Multiregional PI control strategy for dissolved oxygen and aeration system control at biological wastewater treatment plant

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Abstract

The dissolved oxygen is a key parameter for biological processes at wastewater treatment plant. The dissolved oxygen tracking problem is one of the most complex and fundamental issue of biological processes. The paper proposes a new multiregional control strategy for dissolved oxygen tracking problem. The aeration system is included in overall control structure. The control mechanism within the operating point area is based on PI controllers with the Takagi-Sugeno-Kang method of defuzzification. The proposed control strategy is designed and tested based on the real data records. It is applied to biological wastewater treatment plant at Nowy Dwor Gdanski, Northern Poland and is validated by simulation.

1. Introduction

The wastewater treatment plant (WWTP) is a complex, nonlinear biological-chemical-physical system with strong interactions between processes. Biological processes are difficult to control due to large disturbances such as inflow and load, nonlinearity, time-varying and complexity with strong coupling of the process variables.

The dissolved oxygen (DO) level in aerobic tanks has significant influence on behaviour and activity of the microorganism inhabiting a WWTP and is used in different operations at the WWTP (e.g. nitrification, denitrification, phosphorus removal). Moreover, on-line measurements of DO are among the most frequently performed ones at a WWTP. The DO concentrations in aerobic zones of the biological activated sludge reactor are considered as the most important control parameters. During the last years different control algorithms for the DO concentration have been designed intensively [e.g. 17, 1, 5, 8]. Other control strategies of DO control using N-NH$_4$, N-NO$_3$ and P-PO$_4$ measurements have also been investigated [e.g. 7, 16]. In all cases, the aeration system is neglected. In this paper an aeration system is combined with a biological processes for control strategy design.

The oxygen is delivered into the aerobic zones by the aeration system (blowers, pipes, throttling valves and diffusers). The aeration energy cost is very high (about 60% of the total WWTP electrical power consumption). Furthermore, it is essential to maintain the DO in a biological reactor at the right level. At least 0.5 O$_2$ mg/dm$^3$ is required for the nitrification processes to be carried out. An excessive DO concentration does not accelerate the nitrification but only increases the energy cost due to airflow pumping and may also affect of anoxic processes. Hence, DO control is very important for saving energy and improving biological processes efficiency.

The paper [11] propose biological reactor to be coupled with an aeration system and a two-level hierarchical controller in order to track prescribed DO trajectories. The upper level controller prescribes trajectories for airflows desired to be delivered into the aerobic biological reactor zones. The lower level controller forces the aeration system to follow those set point trajectories. In [2] derived a nonlinear hybrid predictive control algorithm for the lower level controller. Dedicated operators are used to derive genetic algorithms, thus allowing for efficient handling of the switching constraints and nonlinear hybrid system dynamics. The other researches have shown that for certain structures of WWTPs can be effectively controlled in a centralized structure (biological reactor with aeration system) [12]. Nonlinear model predictive controller of DO tracking and aeration system control is designed.

Advanced control methods (e.g. predictive control) often require large modification in the hardware-software structure at WWTP and long time training of the staff. In this paper multiregional PI control system is investigated and tested. The proposed controller is designed including off-line tuning the PI controllers. In opposite to previous paper [18] an aeration system is included for control system design. The DO tracking
means in this paper jointly considering the biological reactor and the aeration system with the blowers controls as the control inputs and the DO concentrations as the control outputs.

The paper is organised as follows. The biological processes at WWTP and aeration system are described and modelled in Section 2. Section 3 presents the multiregional PI control system design. The simulation results are described in Section 4. Finally, the conclusions are drawn.

2. Plant description and modelling

2.1. Biological processes at WWTP

A WWTP at Nowy Dwor Gdanski (NDG) is located in Northern Poland. It is a conventional plant with a continuous flow throughout the plant and mechanical-biological processes. In this paper a biological part and activated sludge method is considered (see Figure 1). Nitrification, denitrification and phosphorus removal processes are applied. The influent daily average flow rate (Q<sub>in</sub>) is 2250 m<sup>3</sup>/day. Average organic, nitrogen and phosphorus loads are: 1160 mg/dm<sup>3</sup> of chemical oxygen demand (COD), 49 mg/dm<sup>3</sup> of total nitrogen (TN) and 4.2 mg/dm<sup>3</sup> of total phosphorus (TP).

