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ADAPTIVE REGULATION OF A BIOGAS TOWER REACTOR

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Abstract

A simple adaptive high–gain regulator is designed for a nonlinear multivariable Biogas Tower Reactor. The controller achieves tracking of the constant reference signals within a prespecified λ–neighbourhood within a prespecified time T. The adaptation strategy is very robust and tolerates large disturbances. The results have been tested on an industrial pilot reactor of almost full scale plant.

1 Introduction

In this paper, we introduce an adaptive pH–controller for a Biogas Tower Reactor. The reactor principle is a new type for anaerobic waste water treatment which was developed at the Department of Bioprocess and Biochemical Engineering at the Technical University of Hamburg–Harburg. The aim of the paper is to describe the controller design, where the adaptation strategy is similar to that proposed in Ilchmann and Ryan (1994). An overall model of the Biogas Tower Reactor has been set up by theoretical process analysis as described in Pahl et al. (1996). For the design a reduced four–dimensional nonlinear model has been derived from an overall model of 36th order. Because of the simplifications made, the model parameters are uncertain and strong perturbations may occur. Adaptive control based on system identification cannot be applied since the main time constants of the process are too large, and the process is disturbed considerably. For this reason, we design a simple nonlinear, multivariable, high–gain based adaptive regulator, where no internal model is invoked. The *design* and the *application* at an *industrial plant* is described in this paper.

1.1 The Biogas Tower Reactor

The reactor in pilot scale, see Märkl and Reinhold (1994), is shown in Fig. 1. Waste water from a baker's yeast production is processed which contains sulfuric acid and organic compounds. The waste water is fed into the Biogas Tower Reactor, where via microorganisms, a mesophile (i.e. at $38^\circ C$) anaerobic biochemical conversion of the organic influent compounds takes place. The total organic carbon is converted into carbone dioxide and methane, and, as a byproduct, hydrogen sulphate is produced. Hydrogen sulphate inhibits the activity of the methane–forming microorganisms. The overall biochemical reactions are described in detail in Friedmann (1992).

The reactor consists of four identical modules (Fig. 1). At the top, a settler for effective biomass retention is integrated. For better mixing conditions, the influent f_{feed} can be split up into influents for modules 1–4. To avoid gas accumulation in the upper zones of the reactor, gas collecting devices are installed in each module. By these devices, the gas can be drawn off from the system. For better liquid–gas mass transfer, biogas is recirculated into the bottom of the reactor. To avoid accumulation of inhibiting hydrogen sulphate in the liquid phase, only methane and carbone dioxide are recirculated, whereas hydrogen sulphate is removed chemically. A single reactor module is shown in detail in Fig. 2.

Hydrodynamics. A baffle plate divides each module into two parts. Since the gas concentrations at both parts differ, a hydrostatic pressure causes a fluid circulation along the baffles similar to those found in airlift loop reactors, see Bailey and Ollis (1986). The fluid circulation brings about a well mixed system within one module. A part of the gas rises from one module to the next and causes an exchange mass flow in the liquid phase between the two modules that works in both directions, see Reinhold (1996).

Biochemical reactions. As shown in Fig. 2, the biomass distribution depends on the sedimentation characteristics and on the circulation flow of the liquid phase. The microbacteria convert the educts of the influent into several products which are given in the liquid phase. By

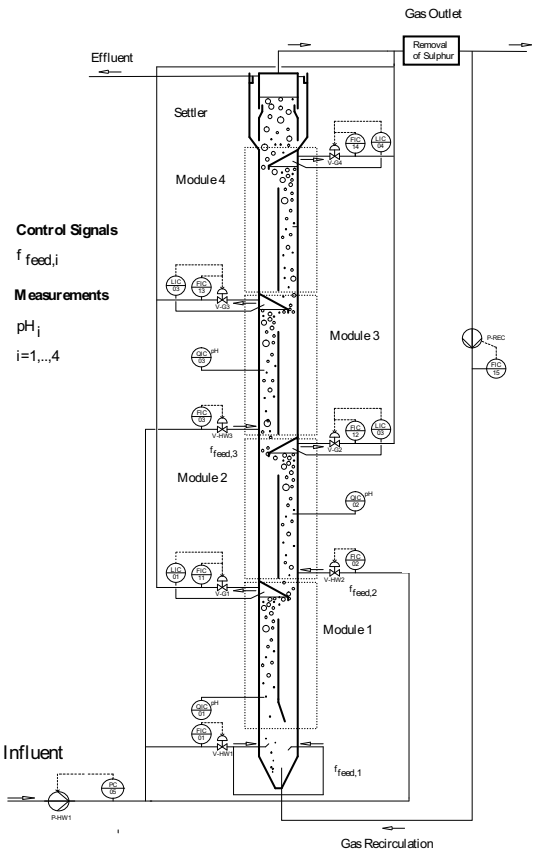

Figure 1: Biogas Tower Reactor in pilot scale with its internal installations (height $20m$, diameter $1m$, volume $15m^3$)

