LOWER - LEVEL CONTROLLER FOR HIERARCHICAL CONTROL OF DISSOLVED OXYGEN CONCENTRATION IN ACTIVATED SLUDGE PROCESSES

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Abstract: The paper addresses control design for an aeration system within a hierarchical structure for an integrated control of dissolved oxygen in the activated sludge processes. In the paper the hybrid predictive controller for the lower control level is developed and its performance is investigated based on real data records.

Keywords: air, biotechnology, dynamic systems, hierarchical control, integer programming, nonlinear systems, predictive control, waste treatment.

1. INTRODUCTION

The aeration is used in different operations at wastewater treatment plants (*WWTP*). The biological processes that are carried out at WWTP require that the dissolved oxygen (*DO*) concentration is sufficiently high to maintain microorganisms in an activated sludge. The *DO* concentrations in aerobic zones of the biological activated sludge reactor are considered as the most important control parameters. The biological processes (nitrification, denitrification) are dependent on the concentration of *DO* in the aerobic zones.

An aeration system is very complex, nonlinear, hybrid, time-varying and multivariable with strong interactions between the system components. The major objectives of aeration control are effective control of air delivery and oxygen transfer to minimize the associated cost. The control of *DO* concentrations in the aerobic zones is usually carried out using a simple feedback loops starting from the *DO* and pressure measurements. The control loop set points are typically fixed at the constant values.

During the last years control strategies for the *DO* concentrations have been investigated intensively. The DO control design was considered in (e.g., Olsson and Newell, 1999; Brdys and Diaz-Maiquez, 2002; Yoo, *et al.*, 2002; Sanchez and Katebi, 2003).

Usually, in papers describing *DO* control, the aeration system dynamics is neglected and the system is treated as an actuator with rate and magnitude constraints imposed on the airflow.

The *DO* tracking means in this paper jointly considering the biological reactor and the aeration system with the blower and valve controls as the control inputs and the *DO* concentrations as the control outputs. An overall controller is hierarchically structured into two levels in order to efficiently handle complicated hybrid nonlinear dynamics of the aeration system and complex dynamics of the biological reactor. The upper level controller (*ULC*) is synthesised as a nonlinear model predictive controller (*NMPC*) to produce the airflow demands as set points for the lower level controller (*LLC*). The *LLC* is synthesised as a hybrid model predictive controller to follow the prescribed set points by using valves and controls variables of the blowers.

Control of aeration system is very important and difficult activity in an overall control of *DO* in the activated sludge processes. In the paper the hybrid predictive controller at the lower level is derived. Blowers are the main elements in aeration system. In order to model limits on frequency of switching the blowers, the papers proposes hybrid mixed-integer formulation of the *LLC* optimisation problem. The overall hierarchical controller is validated by simulation using real data sets and activated sludge model 2d (*ASM2d*) of the biological reactor. Simulation tests for aeration system at Kartuzy *WWTP* in Poland are presented.

2. HIERARCHICAL DISSOLVED OXYGEN TRACKING AND AERATION CONTROL

The overall controller is validated by simulation using *ASM2d* model of the biological reactor that is illustrated in Fig. 1. This controller operates within multilevel-multilayer control structure (Brdys, *et. al.,* 2002b; Grochowski, *et. al.,* 2004). A structure of hierarchical *DO* tracking and aeration control is illustrated in Fig. 2.

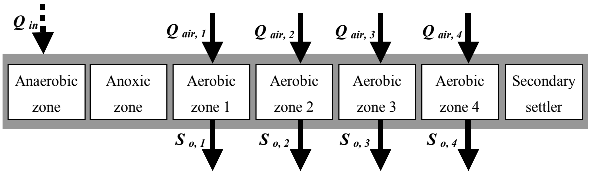

Fig.1. Structure of the biological reactor.

