ROBUST MULTIMODEL CONTROL USING QFT TECHNIQUES OF A WASTEWATER TREATMENT PROCESS

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Abstract: *This paper deals with the design of a robust multimodel controller using QFT (Quantitative Feedback Theory) techniques. The process considered in the paper is a wastewater treatment one and the aim of the control is the obtaining of an effluent having the substrate concentration within the standard limits established by law (under 20 mg/l). The process has been linearized in three steady state functioning points, corresponding to the three main functioning regimes: rain/flood, normal, and drought. For each regime a QFT controller has been designed. Finally a general controller was built through the fuzzy aggregation of the three QFT controllers mentioned above.*

Keywords: *Wastewater Treatment, Robust Control, Multimodel Control, QFT Techniques, Linearization.*

1. INTRODUCTION

The wastewater treatment process is a very complex process consisting in three phases: primary treatment (the first phase) simply screens and settles large particles and skims off floating greases and oils; in the second phase the organic carbon, the nitrogen and phosphates are biologically removed. The third treatment (the third phase) attempts to limit the microorganisms and other pathogens in the treated water by membrane filtration or deep-bad filters and some form of disinfection using chlorine, ozone or ultraviolet light. Chemical precipitation of phosphates is common during the first and/or the third treatment phase (Olsson, *et al.*, 1999).

The process complexity, the strong non-linearities and the uncertainties regarding the influent parameters and the process structure make difficult the determining of a good model. Moreover, many wastewater treatment plants don't have measurement and control equipments. Under these circumstances vary models are used in the controller design.

Accordingly to (Lars, *et al.*, 2000) two approaches in choosing the control structure of the process are taken into consideration: the approach oriented to the process and the one based on the mathematical model. The first approach assumes the separated control of the main interest variables: the control of the dissolved oxygen, nitrate and phosphate. The oldest problem regarding the control of the wastewater treatment processes and one of the most important is the control of the dissolved oxygen level. So the guarantee of a satisfactory level of the dissolved oxygen allows the developing of the microorganism' populations used in the process (Olsson, *et al.*, 1985b; Ingildsen, 2002a; Ingildsen, *et al.*, 2002b). Recently the control problem of the nitrate and phosphate level became a priority. The control based on the mathematical model of the wastewater treatment process knew many developing, depending on the type of the mathematical model used in the control algorithm design, as in the case of state estimators. So, the model described in (Olsson, *et al.*, 1985a) allowed the use of the classic and modern techniques. It can be mentioned the classic structures of PI and PID (Katebi, M. R., *et al.*, 1999) type where the non-linear model linearizing around a functioning point is used for the controller design, till the exact linearizing control (multivariable) or in adaptive variant together with a state and parameters estimator (Nejjari, F., 1999). The using of this model leads to the design of an indirect control structure of the process. So, the control of the dissolved oxygen level in the tank practically assures a satisfactory level for the organic substrate. This problem - the control of the dissolved oxygen concentration - has been approached with good results in the control of a non-linear process using multi-model techniques (Barbu, M., *et al.*, 2004).

The using of ASM1 model (Activated Sludge Model 1) 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, M. A., *et al.*, 2001a) used a non-linear predictive control technique for the indirect control of the organic substrate by the control of the dissolved oxygen level. For the same model (Brdys, M. A., *et al.*, 2001b) proposes a hierarchic control structure. The structure mentioned before contains three levels: a superior level where a stable trajectory for the process on a time horizon is calculated, a mean level where the optimization of the trajectories for the dissolved oxygen concentration, the recirculated active sludge flow and the recycled nitrate flow takes place and the inferior level where the control of the dissolved oxygen level based on the setpoint imposed by the mean level.

An approach that is very appropriated at present is the control based on the artificial intelligence. It used 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 (Manes, S. A., *et al.*, 1998), (Yagi, S., *et al.*, 2002) and (King, R. E., *et al.*, 2004).

The present paper deals with the robust 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).