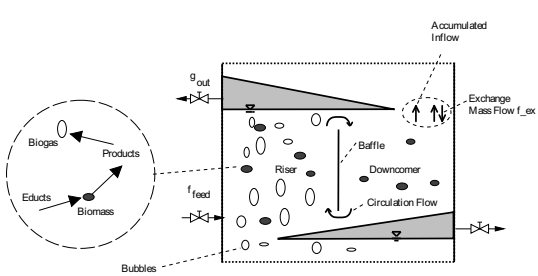

Figure 2: Single module of the reactor

the liquid–gas mass transfer these substances form biogas bubbles.

1.2 Control objectives

The global control objective is to keep the effluent concentrations of the waste water within the legal limits. This means that the removal rates have to be stabilized. They depend on the biomass concentration inside the reactor. The microorganisms only work under certain surrounding conditions such as pH-values, temperature a.o. Constant pH–values in all modules are necessary to achieve constant removal rates.

Control variables are the pH–values in each module. They are measurable on–line and are determined by the concentrations of compounds in the liquid phase, such as acetic acid and carbone dioxide. Changes of these educt and product concentrations are caused by the biochemical reactions and the liquid gas mass transfer. The pH-value in the coupled i-th modules is also influenced by the waste water flow rates which consist of the exchange flow between neighbouring modules, the accumulated inflow rates from the bottom modules and the inflow rates fed directly into the module.

Manipulated variables are the inflow rates $f_{feed,i}, i = 1, \ldots, 4$.

The controller design has to obey the following **restrictions**:

- The main *time constants* of the process are about 6 hours. Time changes concerning the growth of biomass are even more than one order of magnitude higher. Compared to these main time constants, the reactor is available for experiments only for a very short time. This limitation concerns the kind and number of experiments made. As the main consequence, well known methods for system identification and adaptive control cannot be applied.

- Since the process knowledge is incomplete, the process model has *uncertainties in structure and parameters*. Upper bounds of parameter errors are known but the uncertainty of some parameters covers orders of magnitude.

- *Input constraints.* The amplitudes of the manipulated variables are restricted due to constraints of the reactor principle. To avoid the wash–out of the biomass, the sum of the influent rates must not exceed prescribed bounds.

Control objective: The pH–controller has

1. to start up the reactor within 12 hours at the beginning of the week in such a way that the pH–values reach the prespecified operation area,

2. to attenuate the disturbances in order to keep all pH–values within a prespecified operating region. The controller should hold *all* pH–values within an interval of ± 0.05 around the setpoints. A smaller band is not sensible because of the measurement errors (drift) of pH–sensors.

The control objective has to be satisfied under the following **plant uncertainties and disturbances**:

- The plant characteristics change considerably at varying exchange flow rates between neighbouring modules and the changing biomass concentration which both influence the reaction rates. This leads to strong *perturbations* of the static reinforcement and the time delays of the plant.
- For the stabilisation of the operating point two main kinds of disturbances are relevant. First, the periodic calibration of the pH-electrodes causes stepwise output disturbances which have to be compensated by the controller. Furthermore, disturbance signals of unknown characteristics such as changing influent concentrations exist.

1.3 Process model

The nonlinear process model consists of four subsystems, where each subsystem represents one module of the reactor. Details are given in Pahl and Lunze (1996). This model takes into account biochemical reactions and knowledge of the reactors hydro–dynamics. It was validated by experiments, see Reinhold (1996). Since the model is of high order and contains strong nonlinearities, it cannot be used directly for the controller design. For the design of the pH–controller, the following model of reduced order and complexity has been derived from the overall model. We define

$$\mathbf{u} = (u_1, u_2, u_3, u_4)^T = \frac{1}{V_{fl}} (f_{feed,1}, f_{feed,2}, f_{feed,3}, f_{feed,4})^T$$

