QFT ROBUST CONTROL OF A WASTEWATER TREATMENT PROCESS

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Abstract: The paper deals with the wastewater treatment process control using QFT (Quantitative Feedback Theory) techniques. The aim of the control is to obtain an effluent having the substrate concentration within the standard limits established by law (under 20 mg/l). It has been admitted variable operating regimes in large limits. Three main regimes have been taken into account: rain, normal, and drought. In these conditions two aspects were considered: a QFT controller designed to assure good properties for the three regimes mentioned before; a control structure that adjusts the dissolved oxygen setpoint as a function of the influent regime. The purpose is to stabilize the operating regime with respect to the quality variable (the effluent substrate concentration) and the command variable (the dilution rate).

Keywords: Robust control, Biotechnology, Wastewater treatment, Linearization.

1. INTRODUCTION

The wastewater treatment processes are very complex, non-linear and characterized by many uncertainties regarding the influent parameters which leads to the difficulty of choosing the structure and the coefficients of the model. Moreover, many wastewater treatment plants are not provided with measurement and control equipments. Under these circumstances different solutions are used in the controller design.

According to Larsson and Skogestad two approaches in choosing the control structure of the process are taken into consideration: the approach oriented on the process and the one based on the mathematical model (Larsson and Skogestad, 2000).

The first approach assumes the separated control of the main interest variables: the dissolved oxygen, nitrogen and phosphorus. The oldest problem regarding the control of the wastewater treatment processes and in the same time one of the most important is the control of the dissolved oxygen level. If the satisfactory level of the dissolved oxygen is guaranteed then the microorganism' populations used in the process can develop properly (Ingildsen, 2002a; Ingildsen, *et al.*, 2002b). Recently the control problem of the nitrogen and phosphorus level became a priority.

The second approach is the control based on the mathematical model of the wastewater treatment processes. This problem knew many developing stages, depending on the type of the mathematical model used in the control algorithm design. The model described in (Nejjari *et al.*, 1996) allowed the use of the classic and modern control techniques**.** A large set of control structures can be mentioned, beginning with the classic structures PI and PID, where the linearization of the nonlinear model around an operating point is used for the design of the controller. It arises then the possibility to design the exact linearizing control or to adopt the adaptive control together with the state and parameter estimation (Nejjari *et al.*, 1999). The use of this model allows the design of an indirect control structure of the process. It consists in the control of the dissolved oxygen level in the tank which practically assures a satisfactory level for the organic substrate. This problem - the control of the dissolved oxygen concentration - has been studied good results in the control of a non-linear process using multi-model techniques (Barbu *et al.*, 2004).

The use of ASM1 model (Activated Sludge Model 1) (Henze *et al.*, 1987) determined by a work group belonging to IAWQ (International Association of Water Quality) makes the control problem more difficult and the results are less numerous. Based on ASM1 model, Brdys and Zhang used a non-linear predictive control technique for the indirect control of the organic substrate by controlling the dissolved oxygen level (Brdys and Zhang, 2001a). For the same model Brdys and Konarczak propose a hierarchic control structure (Brdys and Konarczak, 2001b). The structure mentioned above contains three levels: a superior level where a stable trajectory for the process on a time horizon is calculated; a mean level where we have the optimization of trajectories of the following variables: the dissolved oxygen concentration, the recycled active sludge flow and the recycled nitrate flow; the inferior level where the dissolved oxygen level is controlled to the setpoint imposed by the mean level.

An approach that is very appropriated nowadays is the control based on the artificial intelligence. It uses the knowledge and the expertise of the specialists obtained from the process management. Expert systems, fuzzy and neuro-fuzzy systems have been used for the control of the wastewater treatment processes (Manesis *et al.*, 1998), (Yagi *et al.*, 2002) and (King and Stathaki, 2004).

