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ROBUST CONTROL SOLUTIONS TO REDUCE THE INFLUENCE OF INFLUENT VARIATIONS ON A WASTEWATER TREATMENT PLANT

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Abstract

An important issue that affects the performances obtained in a Wastewater Treatment Plant (WWTP) is the influence of the influent variations, especially in case of urban WWTPs. These variations act like disturbances on the control loops of the plant. Although in the literature periodic or quasi-periodic variations are systematically adopted for the influent description, the control solutions to reject these disturbances are not taken into consideration. This paper presents an overview of the previous results obtained by the authors regarding the rejection of the disturbances represented by the periodical or quasi-periodical variations of the influent. The control strategies were validated on a Activated Sludge Model No. 1 (ASM1) based WWTP implemented in SIMBA®.

Keywords: wastewater treatment processes; resonant control; fractional order systems; robust control; identification.

1 INTRODUCTION

Wastewater treatment processes are a topic of great interest and extensively investigated due to its influence on the environment. One of the most effective method to improve the performance of WWTP is the use of automatic control solutions. The control problem is essentially connected to the mathematical modeling of the process. Currently, there are already established models like ASM1, ASM2, ASM2d, ASM3, models proposed under the coordination of the International Water Association [1], [2], and for processes dynamics analysis were developed several simulators, e.g., SIMBA, WEST or BioWin [3].

Currently there are a variety of approaches in designing WWTP control structures. The most commonly used are conventional controllers (PI or PID) [5], [6], in classical or multivariable control loops [4]. There are many papers that use the Model Predictive Control (MPC) strategy [7] - [9], robust control solutions [10], data-driven control techniques [4] and solutions based on the use of artificial intelligence techniques [11]-[12].

An important issue in analyzing a urban WWTP is that of modeling the disturbances acting on the control loops of the plant. In the numerical simulators used for the WWTP dynamics analysis, periodic signals are considered for all the components of the influent. In the literature the effect of these periodic disturbances on the performances of the control structures of the plant are highlighted, i.e.: ammonium, nitrate and dissolved oxygen loops. In Figure 1 it is shown the evolution of the influent ammonium concentration over a 10 days period in the case of the SIMBA simulator and in Figure 2 is presented the Fourier spectrum of the influent. Although similar periodic disturbances are systematically adopted for the influent description, the control solutions to reject these disturbances are not taken into consideration.

This paper aims to present an overview of two control solution, PI + Resonant controller (PI+R) [13] and PI+ Fractional Order System controller (PI+FOS) [14], suitable for the rejection of the periodical or quasi-periodical disturbances. The main control loop considered is the one for the nitrate concentration control. The design of both control solutions is done taking into consideration the system uncertainties. They refer to two distinct situations: 1) the variation of process parameters due to a change in the average components of the ammonium concentration and flow rate into the influent; 2) inherent variations of the process parameters due to other factors (pH, temperature etc.).

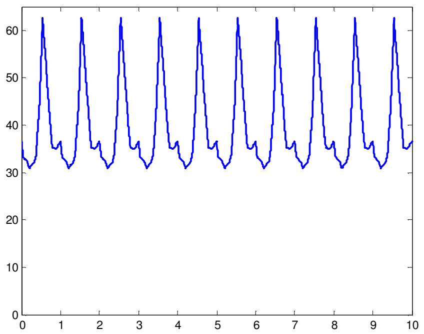

Figure 1: Periodic evolution of the ammonium concentration in influent in SIMBA [13]

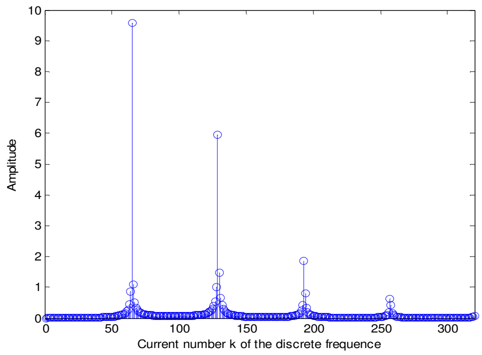

Figure 2: Spectrum of the disturbance signal [13]

The paper is structured as follows: the next section presents the results of identification of the process within the nitrate concentration control loop. The controller structures considered in the paper are presented in the third section and Section 4 is devoted to the robust controllers design using the QFT method. The fifth section presents the numerical simulations results that illustrates the performance of the designed control loops. A conclusion section concludes this paper.