![Figure 1. Technological scheme of the biological WWTP.](image)

The first tank of biological part is predenitrification zone for sludge recirculated (152m<sup>3</sup>). Next there is an anaerobic tank (455m<sup>3</sup>) where phosphorus is released. Next, the processes are divided into two identical separable zones (anoxic tank – 1485m<sup>3</sup>, aerobic tank – 1622m<sup>3</sup> and secondary settler – 401m<sup>3</sup>). In the anoxic zone denitrification processes are conducted. In the aerobic zone nitrification processes are applied. This zone is aerated by aeration system. There are two identical, independent aeration systems and the first one is considered. The wastewater and activated sludge are separated into secondary settler. The activated sludge is internal recirculated from the aerobic tank to the anoxic zone. Furthermore, the sludge is recirculated from the secondary settler to the predenitrification tank. The excess waste sludge is stored and used for agricultural purposes. Based on measurements, the average values of the internal and external recirculations and the excess waste sludge are set to be: 3387 m<sup>3</sup>/day, 1913.7 m<sup>3</sup>/day and 258 m<sup>3</sup>/day, respectively.

Activated sludge models (ASMs) proposed by International Water Association task group are the most popular mathematical description of biological processes taking place at a WWTP. In this paper, the biological processes were modelled by using the ASM2d model [4]. This model consists of 18 nonlinear differential equations, 21 state variables and 20 kinetic and stoichiometric parameters. ASM2d model was calibrated based on real data sets from the case study plant. Also determined were values of all recirculations and values of inputs (disturbances): Q<sub>in</sub>, COD, TN and TP. Modelling results were verified with satisfying outcomes and next they were used for control purposes.

2.2. Aeration system

In literature [9] diffused aeration, mechanical aeration and high purity oxygen aeration methods are proposed and widely described. The first technique is applied at NDG WWTP. Oxygen is supplied to aerobic tanks by the aeration system. Two identical and independent aeration systems are installed at NDG WWTP (see Figure 1) and the first one is described and modelled in the paper. Scheme of the case study aeration system 1 is illustrated in Figure 2.

![Figure 2. Scheme of the aeration system.](image)

The first element of the aeration system is variable speed blower with speed controlled by inverter. A blower can run within the speed range of 1500-4800 rpm. Relationship between airflow through the blower, rotation speed and the pressure drop across the blower is nonlinear. A blower compresses air and it is sent then to the main pipe (diameter = 0.15m, length = 44m). Next, the airflow is divided among aerator segment unit: pipe (diameter = 0.15m, length = 12m) and diffuser system. The diffuser system is composed of 408 diffusers in parallel located inside aerobic tank at a level 3.9m. Membrane of disk type diffusers are applied at NDG WWTP. Diffusers are described by nonlinear relationship between airflow and pressure drop across.

The general methodology of aeration system modelling was presented in [11]. This approach was applied for modelling of different plants, e.g. Swarzewo aeration system [6], Kartuzy aeration system [11, 2].
A model of NDG aeration system was first presented in [12]. An aeration model was built based on theoretical knowledge, data records from case study plant and technical documentation of NDG aeration system elements. This paper presents only short description of this model.

Aeration system is modelled by treating the elements as equivalent to the electrical elements [11]. Airflow \( Q \) is an analog of the current while the pressure drop across \( \Delta p \) is equivalent to voltage in the circuit (see Figure 3) [12].

![Figure 3. Model of aeration system at NDG WWTP – electrical analogy.](image)

The blower is assumed to be a flow source and is modelled as the current source with nonlinear characteristic. For the control purposes this relationship is linearized based on real data sets and linear regression:

\[
\begin{align*}
Q_b & = -1.291 \cdot \Delta p_b + 0.323 \cdot n_b - 60.966 & (1a) \\
\Delta p_b & = p_b - p_a & (1b)
\end{align*}
\]

where \( Q_b, \Delta p_b, n_b, p_a \) are the blower output airflow, pressure drop across a blower, motor rotational speed and atmospheric pressure, respectively.

Connecting the blower to main pipe is modelled as fluid-flow nonlinear resistance \( R_c \):

\[
\Delta p_c = R_c \left( Q_b \right) \cdot Q_b = 2.59 \cdot e^{-7} \cdot Q_b^2
\]

where \( \Delta p_c \) is the pressure drop across the blower – main pipe connection.

The main pipe is treated as capacitor with nonlinear variable capacity \( C_c \):

\[
\begin{align*}
\frac{dp_c}{dt} & = \frac{1}{C_c} \cdot \left( Q_b - Q_c \right) & (3a) \\
C_c & = \frac{V_c}{p_c} ; \quad V_c = \frac{\pi \cdot d_c^2 \cdot l_c}{4} & (3b)
\end{align*}
\]

where \( p_c, Q_c, V_c, d_c=0.15m, l_c=44m \) are the pressure at the main pipe, main pipe airflow, main pipe volume, diameter and length, respectively.