The present paper deals with the control of a wastewater treatment process, the main objective being the obtaining of an effluent having the substrate concentration within the standard limits established by law (under 20 mg/l). Three main regimes have been taken into account: rain, normal, and drought. In these conditions two aspects were approached: a QFT controller designed to assure good properties for the three regimes mentioned before; a control structure that adjusts the dissolved oxygen setpoint as a function of the influent regime. The purpose is to stabilize the operating regime with respect to the quality variable (the effluent substrate concentration) and the command variable (the dilution rate).

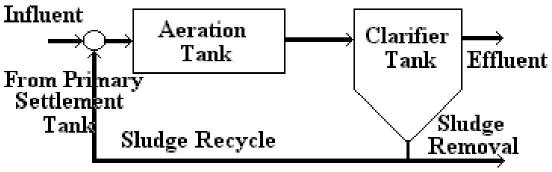


Fig. 1. Activated Sludge Process

The paper is structured as follows: the second section presents the wastewater treatment process and its mathematical model, the third section contains the linearized model of the process, the fourth section presents the process control using a QFT robust controller, the fifth section shows the simulation results and the last is dedicated to the conclusions.

2. THE MODEL OF THE WASTEWATER TREATMENT PROCESS

The main components of the wastewater treatment process are presented in figure 1 (Katebi *et al*, 1999).

The *Aeration Tank* is a biological reactor containing a mixture of liquid and suspended solid where a microorganism's population is developed aiming to remove the organic substrate from the mixture. The *Clarifier Tank* is a gravity settlement tank where the sludge and the clear effluent are separated. A part of the removed sludge is recycled back to the aeration tank and the other part removed.

The systemic scheme of the process is given in figure 2.

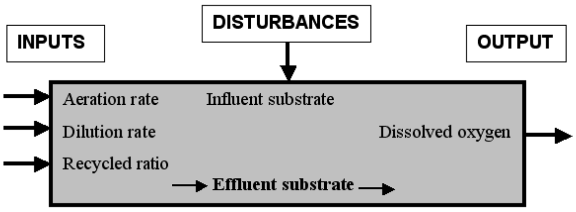


Fig. 2. The systemic scheme of the wastewater treatment process

The process model was determined on the basis of mass balance equations. It is given by the following equations (Nejjari *et al.*, 1996):

$$\frac{dX}{dt} = m(t)X(t) - D(t)(1+r)X(t) + rD(t)X_r(t) \tag{1}$$

$$\frac{dS}{dt} = -\frac{m(t)}{Y}X(t) - D(t)(1+r)S(t) + D(t)S_{in} \tag{2}$$

$$\frac{dX_r}{dt} = D(t)(1+r)X(t) - D(t)(b+r)X_r(t) \tag{3}$$

$$\begin{aligned}\frac{dDO}{dt} = &-\frac{K_0 m(t)X(t)}{Y} - D(t)(1+r)DO(t) + \\ &+ aW\left(DO_{\max} - DO(t)\right) + D(t)DO_{in}\end{aligned} \tag{4}$$

$$m(t) = m_{\max}\frac{S(t)}{k_s + S(t)}\frac{DO(t)}{K_{DO} + DO(t)} \tag{5}$$

where: $X(t)$ – biomass; $S(t)$ – substrate; $DO(t)$ – dissolved oxygen; DO_{max} – maximum dissolved oxygen, $X_r(t)$ – recycled biomass; $D(t)$ – dilution rate; S_{in} and DO_{in} – substrate and dissolved oxygen concentrations of the influent; Y – biomass yield factor; m – biomass growth rate; m_{max} – maximum specific growth rate; k_s and K_{DO} – saturation constants; a – oxygen transfer rate; W – aeration rate; K_0 – model constant; r and b – ratio of recycled and waste flow to the influent. The model coefficients have the following values:

$$Y = 0.65;\ b = 0.2;\ a = 0.018;\ K_{DO} = 2\text{ mg/l};\ ;\ K_0 = 0.5$$
$$m_{\max} = 0.15\text{ mg/l};\ k_s = 100\text{ mg/l};\ DO_{\max} = 10\text{ mg/l};\ r = 0.6$$

The simulation results concerning the free dynamics of the model are presented in figure 3.

