopting a classical approach of comparing the trajectory of the process output against a desired trajectory, GMC defines the performance objective in terms of the time derivatives of the process output, i.e. minimizing the difference between the desired derivative of the process output and the actual derivative. Good control performance will be given by choose the following desired trajectory [3].

$$\dot{y}_d = \alpha_1(w - y) + \alpha_2 \int (w - y)dt \quad (8)$$

Where α_1 and α_2 are design constants and w is the set point. In order to design a controller so that the system follows the trajectory defined by equation (8) as closely as possible, the following performance index is specified:

$$J = \int_0^t e^2\, dt = \int (\dot{y}_d - \dot{y})^2 dt \quad (9)$$

i.e. minimize the error squared over a specified time horizon. In order to obtain $\dot{y}$ from equation (7) the chain rule must be used,

$$\frac{dy}{dx} = \frac{dy}{dx}\frac{dx}{dt} \quad (10)$$

Where

$\frac{dy}{dx}$ is a row vector

$\frac{dx}{dt}$ is a column vector given by eq.(1)

$\frac{dh}{dx}$ is also a row vector and,

$$\frac{dy}{dt} = \frac{dh}{dx}f(x) + \frac{dh}{dx}g(x)u \quad (11)$$

Using equation (11) the performance index, the equation (10) is minimized when $e = 0$,

$$\alpha_1(w - y) + \alpha_2 \int (w - y)dt - \left[\frac{dh}{dx}\ f(x) + \frac{dh}{dx}g(x)u\right] = 0 \quad (12)$$

IV. Generic Model Control Law Design

The choice of a controller based on Generic Model Control for the methane gas production control loop is based on the fact that the methane gas production is highly non –linear and the GMC allows including a non-linear model in the control algorithm. In this paper, we consider a biomethanation process – wastewater biodegradation with production of methane gas that takes place inside a Continuous Stirred Tank Bioreactor whose reduced model is presented in [1],[2].

These differential equations (1-5) of biomethanation process can be rearranged into the generic vector representation of the process with the following vector and scalar fields:

State Vector: $x = (X_1, S_1, X_2, S_2, P)$

Vector fields: $f(x) = (f_1(x), f_2(x), f_3(x), f_4(x), f_5(x))$

$$f_1(x) = \emptyset_1 - DX_1 \quad (13)$$

$$f_2(x) = -K_1\emptyset_1 - DS_1 + DS_{in} \quad (14)$$

$$f_3(x) = \emptyset_2 - DX_2 \quad (15)$$

$$f_4(x) = K_2\emptyset_1 - K_3\emptyset_2 - DS_2 \quad (16)$$

$$f_5(x) = K_4\emptyset_2 - DP - Q \quad (17)$$

g vector fields: $g(x) = (g_1(x), g_2(x), g_3(x), g_4(x), g_5(x))^T$

The h scalar field describing the output function is simply the state itself,

$$y = h(x) = P \quad (18)$$

These scalar and vector fields are important for the design of GMC law.

With $y = h(x) = P$ therefore,

$$\frac{dh}{dx_1} = \frac{dh}{dX_1} = 0, \quad \frac{dh}{dx_3} = \frac{dh}{dS_1} = 0,$$

$$\frac{dh}{dx_2} = \frac{dh}{dX_2} = 0, \quad \frac{dh}{dx_4} = \frac{dh}{dS_2} = 0, \quad \frac{dh}{dx_5} = \frac{dh}{dP} = 1$$

$$\frac{dh}{dx} = [0,0,0,0,1] \ \ggg \ \frac{dy}{dt} = \dot{y} = f_2(x) + g_2(x)u$$

In other words, the GMC controller law is given by:

$$\propto_1 (w - y) + \int \propto_2 (w - y)dt - \left[\frac{dh}{dx}f(x) + \frac{dh}{dx}g(x)u\right] = 0 \quad (19)$$

And solving for the manipulated variable $D(t)$, yields,

$$\propto_1 (P_{set} - P) + \int \propto_2 (P_{set} - P)dt - [K_4\emptyset_2 - DP - Q] = 0 \quad (20)$$

$$\propto_1 (P_{set} - P) + \int \propto_2 (P_{set} - P)dt - K_4\emptyset_2 + DP + Q = 0 \quad (21)$$

Then, the control law is:

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$$u(t) = D(t) = \frac{1}{P}\left[-\propto_1 (P_{set} - P) - \int \propto_2 (P_{set} - P)dt + K_4 \emptyset_2 - Q\right] \quad (22)$$

V. Simulation Results and Discussion

In order to examine the effectiveness of the developed control strategies, simulation studies were conducted using the model described above for the behavior of the biomethanation process. The model was initialized in reference to the listed values in [1-2] with the following (Monod-type) model for the reaction rates:

$$\emptyset_1 = \mu_1 \frac{S_1 \cdot X_1}{K_{M1} \cdot S_1}$$

and the Haldane Kinetic model [1]

$$\emptyset_2 = \mu_2 \frac{S_2 \cdot X_2}{K_{M2} + S_2 + S_2^2/K_i}$$

where K_{M1}, K_{M2} are Michaelis-Menten constants, μ_1, μ_2 represent specific growth rates coefficients and K_i is the inhibition constant.