The paper is structured as follows: the second section presents the non-linear model of the wastewater treatment process, three linear models corresponding to the three functioning regimes (normal, rain and drought) and some results concerning the process control by linear controllers, the third section deals with the design of three QFT robust controllers for the three regimes mentioned above, the fourth section presents simulation results of the entire system with the aggregated controller and the last section is dedicated to the conclusions.

2. CONSIDERATIONS ABOUT THE MODEL LINEARIZATION OF THE WASTEWATER TREATMENT PROCESS

The nonlinear model considered in the paper is given by the following equations (Katebi, M. R., *et al.*, 1999):

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

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

$$\begin{aligned}\frac{dDO}{dt} = -\frac{K_0\mu(t)X(t)}{Y} - D(t)(1+r)DO(t) + \\ + \alpha W\left(DO_{\max} - DO(t)\right) + D(t)DO_{in}\end{aligned} \tag{3}$$

$$\frac{dX_r}{dt} = D(t)(1+r)X(t) - D(t)(\beta + r)X_r(t) \tag{4}$$

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

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; μ – biomass growth rate; μ_{max} – maximum specific growth rate; k_s and $\boldsymbol{K_{DO}}$ – saturation constants; α – oxygen transfer rate; W – aeration rate; K_0 – model constant; r and β – ratio of recycled and waste flow to the influent.

The process has been linearized in three steady state functioning 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 mean 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:

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

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

$$\frac{d\Delta DO}{dt} = -\Delta X\cdot\frac{K_0\cdot\bar{\mu}}{Y} - \Delta S\cdot\frac{K_0\cdot\bar{X}}{Y}\cdot\left(\frac{1}{\bar{S}} - \frac{1}{k_s+\bar{S}}\right) - \Delta DO\cdot\left[\frac{K_0\cdot\bar{X}}{Y}\cdot\left(\frac{1}{\overline{DO}} - \frac{1}{k_{DO}+\overline{DO}}\right) + D\cdot(1+r) + \alpha\cdot W\right] + D\cdot\left[DO_{in} - (1+r)\cdot\overline{DO}\right] + \alpha\cdot W\cdot\left(DO_{\max} - \overline{DO}\right) \tag{8}$$

$$\frac{d\Delta X_r}{dt} = \Delta X\cdot(1+r)\cdot D - \Delta X_r\cdot(\beta+r)\cdot D + D\cdot\left[(1+r)\cdot\bar{X} - (\beta+r)\cdot\bar{X}_r\right] \tag{9}$$

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

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:

$$H_1(s) = \frac{9.38(s+4.9)(s+0.045)(s+0.0026)}{(s+0.76)(s+0.36)(s+0.045)(s+0.0026)} \tag{11}$$

- normal:

$$H_2(s) = \frac{11.16(s+3.9)(s+0.065)(s+0.0037)}{(s+1.25)(s+0.43)(s+0.065)(s+0.0037)} \tag{12}$$

- drought

$$H_3(s) = \frac{10.03(s+2.8)(s+0.11)(s+0.0057)}{(s+1.69)(s+0.35)(s+0.11)(s+0.0057)} \tag{13}$$

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

$$H_1(s) = \frac{K_1(s+a_1)}{(s+b_1)(s+c_1)} \tag{14}$$

with: $K_1 \in [9.5\ \ 10.5], a_1 \in [2\ \ 3.5], b_1 \in [1.5\ \ 2]$
$c_1 \in [0.3\ \ 0.4]$

$$H_2(s) = \frac{K_2(s+a_2)}{(s+b_2)(s+c_2)} \tag{15}$$

with: $K_2 \in [10.5\ \ 11.5], a_2 \in [3\ \ 4.5], b_2 \in [1\ \ 1.5]$
$c_2 \in [0.4\ \ 0.5]$

$$H_3(s) = \frac{K_3(s+a_3)}{(s+b_3)(s+c_3)} \tag{16}$$

with: $K_3 \in [9\ \ 10.5], a_3 \in [4.5\ \ 5.5], b_3 \in [0.5\ \ 1]$
$c_3 \in [0.3\ \ 0.4]$

An attempt was made to solve the problem by means of three linear controllers suitably adjusted for three operation regimes as described above. It was found that the three linear controllers ensure good system operation in a close vicinity of the selected operating points; however, they fail to cover a large enough zone around these points, a situation which may occur quite frequently during the process operation with negative effects on the desired performance. In the paper this will be illustrated for the drought case/regime.