The initial conditions considered in the simulation are:

$X(0)$=200mg/l, $S(0)$=88mg/l, $DO(0)$=5mg/l, $X_r(0)$=320mg/l, DO_{in}=0.5mg/l and S_{in}=200mg/l.

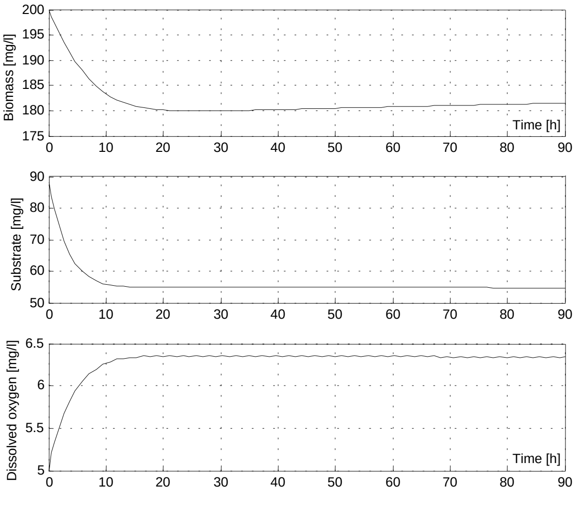


Fig. 2. The simulation results of the model in open loop

3. THE LINEARIZED MODEL OF THE WASTEWATER TREATMENT PROCESS

The nonlinear model has been linearized in three steady state operating points, corresponding to the three main functioning regimes: rain (D=1/20h^{-1}, W=80h^{-1}), normal (D=1/35h^{-1}, W=60h^{-1}) and drought (D=1/50h^{-1}, W=20h^{-1}). The first case is characterized by maximum values for the aeration and dilution rates, the second regime considers average values for the two parameters mentioned before and the third case is characterized by small values for the same parameters. The linearized model is given by the following equations:

$$\frac{d\Delta X}{dt} = \Delta X \cdot \left[\bar{m} - D\cdot(1+r)\right] + \Delta S \cdot \left[\bar{X}\cdot \bar{m}\cdot\left(\frac{1}{\bar{S}} - \frac{1}{k_s+\bar{S}}\right)\right] + \Delta DO \cdot \left[\bar{X}\cdot\bar{m}\cdot\left(\frac{1}{\overline{DO}} - \frac{1}{k_{DO}+\overline{DO}}\right)\right] + r\cdot D\cdot \Delta X_r + r\cdot D\cdot \bar{X}_r - D\cdot(1+r)\cdot\bar{X} \tag{6}$$

$$\frac{d\Delta S}{dt} = -\Delta X\cdot\frac{\bar{m}}{Y} - \Delta S\cdot\left[\frac{\bar{X}\cdot\bar{m}}{Y}\cdot\left(\frac{1}{\bar{S}} - \frac{1}{k_s+\bar{S}}\right) + D\cdot(1+r)\right] - \Delta DO\cdot\frac{\bar{X}\cdot\bar{m}}{Y}\cdot\left(\frac{1}{\overline{DO}} - \frac{1}{k_{DO}+\overline{DO}}\right) - D\cdot\left[(1+r)\cdot\bar{S} - S_{in}\right] \tag{7}$$

$$\frac{d\Delta X_r}{dt} = \Delta X\cdot(1+r)\cdot D - \Delta X_r\cdot(b+r)\cdot D + D\cdot\left[(1+r)\cdot\bar{X} - (b+r)\cdot\bar{X}_r\right] \tag{8}$$