2 IDENTIFICATION OF THE PROCESS WITHIN THE NITRATE CONCENTRATION CONTROL LOOP

Establishing a suitable model of the process within the control loops of the WWTPs is a difficult problem, which is often treated briefly in the literature [3]. The most commonly used models are the linear ones, as in [15], where the sub-space method identification is used, and in [8], where statistical identification methods are used, for example incremental ARX model in the context of model predictive control. In [7] comparative results to illustrate the performance achieved by the identification of a bilinear system compared to the case of a linear system, in a MPC structure are presented. In relation to the mentioned papers, the objectives followed in this paper for the identification of the process within the control loops of the WWTPs are:

- getting a nominal structure of a linear model, in a representative operating point so that the model properties to accurately reflect the dynamic properties of the process within WWTP;
- obtaining data that reflects how the parameters in the process model varies when operating regimes are significantly different from the operating regime corresponding to the nominal model. This is necessary to design the robust controllers using QFT method;
- establishing a model identification solution for the black box or adjustable models, given the fact that the disturbances acting on the process are very high and have the shape like in Figure 1.

The first objective is defined in relation to the problem of process identification within the nitrate concentration control loop in a operating point considered as nominal. In the paper [13], several methods were investigated: the least squares method (arx), instrumental variables method (iv4) or sub-space method (n4sid function from Matlab [16]). The dynamic performances of the models obtained by the three mentioned identification methods in the case of a black box type model are modest. One possibility to improve the identified model dynamic is to impose the structure of this model based on analyzing the process step response. Based on system analysis, one can adopt a structure consisting of two first-order subsystems with very different time constants connected in parallel. As a result, it has been adopted a model of the form:

$$P(s) = -\left(\frac{K_1}{T_1 s+1}+\frac{K_2}{T_2 s+1}\right)\left(H_0(s)\right)^m \qquad (1)$$

where T_1 and T_2 are at a ratio of about 10:1, $K_1+K_2=K$, where K is readily obtained and $\left(H_0(s)\right)^m, m=1,2,...$ is a subsystem with very fast dynamics, which improves the step response at high frequencies. $H_0(s)$ was adopted as a first-order system with time constant $T_0 \le T_2/5$.Figure 3 presents the process and model responses to the system identification by adjusting parameters of the model (1). The model obtained by adjusting the parameters of the transfer function (1) was used most frequently in the results presented in the following sections and it has the following parameters $K_1 = 0.33$, $T_1 = 0.85$, $K_2 = 0.11$, $T_2 = 0.06$, $T_0 = 0.01$ and $m = 1$.

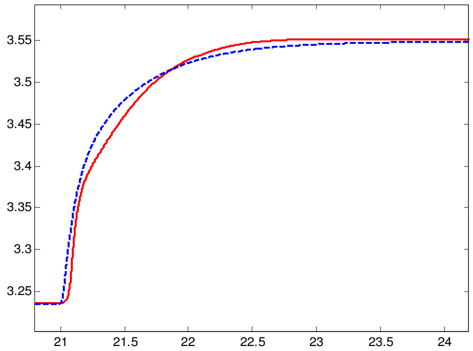

Figure 3: Process (solid line) and model (dashed line) responses for system identification by adjusting the parameters of the model (1) [13]

For an evaluation of the variation of the model parameters when the operating regimes are different from the nominal one, it was considered the case when the input signal has the same average as in the nominal case but having an amplitude that brings the process into operating regimes significantly different from the nominal one. The obtained results, shown in Figure 3, illustrates a satisfactory identification in the nominal regime, but outside this regime results an important variation of the static gain: it increases at higher internal recycle flow and reduced to small values of this flow. In Figure 4 is shown the dynamic regime to a significant variation of internal recycle flow from 59200 m³/day to 25000 m³/day, which can be used to evaluate the variation of the identified dynamic model parameters when operating regime changes.

Based on the data shown in Figure 4 $\pm 50\%$ variations of the nominal value for the static gain and $\pm 20\%$ variations of the nominal value for the dominant time constant of the model (1) were estimated, when the operating regime changes relative to the nominal one. The variation limits considered for the process parameters given by model (1) are the following: process parameters identified by the given equation (1): $K_1 = [0.25 \quad 0.4]$, $T_1 = [0.83 \quad 0.91]$, $K_2 = [0.07 \quad 0.15]$, $T_2 = [0.055 \quad 0.067]$.