as input signals and the pH–values in module 1–4 as output signals,

$$\mathbf{y} = (y_1, y_2, y_3, y_4)^T = (pH_1, pH_2, pH_3, pH_4)^T .$$

The inputs are restricted by, for some $u_{max} > 0$,

$$\sum_{i=1}^{4} u_i \quad \leq \quad u_{max}, \qquad u_i \geq 0. \tag{1}$$

If we substitute $f_{ex,i}$ by a_i, then the model may be written as

$$\dot{\mathbf{y}}(t) = \mathbf{A}\mathbf{y}(t) + \mathbf{r}(\mathbf{y}(t)) - \mathbf{G}(\mathbf{y}(t))\,\mathbf{u}(t) \tag{2}$$

where $\mathbf{y} = (y_1, ..., y_4)^T \in \mathbb{R}^4$, $\mathbf{u} = (u_1, ..., u_4)^T \in \mathbb{R}^4$ and for $a_1, a_2, a_3 > 0$, $y_{in} > 0$

$$\mathbf{A} \quad = \quad \begin{pmatrix} -a_1 & a_1 & 0 & 0 \\ a_1 & -(a_1+a_2) & a_2 & 0 \\ 0 & a_2 & -(a_2+a_3) & a_3 \\ 0 & 0 & a_3 & -a_3 \end{pmatrix},$$

$$\mathbf{G}(\mathbf{y}) \quad = \quad \begin{pmatrix} y_1 - y_{in} & 0 & 0 & 0 \\ y_2 - y_1 & y_2 - y_{in} & 0 & 0 \\ y_3 - y_2 & y_3 - y_2 & y_3 - y_{in} & 0 \\ y_4 - y_3 & y_4 - y_3 & y_4 - y_3 & y_4 - y_{in} \end{pmatrix},$$

$$\mathbf{r}(\mathbf{y}) \quad = \quad (r_1(y_1), r_2(y_2), r_3(y_3), r_4(y_4)) .$$

r_i denote some locally Lipschitz nonlinear function with affine linear bounds given in Pahl and Lunze (1996).

This model is the basis for our adaptive controller design which is introduced in the next section.

2 Adaptive controller applied

2.1 The high-gain approach to adaptive control

The concept of high-gain stabilization without identification was initiated by Willems and Byrnes (1984) and Morse (1983). From then on, it became a rapidly growing field of interest for many different system classes, see Ilchmann (1993) for a bibliography. The idea of incorporating a "dead–zone" in the adaptation was first used by Miller and Davison (1991) and the λ-tracking concept as used in the present paper was introduced by Ilchmann and Ryan (1994). To provide the reader with an intuition of this concept, we consider a very simple example. Although the actual model, to which the adaptive regulator is applied to, is nonlinear, we will first study the effect of the adaptive controller on a linear first order system of the form

$$\dot{y}(t) = a\,y(t) + g\,u(t) \quad , y(0) = y_0 \tag{3}$$

for some unknown $y_0, a \in \mathbb{R},\ g > 0$.
Consider the time-varying proportional error feedback

$$\left.\begin{array}{rcl} e(t) & = & y(t) - y_{ref} \\ u(t) & = & -k(t)e(t) \end{array}\right\} \tag{4}$$

where $y_{ref} \in \mathbb{R}$ denotes the set point to be tracked and the monotonically non-decreasing function $k(\cdot) : [0, \infty) \to [0, \infty)$ is determined by the gain-adaptation

$$\begin{array}{rcl} \dot{k}(t) & = & \left\{ \begin{array}{ccc} (|e(t)| - \lambda)|e(t)| & , & |e(t)| \geq \lambda \\ 0 & , & |e(t)| < \lambda \end{array} \right. \\ k(0) & = & k_0 \geq 0, \end{array} \tag{5}$$

where $\lambda > 0$ is prespecified and chosen arbitrarily by the designer. It is a straightforward calculation that the solution of the closed–loop system satisfies

$$|e(t)| \leq e^{[a-k(t_0)g](t-t_0)}|e(t_0)| + \frac{|ay_{ref}|}{-[a-k(t_0)g]} \tag{6}$$

and hence, for $k(t_0)$ sufficiently large, $|e(t)|$ enters the λ–strip and the gain adaptation is switched off.