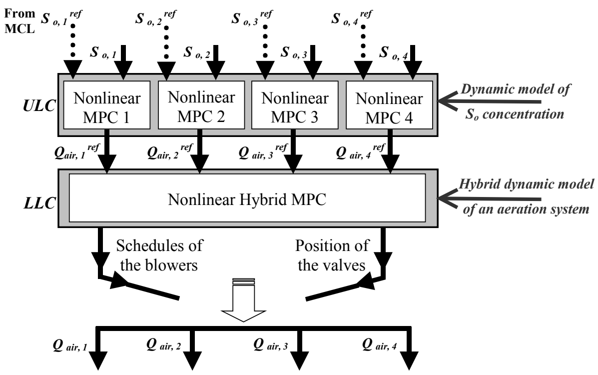

Fig. 2. Hierarchical structure of DO tracking and aeration control.

The robustly optimised *DO* trajectories $S_{o,j}^{ref}$ are prescribed by the medium control layer (*MCL*) (Brdys, *et. al.,* 2002b; Grochowski, *et. al.,* 2004) and they are to be followed by the *DO* controller. The airflows $Q_{air,j}(t)$ are used as the control inputs to the *ULC* in order to track a prescribed by the *MCL* trajectories $S_{o,j}^{ref}(t)$ of the *DO*. The *ULC* produces desired set points of the aeration flows $Q_{air,j}^{ref}$ to be provided by the *LLC.* Details of a completely decentralized *ULC* for Kartuzy *WWTP* are presented in (Brdys and Konarczak, 2001; Brdys, *et. al.,* 2002a). Details of a multivariable *ULC* for Kartuzy *WWTP* were presented by Piotrowski, *et. al.* (2004).

The aeration system is a complicated nonlinear dynamical system with fast dynamics. The model of the aeration system for Kartuzy *WWTP* includes blowers (fixed speed and variable speed), air distribution piping (pipes, throttling valves, diffusers) and measurement instrumentation (*DO* meters, pressure sensors and airflows devices). Details of aeration system modeling for Kartuzy *WWTP* are presented in (Brdys, *et. al.,* 2002a; Piotrowski, *et. al.,* 2002). New developments of this system are presented in (Piotrowski, *et. al.,* 2004).

The control problem at the *LLC* is to schedule the blowers, determine speeds of the blowers to be *on* and control the throttling valve openings by local regulators so that the airflow demand $Q_{air,j}^{ref}$ is met and at the same time the energy cost is minimised. In next section details of *LLC* modeling are presented. In order to model limits on frequency of blower switching a number additional constraints and additional binary valued variables will be introduced to describe evolution of the blower structure state in time. The hybrid mixed-integer formulation for control of blowers will be presented in subsection 3.2.

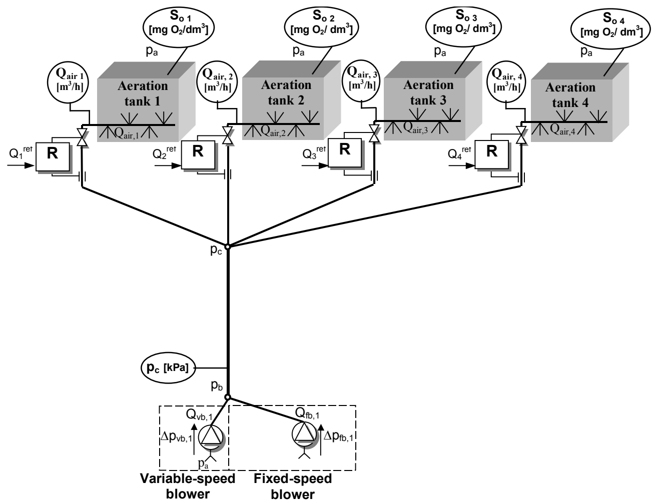

Fig. 3. Aeration system for Kartuzy *WWTP*.