Any procedure for the process identification uses output data that are affected by the periodic disturbance with the shape shown in Figure 1. Frequently, the amplitude of the oscillation disturbance of the output variable is larger than the variation generated by the pseudo random signal applied to the input, for carrying out the process identification in the nominal regime. In these circumstances, the identification using the above mentioned procedures (arx, iv4, n4sid, adjustable model) fails. It results the need of periodic disturbance rejection. For this purpose a band pass filter was used. In Figure 5 is presented a segment of the recorded output signal from the identification procedure.

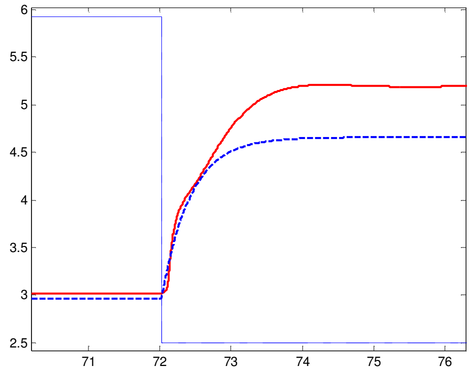

Figure 4: Results on the identification at high variations of the input signal (solid blue line - process input; solid red line - process output; dashed line - model output) [13]

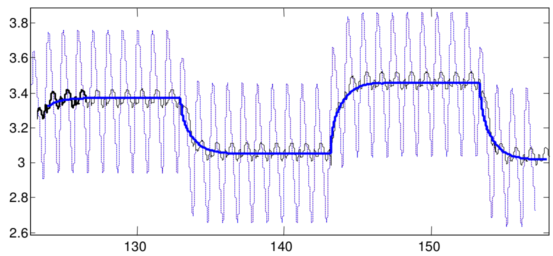

Figure 5: Identification of the process in nominal regime: measured output signal (thin dashed line), filtered output variable (thin solid line) and identified model response (solid thick line) [13]

3 CONTROLLER STRUCTURE

According to the Internal Model Principle, the considered controller contains an integral component (I) for the rejection of the disturbance constant component and a resonant component (R) for the rejection of the disturbances in the permanent regime. The resonant component contains three resonant blocks in a parallel connection. The three resonant blocks are obtained based on Fourier analysis of the periodic disturbance of the form shown in Figure 6. From the spectrum of the disturbance signal, shown in Figure 2, were considered the harmonics of $k\omega_0, k = 1,2,3$ frequencies. The structure of the R + PI controller is given in Figure 3, where $a_1 = 1$, $a_2 = A_2 / A_1$, $a_3 = A_3 / A_1$, with A_1, A_2 and A_3 being the amplitudes of the three harmonics considered in the spectrum of the disturbance signal. The controller parameters are: K_p, K_R and T_i. It must be also considered the ς parameter that determines the selectivity of the resonant component of the controller.

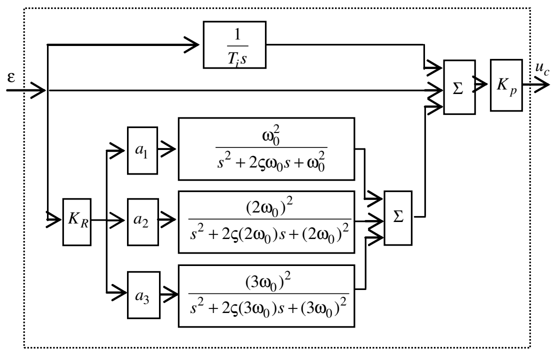

Figure 6: PI+R controller structure [13]

The Bode characteristics of the proposed PI+R controller at different time scale (days and seconds) are given in Figure 7.