A PI controller was designed for the drought regime. Figure 1 shows that the controller follows the setpoint in compliance with the controller design requirements. If the process gets farther from the nominal point (drought) then the setpoint tracking property is no longer complied with, as shown in Figure 2.

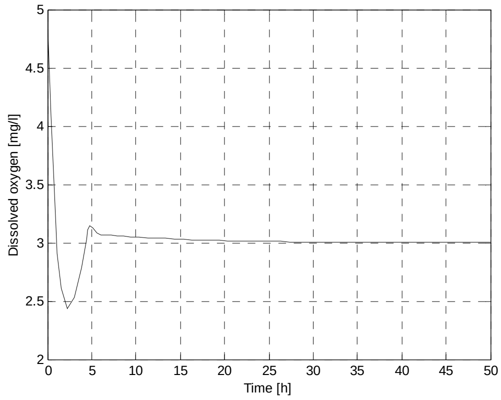

Fig. 1. The response of the system with PI controller designed for drought regime working in the nominal regime (the same regime – drought).

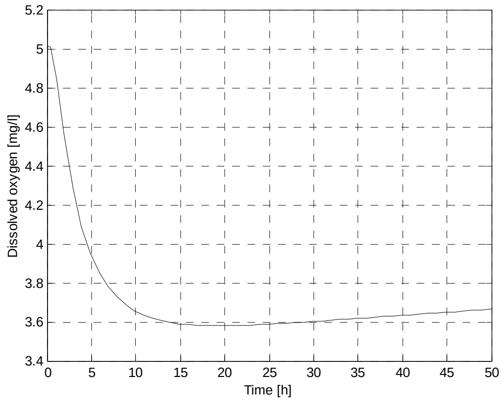

Fig. 2. The response of the system with PI controller designed for drought regime working in normal pluviometric regime.

This study underlines the need to design three robust controllers for each rain regime. The three controllers have been design in accordance with the QFT techniques. (Houpis *et al.*, 1999).

3. THE DESIGN OF THE THREE ROBUST CONTROLLERS USING QFT TECHNIQUES

Three QFT controllers for the three functioning regimes mentioned in the previous section have been designed.

The drought regime:

It is characterized by the transfer function (14). Two transfer functions, *upper limit* and *lower limit*, have been chosen, as follows:

$$H_{U1} = \frac{0.02225(s+10)}{(s+0.25 \pm j \cdot 0.4)} \qquad (17)$$

$$H_{L1} = \frac{0.1}{(s+0.25)(s+0.4)(s+1)} \qquad (18)$$

Figure 3 shows the result of the controller design.

The transfer functions of the controller and the prefilter obtained by applying QFT techniques are given by equations (19) and (20).

$$G_1(s) = \frac{0.055 \cdot (s+0.5)}{(s+0.00016)(s+1.637)(s+3.42)} \qquad (19)$$

$$F_1(s) = \frac{0.886 \cdot (s+0.964)}{(s+0.854)} \qquad (20)$$

Figure 4 presents the check of the framing between the limits imposed to the frequency characteristic of the process in closed loop.