$$\frac{d\Delta DO}{dt} = -\Delta X\cdot\frac{K_0\cdot\bar{m}}{Y} - \Delta S\cdot\frac{K_0\cdot\bar{X}\cdot\bar{m}}{Y}\cdot\left(\frac{1}{\bar{S}} - \frac{1}{k_s+\bar{S}}\right) - \Delta DO\cdot\left[\frac{K_0\cdot\bar{X}\cdot\bar{m}}{Y}\cdot\left(\frac{1}{\overline{DO}} - \frac{1}{k_{DO}+\overline{DO}}\right) + D\cdot(1+r) + a\cdot W\right] + D\cdot\left[DO_{in} - (1+r)\cdot\overline{DO}\right] + a\cdot W\cdot\left(DO_{\max} - \overline{DO}\right) \tag{9}$$

with

$$\Delta m = \bar{m}\cdot\Delta S\left(\frac{1}{\bar{S}} - \frac{1}{k_s+\bar{S}}\right) + \bar{m}\cdot\Delta DO\left(\frac{1}{\overline{DO}} - \frac{1}{k_{DO}+\overline{DO}}\right) \tag{10}$$

where $\bar{v}$ represents the nominal regime value of the variable v. Based on the linear model given by the equations (6) – (10) three transfer functions corresponding to the three regimes mentioned above have been determined.

- rain/flood:

$$H(s) = \frac{9.38(s+4.9)(s+0.045)(s+0.0026)}{(s+0.76)(s+0.36)(s+0.045)(s+0.0026)} \tag{11}$$

- normal:

$$H(s) = \frac{11.16(s+3.9)(s+0.065)(s+0.0037)}{(s+1.25)(s+0.43)(s+0.065)(s+0.0037)} \tag{12}$$

- drought

$$H(s) = \frac{10.03(s+2.8)(s+0.11)(s+0.0057)}{(s+1.69)(s+0.35)(s+0.11)(s+0.0057)} \tag{13}$$

After the equations (11) – (13) have been simplified, all the three regimes can be described by a second order transfer function with variable parameters:

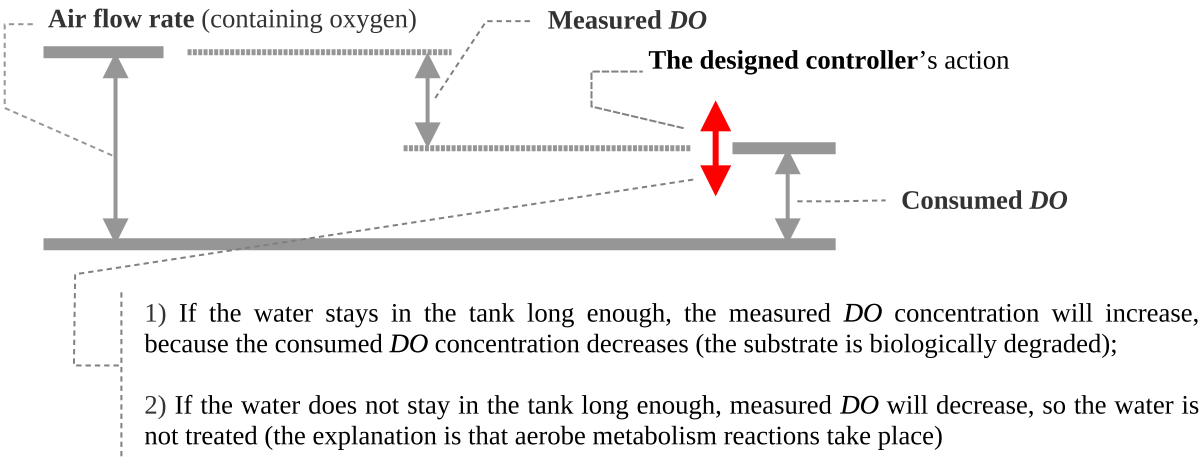
$$H(s) = \frac{K(s+a)}{(s+b)(s+c)} \tag{14}$$

where

$$K \in [9\ \ 12],\ a \in [2.5\ \ 5.5],\ b \in [0.5\ \ 2],\ a \in [0.2\ \ 0.5].$$

The variation limits for the linearized model were established taking into consideration two factors:

1. extreme situations (drought/ flood) could appear in the process;
2. the parameters of the non-linear model varies due to the process variables (ex: temperature).