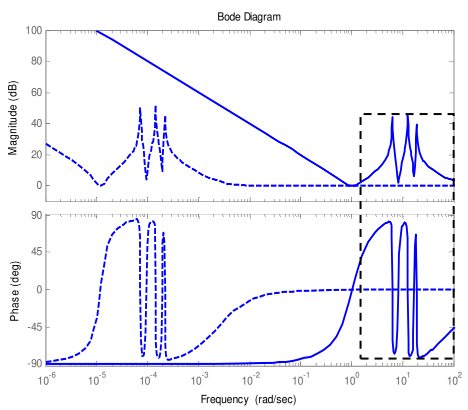

Figure 7: Bode characteristics of the PI+R controller at time scale [s] (solid) and time scale [day] (dash) [14]

The PI+R controller ensures good results for perfectly periodic disturbances, but the results are more modest if there are irregularities on the diurnal variations of ammonia and/or influent flow rate. The diminishing performance is due to noticeable decrease on the resonant controller gain at frequencies lying between the values $k\omega_0, k = 1,2,3$, corresponding to the three harmonics considered on the controller design (ω_0 it is the fundamental frequency). The mentioned decrease is caused by zeros with anti-resonance effect, occurring in the parallel coupling of the 3 basic resonant filters from the controller structure.

The proposed solution aimed to reduce the pseudo-periodic disturbances is based on non-ideal model of these disturbances. Due to the random unevenness of the diurnal variations of the disturbance variable, to consider a classical Fourier spectrum of the type shown in Figure 1, in which a small number of harmonics are adopted, is a rough approximation of perturbation. In reality, the disturbance must be modeled as a random process, close to a periodic variation, through a very selective power spectral density, which is situated in the spectral range of the periodic disturbance.

In the proposed structure of the controller, the resonant filters block is substituted with a subsystem that must replace the multi resonance characteristic from the gain characteristic. The new characteristic, of unimodal type, could be kind of a "wrapped" of maxima corresponding to the resonant filters from PI+R controller structure. Obviously, there may be several solutions to this unimodal characteristic, taking into account the variety of the particularities of the pseudo-periodic disturbance evolution. In the following a simple solution was adopted, in which the subsystem that replace the resonant filters block has a gain characteristic symmetric with a vertical axis and its frequency band include only significant spectral components of the disturbance. The unimodal frequency characteristics of the subsystem must be similar to that of a band-pass filter with steep slopes for gain increase and decrease in the cutoff frequencies area. To generate this characteristics is necessary to use a model with high level of generality. Such a model is that of a fractional-order system having the transfer function of the form:

$$H(s) = H_I(s) H_D(s) \qquad (2)$$

where:

$$H_D(s) = s^r; \quad H_I(s) = s^{-r}; \quad r \in \mathrm{R}^+ \qquad (3)$$

For numerical implementation of this fractional-order system, the Oustaloup method was used [17], [18]. In accordance with the classical Oustaloup algorithm, the transfer function with non-integer order $H(s)$ is approximated between the high and low transitional frequencies, ω_h, ω_b, by rational transfer function:

$$\hat{H}(s) = C_0 \prod_{k=-N}^{N} \frac{s+\omega_k^*}{s+\omega_k} \quad (4)$$

where:

$$C_0 = \left(\frac{\omega_h}{\omega_b}\right)^{-\frac{r}{2}} \prod_{k=-N}^{N} \frac{\omega_k}{\omega_k^*}, \quad (5)$$

$$\omega_k = \omega_b \left(\frac{\omega_h}{\omega_b}\right)^{\frac{k+N+0.5(1+r)}{2N+1}} \quad (6)$$

$$\omega_k^* = \omega_b \left(\frac{\omega_h}{\omega_b}\right)^{\frac{k+N+0.5(1-r)}{2N+1}} \quad (7)$$

Considering a disturbance signal of the form shown in Figure 1, the Oustaloup algorithm was applied to approximate the transfer functions $H_D(s)$ and $H_I(s)$ using a difference of two octaves between the low and high transitional frequencies. To approximate the transfer function $H_D(s)$, the following low and high transitional frequencies were adopted: $\omega_{Db} = 3$ [day^{-1}], respectively $\omega_{Dh} = 12$ [day^{-1}], and to approximate the transfer function $H_I(s)$, were imposed: $\omega_{Ib} = \omega_{Dh} = 12$ [day^{-1}] and $\omega_{Ih} = 48$ [day^{-1}]. The parameter N, which affects the approximation accuracy was adopted at a relatively low value, $N = 3$, in order not to complicate the rational transfer function given in (3). The parameter r largely determine the "selectivity" of the gain characteristics of the fractional-order subsystem that replaces the resonant filters block in the controller structure. Its value is chosen correlated with the transitional frequencies of the transfer functions $H_D(s)$ and $H_I(s)$ so that the gain characteristic to "cover" in a satisfactory way the characteristics of the block resonant.