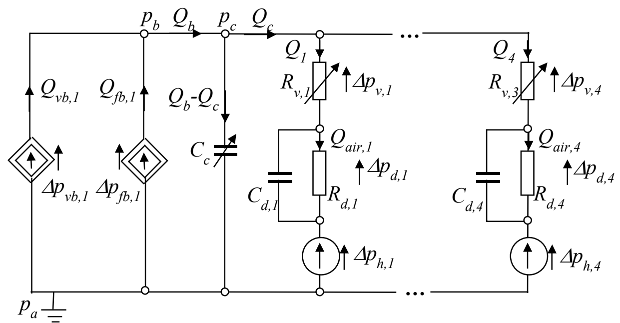

Fig. 4. The electrical analogy of aeration system for Kartuzy *WWTP*.

3. LOWER LEVEL CONTROLLER

3.1 Hybrid model predictive controller

The aeration system together with the biological reactors at Kartuzy is illustrated in Fig. 3. There are four aeration tanks fed by the segment unit flows

$Q_{air,j}$, $j \in \{1,2,3,4\}$. An electrical equivalent circuit for the aeration system is shown in Fig. 4. It is used to calculate the airflow rates based on the following model (Brdys, *et. al.,* 2002a; Piotrowski, *et. al.,* 2002):

$$\frac{dp_c}{dt} = \frac{p_c}{V_c}\left[\sum_{i\in\{1,2\}} Q_{b,i}\left(p_c, \boldsymbol{x}_b, \boldsymbol{n}_{fb}, \boldsymbol{n}_{vb}\right) - \sum_{j\in\{1,2,3,4\}} Q_j\right] \quad (1)$$

$$\frac{dQ_{air,j}}{dt} = \frac{1}{R_{d,j}\cdot C_{d,j}}\cdot\left(Q_j - Q_{air,j}\right); \quad j\in\{1,2,3,4\} \quad (2)$$

$$\begin{aligned} p_c = \Delta p_{d,j}^{open} + R_{d,j}\cdot Q_{air,j} + \Delta p_{v,j}\left(Q_j, \varphi_j\right) + \\ + \Delta p_{h,j} + p_a; \quad j\in\{1,2,3,4\} \end{aligned} \quad (3)$$

where: n_{vb}, n_{fb}, φ_j, p_c, $Q_{b,i}$, $Q_{air,j}$ $j\in\{1,2,3,4\}, i\in\{1,2\}$ are blower fixed speed, blower variable speed, angular valve position, pressure at the collector node blower flows, segment unit flows and, respectively. The binary variable $x_i = 1$ if the blower is *on* and $x_i = 0$ if the blower is *off*; $\boldsymbol{n}_{vb}$, $\boldsymbol{n}_{fb}$, $\boldsymbol{x}_b$, φ_j, $j\in\{1,2,3,4\}$ are control variables; p_c, $Q_{air,j}$, $j\in\{1,2,3,4\}$ are state variables being at the same time output variables.
In the steady state $Q_j = Q_{air,j}$ *for* $j\in\{1,2,3,4\}$ and $\frac{dp_c}{dt} = 0$. Hence, the steady-state model of (1)-(3) can be written as:

$$\sum_{i\in\{1,2\}} Q_{b,i}\left(p_c, \boldsymbol{x}_b, \boldsymbol{n}_{fb}, \boldsymbol{n}_{vb}\right) - \sum_{j\in\{1,2,3,4\}} Q_{air,j} = 0 \quad (4)$$

$$\begin{aligned} p_c = \Delta p_{d,j}^{open} + R_{d,j}\cdot Q_{air,j} + \Delta p_{v,j}\left(Q_{air,j}, \varphi_j\right) + \\ + \Delta p_{h,j} + p_a; \quad j\in\{1,2,3,4\} \end{aligned} \quad (5)$$

with additional constraints:

$$0 \le p_c \le p_c^{max} \quad (6)$$

$$Q_{air,j} \ge 0; \quad j\in\{1,2,3,4\} \quad (7)$$

$$\varphi_j^{min} \le \varphi_j \le \varphi_j^{max}; \quad j\in\{1,2,3,4\} \quad (8)$$

and

$$\begin{aligned} \boldsymbol{x}_b = \left[x_{fb,1}, x_{vb,1}\right]; \quad x_{fb,1}\in\{0,1\}; \quad x_{vb,1}\in\{0,1\} \\ \boldsymbol{n}_{fb} = n_{fb,1}; \quad \boldsymbol{n}_{vb} = n_{vb,1} \end{aligned} \quad (9)$$