A remarkable property of the gain–adaptation (5) is that it tolerates output corrupted by additive noise. If an upper bound for the noise is known in advance and $\lambda > 0$ is chosen larger than this bound, then the error

$$e(t) \;:=\; y(t) + n(t) - y_{ref}, \tag{7}$$

where $n(\cdot)$ denotes the noise–signal, is forced into the λ–strip. This property is due to the "dead–zone" incorporated in the gain adaptation.
In the following subsection, we will prove that this control principle also works for our nonlinear, multivariable model of the Biogas Tower Reactor.

2.2 The λ–tracker

The adaptive controller is very simple in its design. It consists of a nonlinear feedback law with a time-varying gain $k(t)$. This gain is tuned adaptively by the error signals, it is strictly monotonically increasing as long as the norm of the error vector is larger than the given λ. If $\|e\|$ enters the λ–strip, the adaptation is switched off and the gain is kept constant.

The control objective is to λ-track a constant reference signal

$$\mathbf{y}_{ref} = (w_1, ..., w_4)^T \qquad \text{with} \qquad y_{in} < w_1 < ... < w_4.$$

λ-tracking means that we want the output $y_i(t)$ to reach a λ-neighbourhood of the reference signal w_i. More precisely, we want

$$\mathbf{e}(t) = (y_1(t) - w_1, \ldots, y_4(t) - w_4)^T \;=\; \mathbf{y}(t) - \mathbf{y}_{ref}$$

to approach the λ-ball $\left\{\mathbf{e} \in \mathbb{R}^4 \mid \|\mathbf{e}\| < \lambda\right\}$ as t tends to ∞. This will be achieved as follows.

The **nonlinear adaptive feedback** is defined by

$$\mathbf{u}(t) = \bar{\mathbf{u}} + \mathbf{v}(t), \tag{8}$$

where the components of $\mathbf{v}(t) \;=\; \big(v_1(t), ..., v_4(t)\big)^T$ are given by

$$\begin{aligned}
v_1(t) \;&:=\; \tfrac{k(t)}{y_1(t)-y_{in}}(y_1(t) - w_1),\\
v_2(t) \;&:=\; \tfrac{k(t)}{y_2(t)-y_{in}}(y_2(t) - w_2) - \tfrac{y_2(t)-y_1(t)}{y_2(t)-y_{in}}\; u_1(t),\\
v_3(t) \;&:=\; \tfrac{k(t)}{y_3(t)-y_{in}}(y_3(t) - w_3) - \tfrac{y_3(t)-y_2(t)}{y_3(t)-y_{in}}\; [u_1(t) + u_2(t)],\\
v_4(t) \;&:=\; \tfrac{k(t)}{y_4(t)-y_{in}}(y_4(t) - w_4)\\
&\qquad - \tfrac{y_4(t)-y_3(t)}{y_4(t)-y_{in}}\; [u_1(t) + u_2(t) + u_3(t)].
\end{aligned}$$

$\bar{\mathbf{u}} \in \mathbb{R}^4$ may be arbitrary, but a sensible choice would be the component of the equilibrium point $(\bar{\mathbf{y}}, \bar{\mathbf{u}})$, i.e.

$$\mathbf{A}\bar{\mathbf{y}} + \mathbf{r}(\bar{\mathbf{y}}) + \mathbf{G}(\bar{\mathbf{y}})\bar{\mathbf{u}} = \mathbf{0}. \tag{9}$$

Note that the u_i-terms in v_i are chosen so that, if (8) is applied to (2), the strong couplings caused by the non–diagonal elements of the matrix $\mathbf{G}$ are compensated.

The **gain adaptation** is given, for prespecified $\lambda > 0$, by

$$\dot{k}(t) = \begin{cases} \gamma(\|\mathbf{e}(t)\| - \lambda)\; \|\mathbf{e}(t)\| & , \quad \|\mathbf{e}(t)\| \geq \lambda \\ 0 & , \quad \|\mathbf{e}(t)\| < \lambda. \end{cases} \tag{10}$$

The design parameters $k(0) = k_0 \geq 0, \gamma > 0$ influence the dynamics and size of the gain. The gain is strictly increasing as long as the error is outside the closed λ-ball, if the error enters the λ-ball, then it is kept constant.
Our main result is convergence of the simple adaptive strategy (8),(10) if applied to the model (2). Certainly, it will be shown, that the feedback (8) is well-defined, i.e. $y_i(t) > y_{in}$ for all $t \geq 0, i = 1, ..., 4$.
We suppose that the initial values for the pH–values within the modules are strictly increasing from lower to upper modules. This is always the case since weak acids are the more soluble the higher the hydrostatic pressure is. We also suppose that the reference signals, to which the pH–values should converge (within a neighbourhood), are ordered in size.