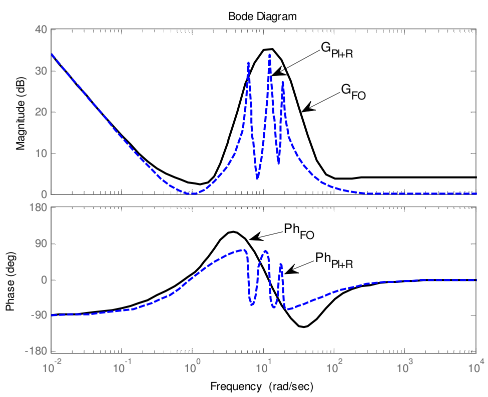

Figure 8: Bode characteristics of PI+R controller and fractional-order controller (G-gain, Ph-phase) [14]

In the case of the disturbance considered in Figure 1, $r = 6.5$ was adopted. In Figure 8 are presented the Bode characteristics of the PI+R controller (with dashed line) and of the fractional-order controller (with solid line), when using the mentioned parameters.

4 ROBUST CONTROLLER DESIGN USING QFT METHOD

For the controller design the QFT method is used. This is a robust control method proposed by Horowitz [19] and it was designed for the control of the processes described by linear models with variable parameters. QFT is a technique that uses Nichols frequency characteristics aiming to ensure a robust design over a specified uncertainty area of the process [20]. In the case of the application considered for this work will be done only the synthesis of the nominal loop transmission, $L(s) = G(s)P(s)$, that satisfies the stability contour constraint. For the controller design the QFT Control Toolbox was used [21].

The parameters of the stability margins imposed for the design procedure are: gain margin $Gm_{\mathrm{dB}} = 4$ and phase margin $Pm = 25^0$. The QFT design leads to the following controller parameters $K_p = 1, K_R = 0.5$, $T_i = 1$, when it is considered that the damping factor of the resonance blocks is $\varsigma = 0.01$. In the case of the fractional order system the QFT design leads to: $K_p = 1, K_F = 0.6$ and $T_i = 0.5$.

5 NUMERICAL RESULTS ON CONTROLLER PERFORMANCE

The performance analysis of the nitrate concentration control system using the two analyzed solutions was performed using the SIMBA simulator. The controlled process consists of one anoxic tank, with denitrification role, one aerobic tank, with nitrification role, and one clarifier tank, with the role to separate the biomass from the treated water. The simulator gives, in addition, the sources that provide periodic variations of the inflow rate and ammonium concentration. The scheme of the control system structure is shown in Figure 9. It includes the cascade control loop for the ammonium concentration, which gives the setpoint for the inner loop of the dissolved oxygen concentration, and the loop controlling the nitrate concentration, which commands the recirculating pump from the aerobic tank to the anoxic one. All three control loops were provided with PI+R/FOS controllers, together with switches that can engage/disengage the resonant blocks. The controller that has been tuned in accordance with the procedure mentioned in the previous section is the one of the loop for nitrate concentration. For the other two controllers parameter values that ensure stable operation of the loops without the use of the robust design procedure were used.

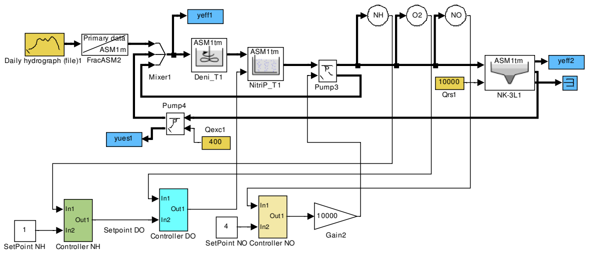

Figure 9: The WWTP control structure implementation using SIMBA simulator [13]