1) If the water stays in the tank long enough, the measured *DO* concentration will increase, because the consumed *DO* concentration decreases (the substrate is biologically degraded);

2) If the water does not stay in the tank long enough, measured *DO* will decrease, so the water is not treated (the explanation is that aerobe metabolism reactions take place)

Fig. 4. The indirect control of the organic substances concentration through the direct control of the dissolved oxygen.

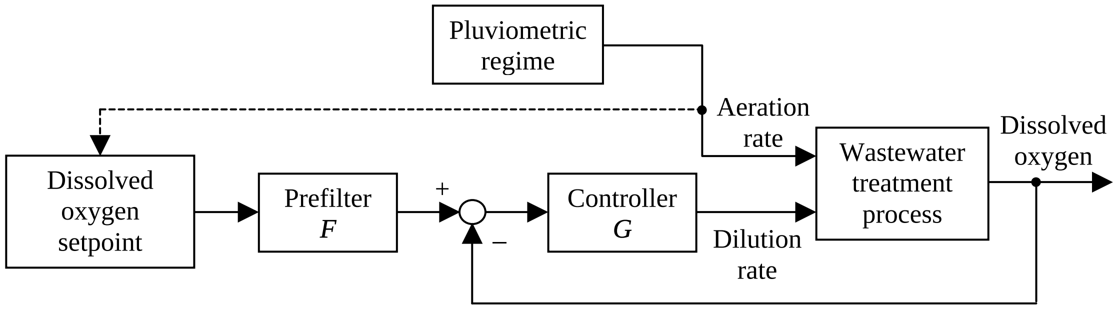


Fig. 5. The structure of the control system

4. THE CONTROL OF THE WASTEWATER TREATMENT PROCESS

4.1 The design principle and the structure of the control system.

The principle used in the paper is the indirect control of the organic substrate through the direct control of the dissolved oxygen concentration, as it is presented in figure 4.

For the wastewater treatment process two command variables are available: the aeration rate and the dilution rate. When it is necessary to treat a large quantity of wastewater in a short time to provide for a good quality of the effluent, the tank is supplied with a bigger amount of oxygen. In these conditions the aeration rate (*W* variable) will be considered depending on the pluviometric regime.

The model obtained in section 3 has variable parameters and this is why the authors propose the QFT technique for the robust controller design. QFT method consist in the design of a controller *G* and a prefilter *F*. The controller *G* is designed so that the output variation due to the process uncertainties is within the allowed tolerances. The prefilter *F* is designed to assure the setpoint tracking by the output.

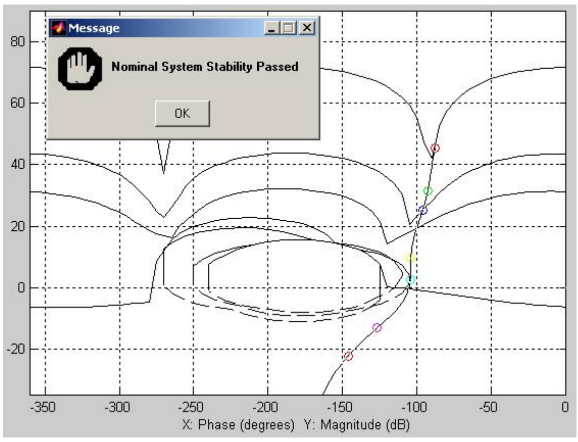
The structure of the control system is presented in figure 5. Let us notice that the dissolved oxygen setpoint depends on the pluviometric regime, as we can see in figure 5.