The equations (5) and (4) constitute nonlinear implicit input – output model of the controlled aeration system. The implicit model will be introduced into an optimisation problem of the hybrid model predictive controller (*HMPC*) in a form of constraints. The optimised values of φ_j, $j\in\{1,2,3,4\}$ are forced in the aeration system by employing local regulators. Each local throttling valve regulator forces Q_j, $j\in\{1,2,3,4\}$ to reach optimised values of $Q_{air,j}$, $j\in\{1,2,3,4\}$ by automatically adjusting φ_j, $j\in\{1,2,3,4\}$. Let us notice that the constraints implied by the equations (5) can be also formulated as:

$$\begin{aligned} p_c = \Delta p_{d,j}^{open} + R_{d,j}\cdot Q_{air,j} + \Delta p_{v,j} + \\ + \Delta p_{h,j} + p_a; \quad j\in\{1,2,3,4\} \end{aligned} \quad (10)$$

and

$$\Delta p_{v,j}\left(Q_{air,j}^{max}, \varphi_j^{min}\right) \ge \Delta p_{v,j} \ge 0; \quad j\in\{1,2,3,4\} \quad (11)$$

An advantage of this formulation is that the constraint (5) is now linear. It is achieved by considering $\Delta p_{v,j}$, $j\in\{1,2,3,4\}$ as a decision variable and by adding the additional constraint (11). Dimension of the decision vector remains the same as the variable φ_j, $j\in\{1,2,3,4\}$ have now been dropped. The decision variables now are: $\boldsymbol{n}_v$, $\boldsymbol{n}_f$, $\boldsymbol{x}_b$ p_c, $Q_{air,j}$, $\Delta p_{v,j}$, $j\in\{1,2,3,4\}$. The additional constraint (8) is now omitted. However, the airflow constraint:

$$Q_{air,j} \le Q_{air,j}^{max}; \quad j\in\{1,2,3,4\} \quad (12)$$

needs to be added.

In summary, the constraints of the *HMPC* optimization problem formulated in the form (5) are as follows:

$$\sum_{i\in\{1,2\}} Q_{b,i}\left(p_c, \boldsymbol{x}_b, \boldsymbol{n}_{fb}, \boldsymbol{n}_{vb}\right) - \sum_{j\in\{1,2,3,4\}} Q_{air,j} = 0 \quad (13)$$

$$\begin{aligned} p_c = \Delta p_{d,j}^{open} + R_{d,j}\cdot Q_{air,j} + \Delta p_{v,j} + \\ + \Delta p_{h,j} + p_a; \quad j\in\{1,2,3,4\} \end{aligned} \quad (14)$$

$$\Delta p_{v,j}\left(Q_{air,j}^{max}, \varphi_j^{min}\right) \ge \Delta p_{v,j} \ge 0; \quad j\in\{1,2,3,4\} \quad (15)$$

$$0 \le p_c \le p_c^{max} \quad (16)$$

$$Q_{air,j} \ge 0; \quad j\in\{1,2,3,4\} \quad (17)$$

$$Q_{air,j} \le Q_{air,j}^{max}; \quad j\in\{1,2,3,4\} \quad (18)$$

$$\begin{aligned} \boldsymbol{x}_b = \left[x_{fb,1}, x_{vb,1}\right]; \quad x_{fb,1}\in\{0,1\}, \quad x_{vb,1}\in\{0,1\} \\ \boldsymbol{n}_{fb} = n_{fb,1} \\ \boldsymbol{n}_{vb} = n_{vb,1} \end{aligned} \quad (19)$$