2.1 Theorem
Suppose $y_{in}, \gamma, \lambda > 0, \quad k_0 \geq 0, \quad \bar{u} \in \mathbb{R}^4_+$,
and

$$\begin{aligned}
\mathbf{y}_0 \quad &= \quad (y_0^1, \ldots, y_0^4) \quad \text{with} \quad y_{in} < y_0^1 < \ldots < y_0^4\\
\mathbf{y}_{ref} \quad &= \quad (w_1, \ldots, w_4) \quad \text{with} \quad y_{in} < w^1 < \ldots < w^4
\end{aligned} \tag{11}$$

are given. The λ-tracker (8),(10) if applied any system (2) with initial conditions $\mathbf{y}(0) = \mathbf{y}_0, k(0) = k_0$, yields a closed-loop system which admits a unique solution

$$\big(\mathbf{y}(\cdot), k(\cdot)\big) \;:\; [0, \infty) \;\to\; \mathbb{R}^4_+ \times [0, \infty)$$

which satisfies

(i) $y_i(t) > y_{in}$ for all $t \geq 0,\; i = 1, \ldots, 4$, i.e. (8) is well defined,

(ii) $\lim\limits_{t\to\infty} k(t) \;=\; k_\infty \in \mathbb{R}$ exists,

(iii) $\|\mathbf{y}(t) - \mathbf{y}_{ref}\|$ approaches $[0, \lambda]$ as t tends to ∞.

2.3 λ–tracking within prespecified time

In Theorem 2.1 we have only guaranteed, that the error approaches the λ–ball asymptotically, nothing is said about the lenght of the time it will take. By a simple modification of the gain–adaptation (10) we can ensure that the error will enter the λ–ball within a prespecified time T. Consider, for prespecified $\gamma_1, \gamma_2, \lambda, T > 0$ and $k_0 \geq 0$,

$$
\begin{aligned}
k(t) &= k_0 + \gamma_1 \int_0^t d_\lambda(\mathbf{e}(s))\,\|\mathbf{e}(s)\| ds \qquad (12)\\
&\quad +\gamma_2 \begin{cases} \frac{\|\mathbf{e}(t)\|^2}{T-t} & , \quad t \in [0, t^*) \\ k^* & , \quad t \geq t^*, \end{cases}
\end{aligned}
$$

where

$$
\begin{aligned}
d_\lambda(\mathbf{e}) &:= \begin{cases} (\|\mathbf{e}\| - \lambda) & , \quad \|\mathbf{e}\| \geq \lambda \\ 0 & , \quad \|\mathbf{e}\| < \lambda \end{cases}\\
t^* &:= \min\left\{ t \in [0, T) \,\middle|\, \|\mathbf{e}(t)\| = \tfrac{3}{4}\lambda \right\}\\
k^* &:= \frac{\|\mathbf{e}(t^*)\|^2}{T - t^*}.
\end{aligned}
$$

The intuition behind this gain adaptation is as follows: If t approaches T, then the third term on the right–hand–side of (12) becomes very large, as long as $\|\mathbf{e}(t)\|$ is not very close to zero. Thus high–gain forces the error to go to zero until it hits $\frac{3}{4}\lambda$, then the error is within the λ–ball and from then on the adaption is not different to the previous one in (10).

2.2 Theorem

Suppose the assumptions of Theorem 2.1 hold and $\gamma_1, \gamma_2, T > 0$. If the λ-tracker (8), (12) is applied to any system (2), then the closed-loop system possesses a unique solution

$$
\big(\mathbf{y}(\cdot), k(\cdot)\big) \;:\; [0, \infty) \;\rightarrow\; \mathbb{R}^4_+ \times [0, \infty)
$$

which satisfies:

(i) $y_i(t) > y_{in}$ for all $t \geq 0$, $i = 1, \ldots, 4$, i.e. (8) is well defined,

(ii) $\lim_{t \to \infty} k(t) = k_\infty \in \mathbb{R}$ exists,

(iii) there exists some $t^* \in [0, T)$ such that $\| bfe(t^*)\| = \frac{3}{4}\lambda$,

(iv) $\|\mathbf{y}(t) - \mathbf{y}_{ref}\|$ approaches $[0, \lambda]$ as t tends to ∞.