4.2 The design of the QFT controller

Taking into account the limits of the parameters presented in section 3 the two tracking models (upper and lower bounds) were imposed (Houpis *et al.*, 1999).

$$H_U = \frac{0.12(s+15)}{(s+0.6 \pm j \cdot 1.2)} \tag{15}$$

$$H_L = \frac{0.9375}{(s+0.375)(s+0.5)(s+5)} \tag{16}$$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Nominal System Stability Passed

Fig. 6. Shaping of the open loop on the Nichols chart for the transfer function (14).

Figure 6 presents the result of the controller design.

One can notice that Black-Nichols characteristic of the open loop system satisfies the stability contours and the tracking bounds for each frequency considered in the controller design.

The transfer function of the controller is the following:

$$G(s) = \frac{1.025 \cdot (s+0.405)(s+0.549)}{(s+0.0005)(s+2.738)(s+6.585)} \qquad (17)$$

Figure 7 also shows results obtained for the prefilter design. One can notice the tracking models (upper and lower bounds) that frame all the models considered in QFT design procedure.

The transfer function of the prefilter is the following:

$$F(s) = \frac{0.364 \cdot (s+3.319)}{(s+0.889)(s+1.361)} \qquad (18)$$

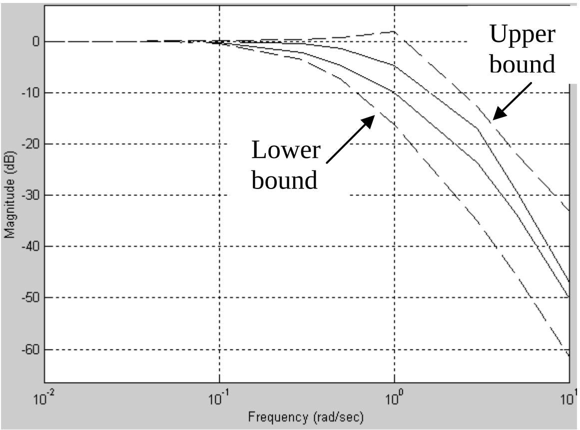

Fig. 7. Requirements and resulting prefilter

5. RESULTS OBTAINED WITH QFT CONTROLLER

This section presents the simulation of the designed controller behavior. At the beginning the dissolved oxygen setpoint is considered constant and the aeration rate is modified due to the modification of the pluviometric regime. The simulation results are presented in figure 8. As it can be seen the designed controller is able to track the dissolved oxygen setpoint (7.5 mg/l) for different pluviometric regimes.

Table 1 presents the dependence of the organic substrate concentration and of the stationary time in the tank on the pluviometric regime when the oxygen setpoint is constant.

Analyzing the data from table 1, the following observations can be made:

1. If the aeration rate is small (corresponding to a drought regime) the stationary time in the tank is long and the amount of energy necessary to assure a constant aeration is big;
2. If the aeration rate is big (corresponding to a rain regime) the organic substrate concentration reaches great values, closed to the legal limit.

As a consequence it is necessary to modify the dissolved oxygen setpoint according to the pluviometric regime. The results are presented in table 2.