The new formulation seems to be superior. However, in order to determine not conservative upper bound in the constraint (11) the nonconservative estimates of $Q_{air,j}^{max}$, $j\in\{1,2,3,4\}$ are needed.
The energy cost in steady state is proportional to the collector pressure p_c. Hence, the performance function is formulated as:

$$J = \sum_{k_l}^{H_p^l}\left[\alpha\cdot p_c(k_l) + \sum_{j\in\{1,2,3,4\}}\left|Q_{air,j}^{ref}(k_l - 1) - Q_{air,j}(k_l - 1)\right|\right] \quad (20)$$

The coefficient α reflects time varying electricity tariff and also incorporates a weighting factor in order to trade between the tracking accuracy and consumed energy cost. The second term in (20) represents the airflow tracking error. Introducing an additional variable z_j, $j\in\{1,2,3,4\}$ the second term can be replaced by the linear one and new linear constraints:

$$J=\sum_{k_l}^{H_p^l}\left[\alpha\cdot p_c(k_l)+\sum_{j\in\{1,2,3,4\}} z_j(k_l-1)\right] \qquad (21)$$
$$-z_j(k_l-1)\le Q_{air,j}^{ref}(k_l-1)-Q_{air,j}(k_l-1)\le z_j(k_l-1)$$

where: H_p^l denotes control horizon at the lower level and $k_l\in\{1,H_p^l\}$ are the lower level controller steps over H_p^l.

In order to convert constraint (5) into mixed integer linear (MINL) form the relationship $\Delta p_{v,j}(Q_{air,j},\varphi_j),\ j\in\{1,2,3,4\}$ should be first planewise linearised. Next, the planewise linear approximation of function $\Delta p_{v,j}(Q_{air,j},\varphi_j),\ j\in\{1,2,3,4\}$ is transformed into λ-form by introducing new binary values vector variable λ. The λ-form is linear in the augmented space (Brdys, *et. al.,* 2001). For each diffuser lower and upper bound on Q_{air}, $[Q_{air}^{min},Q_{air}^{max}]$, and φ, $[\varphi^{min},\varphi^{max}]$ can be determined. The details for Kartuzy *WWTP* are presented in (Piotrowski *et. al.*, 2002).

3.2 Hybrid mixed-integer formulation for blowers

For *MINLP* formulation of the optimization problem at the lower level the control variables x_b are defined for variable speed blower as follows:

$$x_{vb,1}(k_l)=\begin{cases}1 & if\ variable\ speed\ blower\ is\ on\\ 0 & if\ variable\ speed\ blower\ is\ off\end{cases} \qquad (22)$$

As over a selected step k_l a fixed speed blower can run with one speed only the sets:

$$\{\ x_{fb,1}^s(k_l);\ s\in I_s\ \} \qquad (23)$$

where: $x_{fb,1}^s=1$ if fixed speed blower runs on s – th gear, are of the *SOS1* type sets (Williams, 1994).

Applying to (4) the blower models for Kartuzy *WWTP* yields the equation (4) in *MINLP* form as:

$$\begin{gathered}Q_{vb,1}+\sum_{s\in\{1,2\}}Q_{fb,1}^s(k_l)-\sum_{j\in\{1,2,3,4\}}Q_{air,j}=0\\ Q_{vb,1}(k_l)=\{a_{vb,1}\cdot p_c(k_l)+b_{vb,1}\cdot n_{vb,1}+d_{vb,1}\}x_{vb,1}(k_l)\\ Q_{fb,1}(k_l)=\{a_{fb,1}^s\cdot p_c(k_l)+e_{fb,1}^s\}x_{fb,1}^s(k_l);\quad s\in\{1,2\}\\ Q_{vb,1}^{\min}\le Q_{vb,1}(k_l)\le Q_{vb,1}^{\max}\\ Q_{fb,1}^{s,min}\le Q_{fb,1}^s(k_l)\le Q_{fb,1}^{s,max}\\ \sum_{s\in\{1,2\}}x_{fb,1}^s(k_l)=1\end{gathered} \qquad (24)$$

where: $d_{vb,1}=c_{vb,1}-a_{vb,1}\cdot p_a$ and $e_{fb,1}^s=c_{fb,1}^s-a_{fb,1}^s\cdot p_a$.