The performance of the generic model controller presented in section IV has been tested through extensive simulations by using the process model controller presented in section II. The model parameters and the nominal values of parameters of process considered in the simulation are:

$K_1 = 3.2,\quad K_2 = 16.7,\ K_3 = 1.035,\ K_4 = 1.1935$
$K_5 = 1.5,\ K_6 = 3,\quad K_7 = 0.113,$
$\mu_1 = 0.2\ h^{-1},\quad K_{M1} = 0.5\ g/l.\ \square\ \mu_2 = 0.35\ h^{-1}$
$K_{M2} = 4\ g/l,\quad K_i = 21\ g/l,\quad Q_1 = 0;\ S_i = 15\ g/l.$

The nonlinear of biomethanation process model and control structure are expressed using SIMULINK block diagram, and M-file Matlab programs. Three examples are presented to evaluate effectiveness of the proposed control strategies. Trial-and-error method is used to estimate the controller parameters $\propto_1$ and $\propto_2$.

Figures 1 through 3 represent the controlled and manipulated variables response of the GMC controller to methane gas set point tracking and disturbance rejection. Figure 1 illustrates the response of the GMC in tracking the methane gas set point, the controller performance presented fast tracking and no steady state error. Figure 2 illustrates the response of the GMC in tracking the positive change in methane gas set point at time 50 hr, also, the controller performance presented smooth behavior. Figure 3 illustrates the response of the GMC in tracking the negative change in methane gas set point at time 50 hr, also, the controller performance presented smooth behavior.

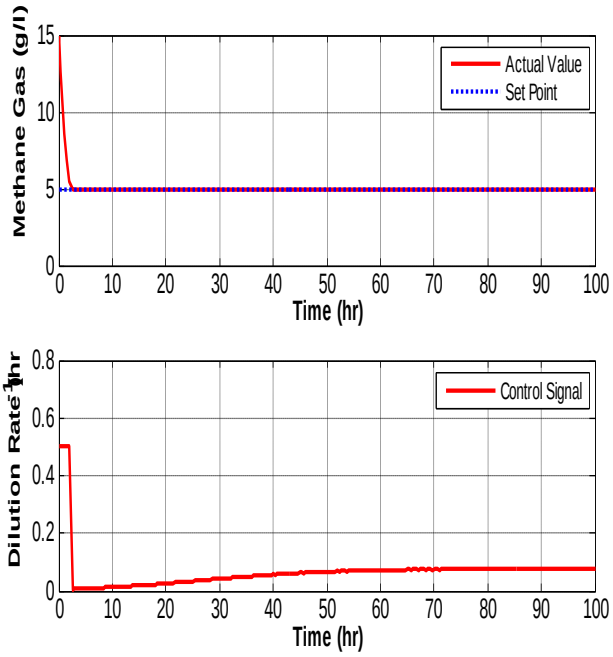

Fig. 1: Simulation results in tracking methane set point

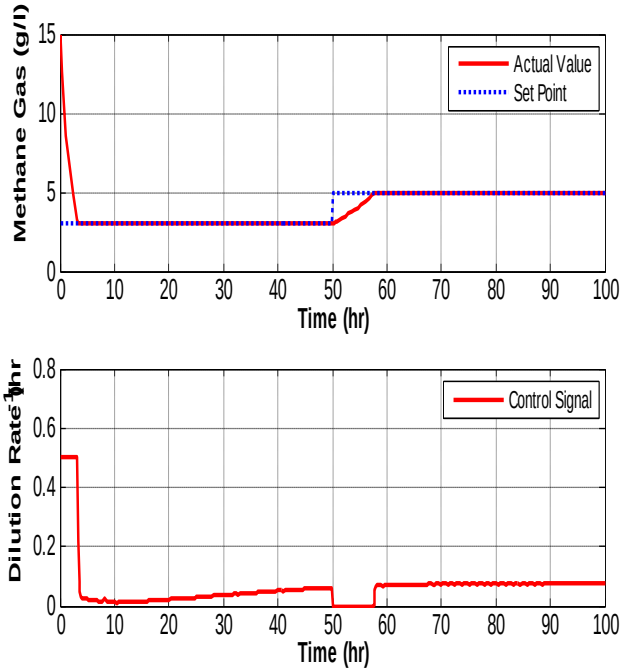

Fig. 2: Simulation results with a change in methane set point from 3.0 g/l to 5.0 mg/l

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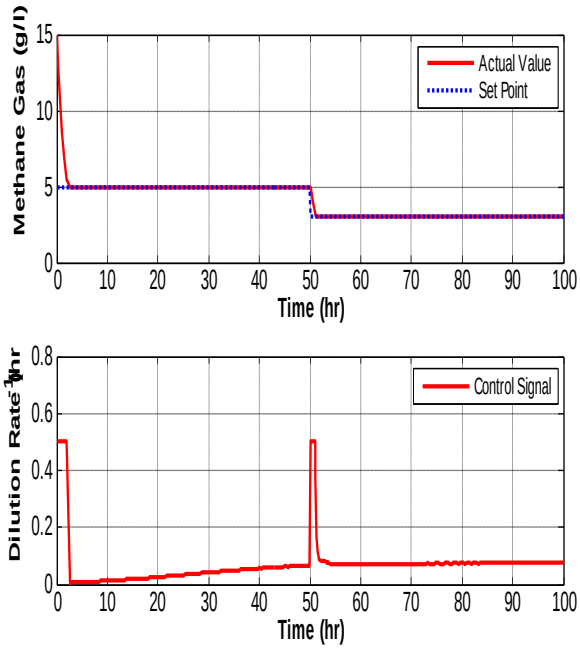

Fig. 3: Simulation results with a change in methane set point from 5.0 g/l to 3.0 mg/l

VI. Conclusion

The GMC controller is designed and implemented to track the methane gas set point and to reject disturbances using a nonlinear model of biomethanation process. The responses of GMC in tracking set point are presented. It is found that the performance of GMC controller is more stable, more fasting, no overshoot. The control action has smooth behavior, but this behavior has sudden change at the moment of set point change and then return to smoothing behavior.

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