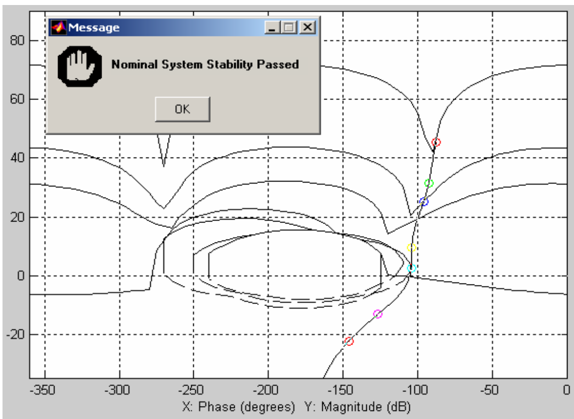

Fig. 3. Shaping of the open loop on the Nichols chart for the transfer function (14).

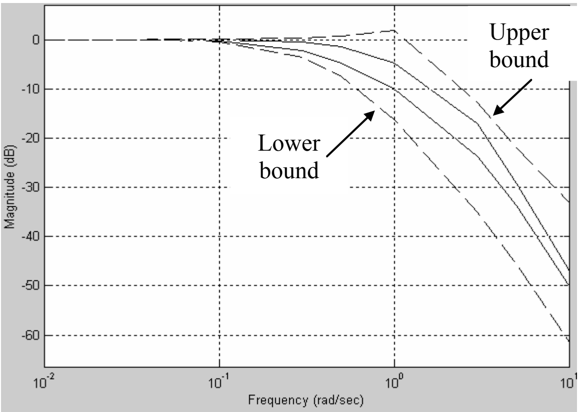

Fig. 4. Requirements and resulting prefilter

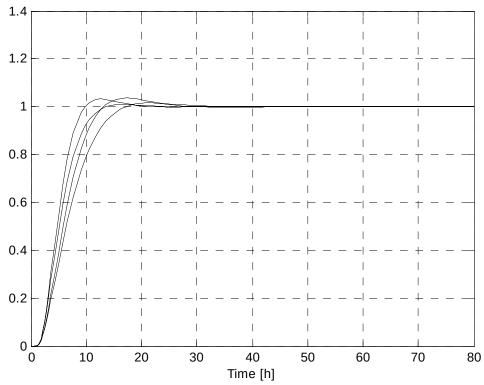

Fig. 5. The response of the loop using the controller (19) and the process described by different linear models for the drought regime.

Figure 5 presents the system responses with the QFT controller (19) designed for linear models of the drought regime.

For the other two cases (normal and rain regimes) the design results are presented:

<u>The normal regime</u>:

- the imposed limits:

$$H_{U2} = \frac{0.028(s+10)}{(s+0.3 \pm j \cdot 0.48)} \tag{21}$$

$$H_{L2} = \frac{0.15}{(s+0.3)(s+0.5)(s+1)} \tag{22}$$

- the transfer functions of the controller and of the prefilter:

$$G_2(s) = \frac{0.019 \cdot (s+0.52)}{(s+0.00032)(s+2.21)} \tag{23}$$

$$F_2(s) = \frac{0.565 \cdot (s+0.85)}{(s+0.48)} \tag{24}$$

- the simulation of the closed loop system for different models of the normal regime:

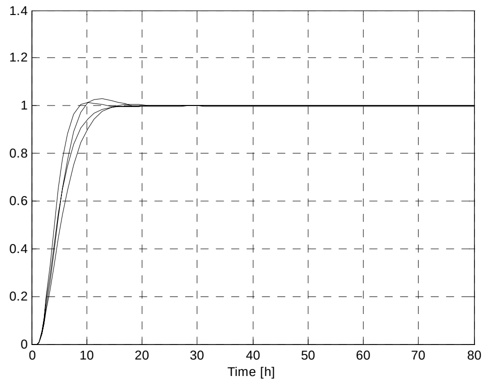

Fig. 6. The response of the loop using the controller (23) and the process described by different linear models for the drought regime.