In order to model limits on the blower switching frequency a number of additional constraints and binary valued variables need to be introduced in order to describe the blower structure state in time. First we shall introduce to the optimisation problem a condition that will imply that a switched off blower cannot be switched on earlier than after certain number of the sampling periods. Let N_s denotes number of forced standstill of the blower after it has been switched off expressed in terms of sampling period at the lower level k_l. Hence:

$$\begin{gathered}x_{b,i}(k_l)=0\Rightarrow x_{b,i}(k_l+1)=0\wedge x_{b,i}(k_l+2)=0\wedge ..\\ ...\wedge x_{b,i}(k_l+N_s-1)=0;\quad i\in\{1,2\}\end{gathered} \qquad (25)$$

The above is guaranteed by meeting the following constraints with binary valued variable that need to be added to the *LLC* optimisation problem:

$$\left.\begin{gathered}x_{b,i}(k_l)=x_{b,i}(k_l-1)-u_{b,i}^{off}(k_l)+u_{b,i}^{on}(k_l)\\ u_{b,i}^{off}(k_l)+u_{b,i}^{on}(k_l)\le 1\\ x_{b,i}(k_l-1)-u_{b,i}^{off}(k_l)\ge 0\\ x_{b,i}(k_l-1)+u_{b,i}^{on}(k_l)\le 1\end{gathered}\right\};\quad i\in\{1,2\} \qquad (26)$$

where: $u_{b,i}^{off}$, $u_{b,i}^{on}$ are switch *off* and *on* variables for i-th blower, respectively.

The first constraint in (26) represents dynamics of the i-th blower state. The second constraint excludes simultaneous switching *off* and *on* of a blower. The third constraint excludes switching *off* the blower that has been already switched *off*. Finally, the fourth constraint excludes switching *on* the blower that has been already switched *on*. Feasible operational states of a blower are illustrated in Table 1.

Let S_b denotes length of a continuous standstill of the blower and $S_b^{(0)}$ length of continuous stand still at the end of previous H_p period. The i-th blower switching limit can now be modelled as:

$$S_{b,i}(0)=S_{b,i}^{(o)};\quad i\in\{1,2\} \qquad (27)$$

$$\left.\begin{gathered}S_{b,i}(k_l)=(1-x_{b,i}(k_l))\cdot S_{b,i}(k_l-1)+(1-x_{b,i}(k_l))\\ (S_{b,i}(k_l-1)-N_s)\cdot u_{b,i}^{on}(k_l)\ge 0\end{gathered}\right.;\ i\in\{1,2\} \qquad (28)$$

The nonlinear term $u_b^{on}(k_l)\cdot S_b(k_l-1)$ in (28) can be linearised as (Williams, 1994):

$$\begin{gathered}S_{b,i}^{prod}(k_l)\overset{\Delta}{=}u_{b,i}^{on}(k_l)\cdot S_{b,i}(k_l-1)\\ S_{b,i}^{prod}(k_l)=S_{b,i}^{min}\cdot u_{b,i}^{on}(k_l)+y\\ -(S_{b,i}^{max}-S_{b,i}^{min})\cdot u_{b,i}^{on}(k_l)\le 0\qquad i\in\{1,2\}\\ y-S_{b,i}(k_l-1)\le -S_{b,i}^{min}\\ S_{b,i}(k_l-1)-y+(S_{b,i}^{max}-S_{b,i}^{min})\cdot u_{b,i}^{on}(k_l)\le S_{b,i}^{max}\\ y\ge 0\end{gathered} \qquad (29)$$

New variable S_b^{prod} replaces the nonlinear term $u_b^{on}(k_l)\cdot S_b(k_l-1)$ in (29). The nonlinear term $x_{b,i}(k_l)\cdot S_b(k_l-1)$ in (29) is handled in the same manner. Applying the same as above linearisation technique the constraints (24) can by transformed into MIL form. Hence, the *LLC* optimisation task is of the MIL type.