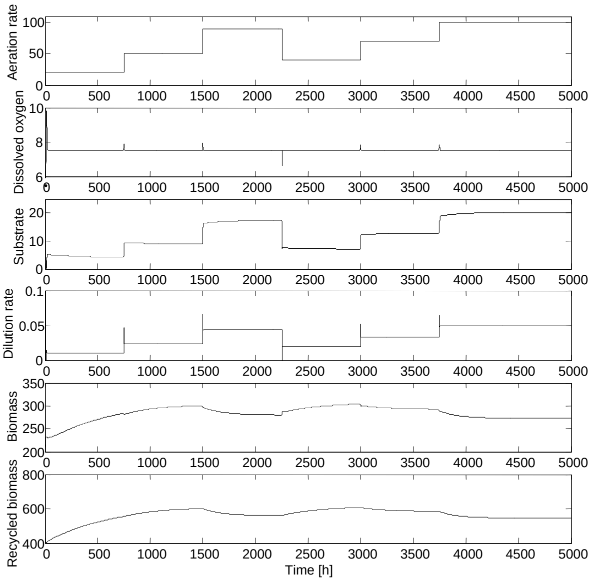

Fig. 8. The simulation results when the dissolved oxygen setpoint is constant and the aeration rate is modified.

Table 1 The dependence of the organic substrate concentration on the pluviometric regime when the oxygen setpoint is constant

w [h^{-1}]	1/D [h]	Substrate [mg/l]
10	158.35	2.49
20	95.24	3.96
30	67.57	5.49
40	51.81	7.12
50	42.02	8.87
60	35.09	10.75
70	29.85	12.80
80	25.90	15.01
90	22.78	17.46
100	20.12	20.16

Table 2 The dependence of the organic substrate concentration on the pluviometric regime when the oxygen setpoint is variable

w [h^{-1}]	DOsetpoint [mg/l]	1/D [h]	Substrate [mg/l]
10	2	55.86	10.82
20	4	40.48	11.12
30	5	33.11	12.81
40	6	31.75	12.69
50	6.5	29.24	13.60
60	7	28.65	13.61
70	7.5	29.85	12.80
80	8	33.11	11.25
90	8	29.32	12.87
100	8	26.25	14.59

Table 2 shows that:

1. If the aeration rate is small the amount of energy necessary to assure a constant aeration decreases (for $W = 10h^{-1}$ the water stays only 55 hours in the tank comparing to the 158 hours in the first case);
2. If the aeration rate is big the effluent quality is improved (for $W = 100h^{-1}$ the organic substrate concentration is 14.59 mg/l compared to the 20.16 mg/l in the first case).

Figure 9 considers the same pluviometric regimes as figure 8 does, but the dissolved oxygen setpoint is variable. It can be seen that the results of the tracking of the dissolved oxygen setpoint by the system with the designed controller are very good.

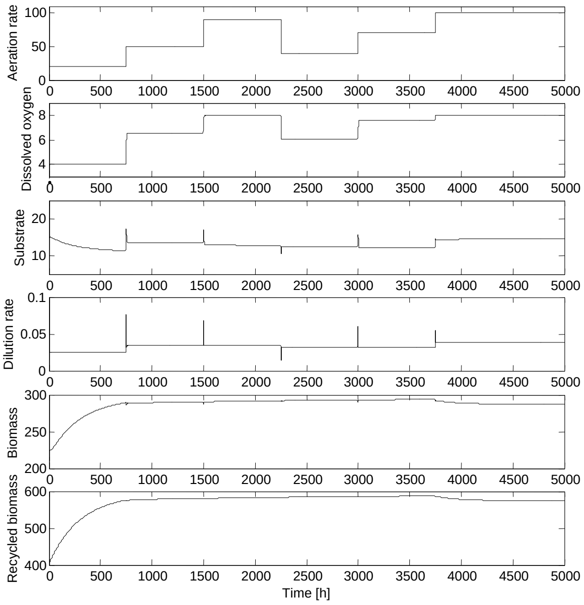

Fig. 9. The simulation results when the dissolved oxygen setpoint is variable and the aeration rate is modified.

6. CONCLUSIONS

This paper shows that in the case of the wastewater treatment processes, characterized by different functioning regimes and uncertainties given by the variable parameters, a very appropriate method to control such processes is QFT technique. It assures the robustness of the control loop in all the possible functioning regimes.

The improving of the performances is achieved by the use of a variable dissolved oxygen setpoint. It assures the decreasing of the amount of energy in drought regime and the increasing of the effluent quality in rain regime.

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