3 Experiments

In this section experimental results are given that show that the controller (8), (10) and its modified version (12) work successfully at the Biogas Tower Reactor. The controller was tested at Modules 1–3. The control law was implemented on the process control system by a discrete integration algorithm where a sampling time of 6 minutes was used. The controller (8), (10) was tested with the parameters

$$
\begin{aligned}
\gamma &= 0.002,\ \lambda = 0.05\\
k(0) &= 0.005,\ y_{in} = 4.5.
\end{aligned}
$$

Note, that the control–loop contains the saturation of control signals (1). The results are shown in Figs. 3 and 4. The command tracking is reached without oscillation. The desired pH–band is entered after 24 hours. The gain of about 0.08 at $t = 75$ is not too large. The stepwise disturbances are caused by the calibration of the sensors at $t = 70\ h$.

In the second experiment the modified controller (12) with parameters

$$
\begin{aligned}
\gamma_1 &= 0.002,\ \gamma_2 = 10,\ T = 720\text{min}\\
\lambda &= 0.05,\ k(0) = 0,\ y_{in} = 4.5
\end{aligned}
$$

is used. The results are depicted in Fig. 5 and 6.

Note that the reactor was shut down over the weekend which means that the influent rates were set to zero.

As shown in Fig.5 the controller was started at pH–values far away from the desired operating point. After less than 6 hours the pH–values were inside the tolerance band. The pH–value of module 3 leaves the tolerance band because of saturation of influent rate 3. But the other pH–values reach and remain inside the tolerance band. With the modified controller the start–up is also performed without any oscillations.

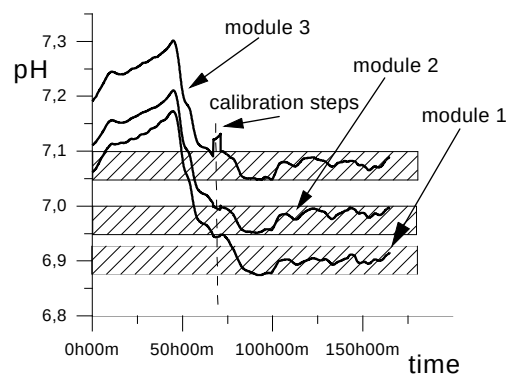

Figure 3: Stabilization of the pH–values, experimental results

The list of references must be at the end of the paper. When referring to them in the text, type the corresponding reference number between brackets [?]. References should be given in the standard style as follows.

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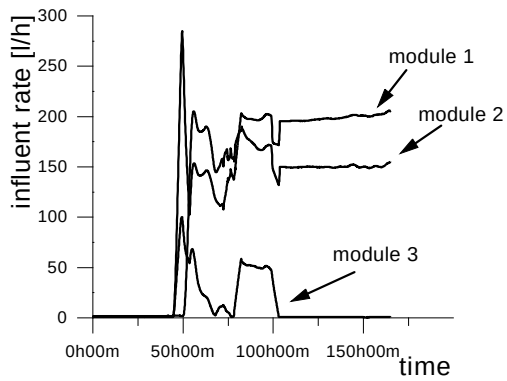

Figure 4: Influent rates that track all pH–values within the desired tolerance band

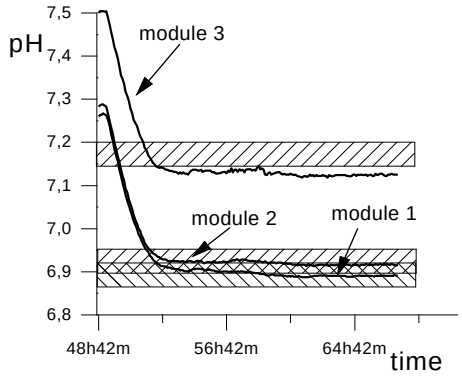

Figure 5: Start–up after the reactor was shut down for several days

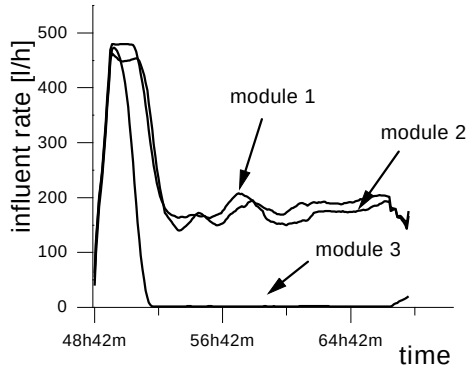

Figure 6: Trajectories of start–up control signals, modified controller

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