4. CASE STUDY SIMULATION RESULTS

Hierarchical *DO* tracking and aeration control results for Kartuzy *WWTP* will now be presented. The control system operation over 24 hours was simulated in Matlab 6.1 and Gams environment (Gams, 2005). One set of sampling rates was investigated: $T_u = T_l = 5$min. The prediction horizons H^l_p, H^u_p at the upper and lower levels were 10 steps. The optimisation task was solved by using *CPLEX* solver that is designed to solve large mixed integer programming problems (Gams, 2005). Two cases of forced standstill period for a two-speed blower were investigated: $t_{off} = 5$ minutes and $t_{off} = 20$ minutes and the results are illustrated in Figs. 4 -7 and in Figs. 8 - 11, respectively. The control schedules of fixed speed blower 1 are presented in Figs. 5 - 6 and in Fig. 9 - 10, respectively. It can be seen that from Figs. 4 and 8 that the controller performance does not significantly deteriorate if t_{off} increases. A wide speed range of the variable speed blower 1200-2900 r.p.m. (see Fig. 7 and Fig. 11) helps to follow the airflow rate trajectory determined by *UCL* with good accuracy (see Fig. 4 and Fig. 8). However, changes in t_{off} have noticable impact on operation of the variable speed blower, hence on operating cost, what is illustrated in Fig. 7 and Fig. 11.

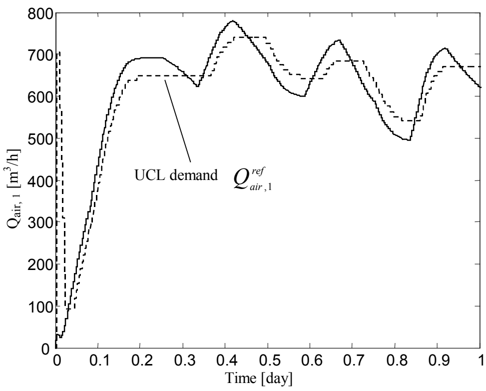

Fig. 4. Air flow comparison Q_{air1}: *UCL* demand $Q^{ref}_{air,1}$ and supplied, t_{off}= 5 min.

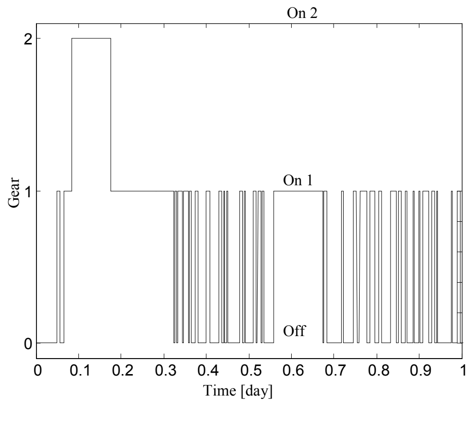

Fig. 5. Schedule of the fixed-speed blower, t_{off} = 5 min.

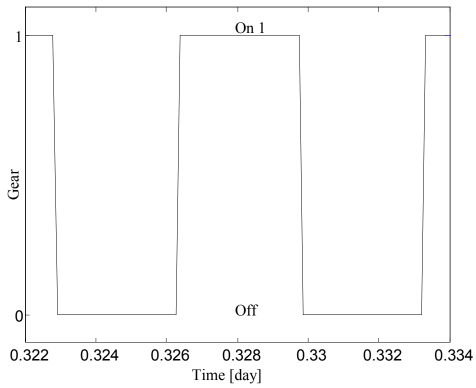

Fig. 6. Zoomed parts of the schedule, t_{off}= 5 min.