<u>The rain regime</u>:

- the imposed limits:

$$H_{U3} = \frac{0.057(s+10)}{(s+0.4 \pm j \cdot 0.64)} \tag{25}$$

$$H_{L3} = \frac{0.28}{(s+0.4)(s+0.7)(s+1)} \tag{26}$$

- the transfer functions of the controller and of the prefilter:

$$G_3(s) = \frac{0.28 \cdot (s+0.26)(s+1.47)}{(s+0.0009)(s+1.39 \pm j \cdot 3.12)} \tag{27}$$

$$F_3(s) = \frac{0.742}{(s+0.8)(s+0.92)} \tag{28}$$

- the simulation of the closed loop system for different models of the normal regime:

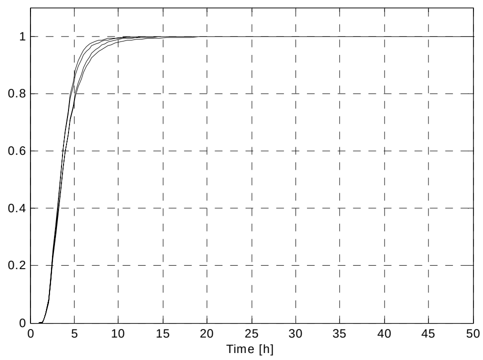

Fig. 7. The response of the loop using the controller (25) and the process described by different linear models for the drought regime.

4. SIMULATION OF THE CLOSED LOOP SYSTEM WITH THE NON-LINEAR PROCESS USING THE AGGREGATED QFT CONTROLLER

The principle used in the paper is the indirect control of the organic substrate by the direct control of the dissolved oxygen concentration (Barbu, M., *et al.*, 2004).

For the wastewater treatment process there are two command variables: the aeration rate and the dilution rate. When 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 structure of the control system is presented in figure 8.