The analysis by numerical simulation of the nitrate concentration loop was done in connection with the regime of the other two control loops, the results being illustrated in Figures 10-11. Until the time instant t_1, marked in these figures, all controllers were of PI type. The setpoint of the control loops for nitrate concentration is 4 mg/l. At the time instant t_1 the resonant component from the nitrate concentration loop was activated. This leads to a spectacular reduction of the effect of periodic disturbances and obviously a reasonable increase of the amplitude of the internal recycle flow oscillations.. At the time instant t_2 switching is made between the PI and PI+R controller in the dissolved oxygen concentration loop. As a result, the amplitude of the ammonium concentration oscillations is reduced correspondingly, and this has an negative effect on the nitrate concentration loop. At the time instant t_3 the resonant block in the ammonium concentration loop was activated. The new controller gives a higher amplitude for the setpoint of the minor loop (the dissolved oxygen loop). In this way the amplitude of the ammonium concentration oscillations is reduced and the disturbance effect on the nitrate concentration loop is negligible, due to the increase in the amplitude of the internal recycle flow.

In the second case, at the time t_0, marked in Figures 12-13, the nitrate concentration controller was switched to the fractional-order controller structure (i.e., PI+FOS). One can notice that there is a reduction of more than 5 times of the oscillation amplitude of the nitrate concentration, and an increase of about 4 times the of the oscillation amplitude of the internal recycle flow rate. In terms of performance indicators that evaluate the control quality, the proposed controller shows excellent performances, illustrated by an important reduction of the oscillation amplitude of the nitrate concentration. However, the practical solution for tuning the controller must consider the system performance defined in relation to technical and economic criteria, and the costs generated by the internal recycle flow rate variation. The proposed structure allows the formulation of a problem of optimal tuning of the control loop with respect to a mixed performance criteria, in which two contradictory factors are found: the quality of the control solution and the cost of the control action.

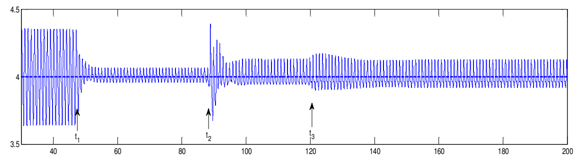

Figure 10: Evolution of the nitrate concentration with PI+R controller [13]

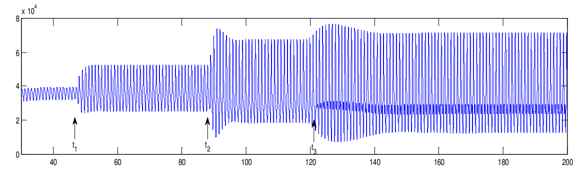

Figure 11: The evolution of the internal recycle flow rate with PI+R controller [13]

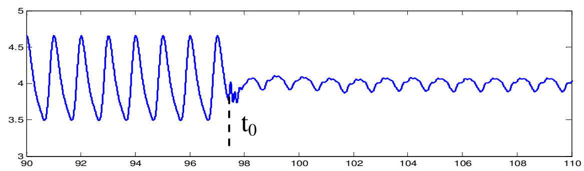

Figure 12: Evolution of the nitrate concentration with PI+FOS controller [14]

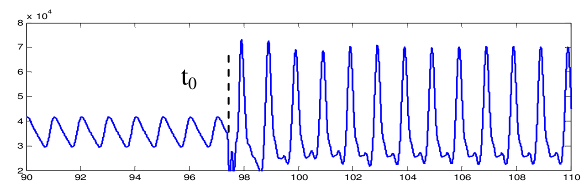

Figure 13: The evolution of the internal recycle flow rate with PI+FOS controller [14]

6 CONCLUSIONS

Using the PI+R controller in the control structure of the urban WWTPs is a natural solution due to the fact that the disturbances from the control loop (i.e. inflow rate and ammonium concentration) have a significant periodic component. However, the influent variations are affected by irregularities, and the obtained results using the resonant control are more modest. In this case, the unimodal frequency characteristic of the subsystem considered for the disturbance rejection should be similar to that of a band-pass filter with steep slopes for gain increase and decrease in the cutoff frequencies area. The solution adopted in this paper is the use of a fractional-order system whose design is based on a pattern of the periodic disturbance waveform that is established by experimental determinations.

Given the important variation of the process parameters with the operating regime and that the controller contain a fractional-order subsystem, the robust QFT frequency method was used. The results of the numerical simulation using the SIMBA simulator shows a significant increase in control system performance of the nitrate concentration and, in the same time, a significant increase of the control effort.

Acknowledgement

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