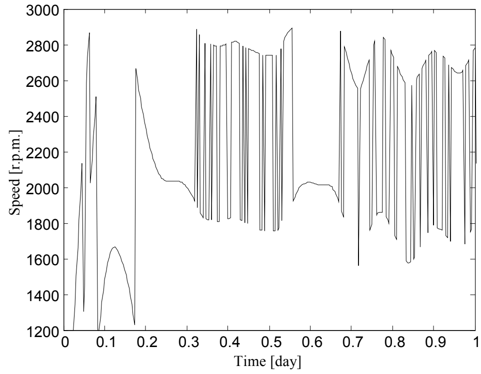

Fig. 7. Speed of the variable speed blower, t_{off} = 5 min.

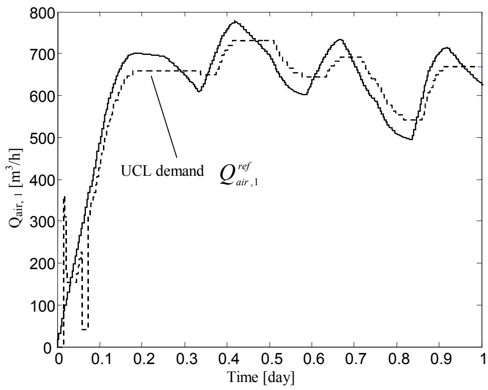

Fig. 8. Air flow comparison Q_{air1}: *UCL* demand $Q^{ref}_{air,1}$ and supplied, t_{off}= 20 min.

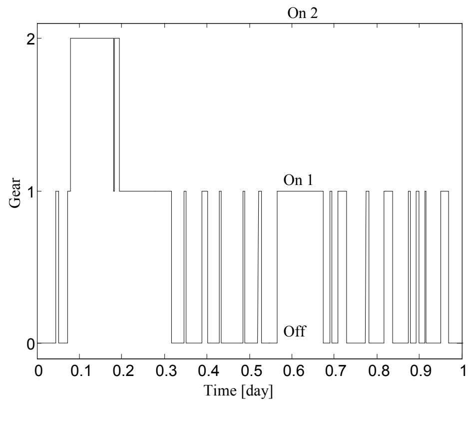

Fig. 9. Schedule of the fixed-speed blower, t_{off} = 20 min.

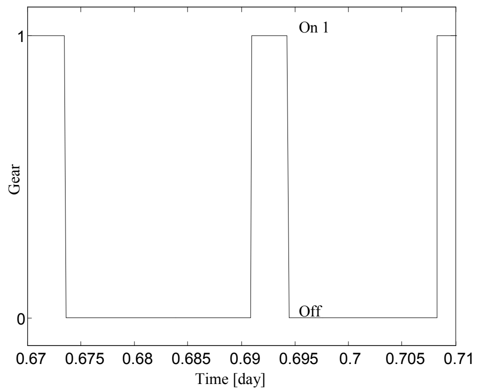

Fig. 10. Zoomed parts of the schedule, t_{off} = 20 min.

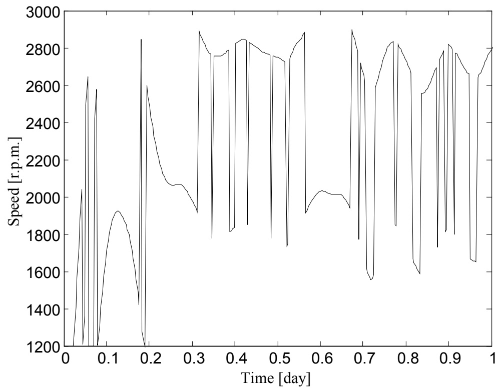

Fig. 11. Speed of the variable speed blower, t_{off} = 20 min.

5. CONCLUSIONS

The paper has addressed an important and difficult problem of control design for the aeration system within developed earlier hierarchical structure for an integrated control of dissolved oxygen in the activated sludge processes. In the paper the hybrid predictive controller for the lower control level has been designed and its performance has been investigated by simulation based on data records from *WWTP* at Kartuzy. Very promising results have been obtained.

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