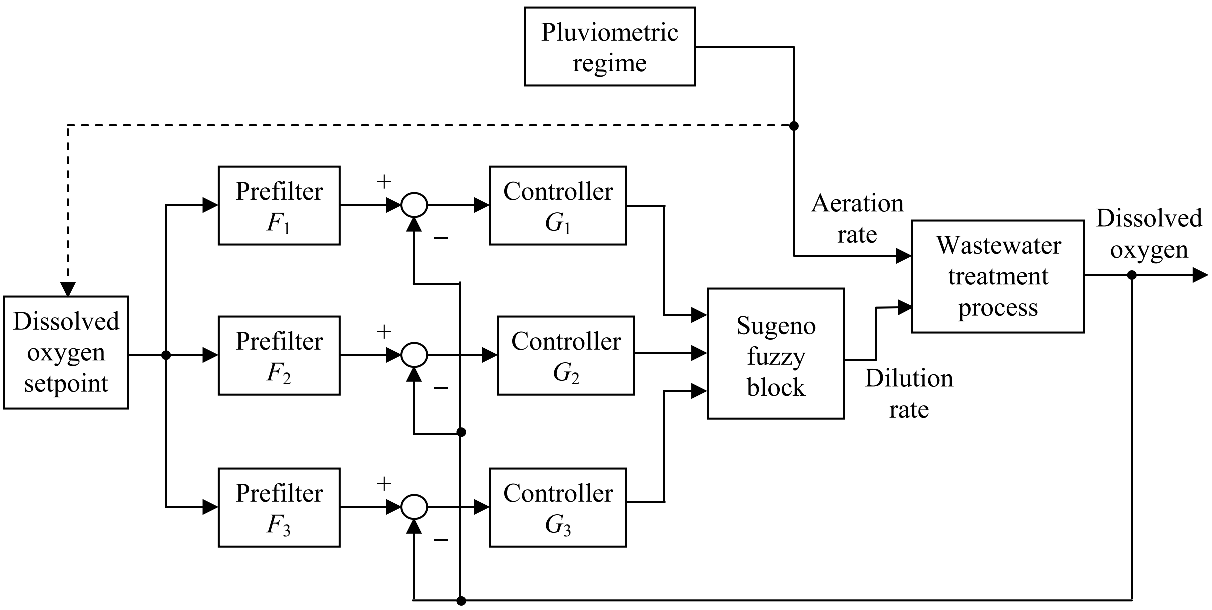

Fig. 8. The structure of the control system

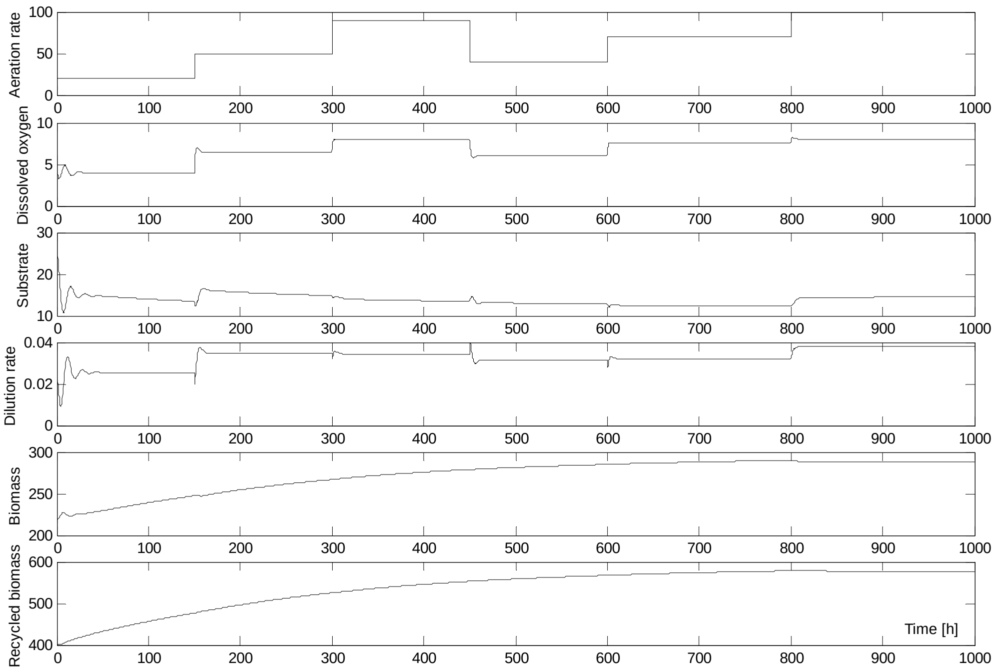

Fig. 10. The simulation results.

The aggregation of the three QFT control loops is done based on a fuzzy block of Sugeno type with the membership functions presented in figure 9, having as input variable the aeration rate (w).

Figure 10 presents the simulation of the entire system where the pluviometric regime varies.

The dissolved oxygen setpoint and the aeration rate are modified meaning the variation of the pluviometric regime. As it can be seen the designed controller is able to track the dissolved oxygen setpoint for vary pluviometric regimes.

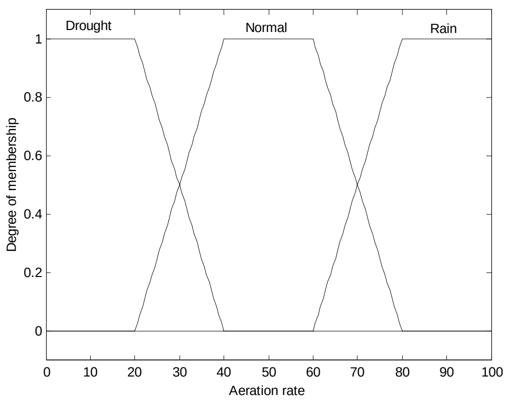

Fig. 9. The membership functions of the Sugeno fuzzy block.

5. CONCLUSIONS

The paper shows that in the case of the wastewater treatment processes, characterized by vary functioning regimes and uncertainties given by the variable parameters, a robust control method must be used. Section 2 proves that a linear controller cannot assure good performances for a regime (rain, normal or drought) if the functioning point changes significantly. This is the reason that three QFT controllers have been designed, each controller covering one of the three regimes. The global controller was obtained through the aggregation of the three QFT controllers with a Sugeno fuzzy block. It assures the robustness of the control loop in all the possible functioning regimes.

REFERENCES

[1] Barbu, M., G. Barbu and E. Ceanga (2004), *The Multi-model Control of the Wastewater Treatment Process with Activated Sludge*, 12th Mediterranean Conference on Control and Automation - MED'04, Kusadasi, Turkey, Proc. CD-ROM, June 6-9.

[2] Brdys, M.A. and Y. Zhang (2001a), *Robust Hierarchical Optimizing Control of Municipal Wastewater Treatment Plants*, Preprints of the 9th IFAC/IFORS/IMACS/IFIP Symposium Large Scale Systems: Theory & Applications, Bucharest, Romania, pp. 540-547, July 18-20.

[3] Brdys, M.A. and K. Konarczak (2001b), *Dissolved Oxygen Control for Activated Sludge Processes*, Preprints of the 9th IFAC/IFORS/IMACS/IFIP Symposium Large Scale Systems: Theory & Applications – LSS'2001, Bucharest, Romania, pp. 548-553, July 18-20.

[4] Henze, M. et al. (1987), Activated Sludge Model No. 1, *IAWQ Scientific and Technical Report No. 1*, IAWQ, London, Great Britain.

[5] Houpis, C.H., and S.J. Rasmussen (1999), *Quantitative Feedback Theory Fundamentals and Applications*, Marcel Dekker, Inc., New York.

[6] Ingildsen, P. (2002a), *Realizing Full-Scale Control in Wastewater Treatment Systems Using In Situ Nutrient Sensors*, Ph.D. thesis, Dept. of Industrial Electrical Engineering and Automation, Lund University, Sweden.

[7] Ingildsen, P., U. Jeppsson, and G. Olsson (2002b), Dissolved oxygen controller based on on-line measurements of ammonium combining feedforward and feedback, *Water Science and Technology*, **Vol. 45**, No. 4-5, pp. 453-460.

[8] Katebi, M.R., M.A. Johnson and J. Wilke (1999), *Control and Instrumentation for Wastewater Treatment Plant*, Springer-Verlag, London, ISBN 1-85233-054-6.

[9] King, R.E. and A. Stathaki (2004), *A multi-layer perceptron for the control of a wastewater treatment plant*, 12th Mediterranean Conference on Control and Automation - MED2004, Kusadasi, Turkey, Proc. CD-ROM, June 6-9.

[10] Larsson, T. and S. Skogestad (2000), Plantwide control – A review and a new design procedure, *Modelling, identification and Control*, **Vol. 21**, No. 4, pp. 209-240.

[11] Manesis, S. A., D. J. Sapidis and R. E. King (1998), Intelligent Control of Wastewater Treatment Plants, *Artificial Intelligence in Engineering*, **Vol. 12**, No. 3, pp. 275-281.

[12] Nejjari, F., C. BenYoussef, A. Benhammou and B. Dahhou (1996), *Procedures for state and parameter estimation of a biological wastewater treatment*, CESA'96 IMACS, Vol.1, pp. 238-243, Lille France , July 9-12.

[13] Nejjari, F., A. Benhammou, B. Dahhou and G. Roux (1999), Non-linear multivariable adaptive control of an activated sludge wastewater treatment process, *International Journal of Adaptive Control and Signal Processing*, **Vol. 13**, Issue 5, pp. 347-365.

[14] Olsson, G., (1985), *Control strategies for the activated sludge process*, Comprehensive Biotechnology, (M. Moo-Young (Ed)), Pergamon Press, pp. 1107-1119.

[15] Olsson, G., Newell, B (1999), *Wastewater Treatment Systems. Modelling, Diagnosis and Control*, IWA Publishing, London. pp. 742.

[16] Yagi, S., H. Kohara, Y. Nakamura and S. Shiba (2002), *Fuzzy Control of a Wastewater Treatment Plant for Nutrients Removal*, Proc. of the International Conf. on Artificial Intelligence in Engineering & Technology, Sabah, Malaysia, June 17-18.