Resistor \( R_e \) corresponds to the pipe resistance:

\[
\Delta p_e = R_e \left( Q_e \right) \cdot Q_e = 2.374 \cdot 10^{-7} \cdot Q_e^2
\]

where \( \Delta p_e \) is the pressure drop across of pipe.

Resistor \( R_d \) is the diffuser resistance and it is described by the nonlinear function between \( Q_{air} \) and \( \Delta p_d \). For control purposes this relationship is linearized based on linear regression:

\[
Q_{air} = \begin{cases} 
4.5432 \cdot n \cdot (\Delta p_d - \Delta p_d^{open}) & \text{for } \Delta p_d \geq \Delta p_d^{open} \\
0 & \text{otherwise}
\end{cases}
\]

where \( Q_{air}, n=408, \Delta p_d, \Delta p_d^{open}=2.25kPa \) are the airflow into aerobic zone, number of diffusers, pressure drop across at the diffusers and pressure drop across for open diffusers, respectively.

\( C_d \) and \( R_d \) describe diffusers capacity and resistance, respectively. Dynamics of the diffusers is described as:

\[
\begin{align*}
R_d \cdot C_d \cdot \frac{dQ_{air}}{dt} + Q_{air} & = Q_c & (6a) \\
C_d & = \frac{V_d}{p_c - p_d} ; \quad V_d = \pi \cdot d_d^2 \cdot l_d & (6b)
\end{align*}
\]

where \( V_d, p_d, d_d=0.15m, l_d=12m \) are the pipe volume, pressure at the pipe, pipe diameter and length, respectively.

Pressure balance over an open diffuser equals:

\[
\Delta p_h = \rho \cdot g \cdot h
\]

where \( \Delta p_h, \rho=1200kg/m^3, g=9.81m/s^2, h=3.9m \) are the hydrostatic pressure drop across, wastewater density, acceleration due to gravity and height of the diffusers into aerobic zone, respectively.

Simulation studies have shown that the dynamics of the aeration system is much larger than the dynamics of biological processes in the biological reactor. Therefore, it can be neglected and it is assumed as in the steady-state that \( dp_c/dt=0 \) and \( dQ_{air}/dt=0 \) (see equations (3a) and (6a)). Above model is applied for design of control system (see section 3).
3. Multiregional PI control system

As previously mentioned, the aeration process is strongly nonlinear. In this case, the use of a PID controller with fixed parameters, when changing the operating point will not provide the appropriate quality control. Therefore the multiregional, softly switched PI controller is applied. The coverage of whole operating area is ensured for every admissible value of reference set point \( S_a \) (DO). This requires the parameters tuning of the local PI controllers. The proposed controller is designed including off-line tuning PI controllers, entirely based on real data records. No on-line explicit controller parameters tuning is required. The mechanism that controls the current operating area is based on PI controllers with the Takagi-Sugeno-Kang (TSK) method of defuzzification [15].

The implementation of control system was made possible by the assumption that the dynamics of aeration system is much larger than the dynamics of biological processes. In the approach a steady-state nonlinear relationship between the control input \( n_b \) and controlled output \( S_a \) is employed (Figure 4).

![Figure 4. The static characteristic of DO at NDG WWTP.](image)

This allowed to find a relationship linking the ASM2d model with a model of aeration system. It is possible to find a direct nonlinear relation between blower rotational speed \( n_b \) and the airflow into the aerobic reactor \( Q_{\text{air}} \):

\[
n_b = \frac{Q_{\text{air}} - a \cdot \left( 2.59e^{-7} \cdot Q_{\text{air}}^2 + \Delta p_{\text{open}} + R_d \cdot Q_{\text{air}} \right)}{b} + \frac{-a \cdot \left( 2.374 \cdot 10^{-7} \cdot Q_g^2 + \rho \cdot g \cdot h + p_d \right) - c}{b}
\]

where \( a=-1.291, \ b=0.323, \ c=-60.966, \ Q_g \) are the parameters of the blower characteristic linearization and current airflow through the aeration segment unit, respectively.

The relation defining the dynamics of the \( S_a \) as the function of \( Q_{\text{air}} \) is given as [10]:

\[
dS_a(t) = k_{L,a}(Q_{\text{air}}(t)) \left( S_{\text{sat}} - S_a(t) \right) \frac{S_a(t)}{K_s + S_a(t)} \cdot R(t)
\]

where \( S_{\text{sat}}, \ k_{L,a}, \ Q_{\text{air}}, \ S_{\text{sat}} = 8.637 \ g \ O_2/m^3, \ K_s = 0.2 \ g/m^3, \ R \) denote DO concentration, oxygen transfer function, airflow, DO saturation concentration, Monod’s constant DO limit and respiration, respectively.

The function \( k_{L,a}(Q_{\text{air}}) \) describes the oxygen transfer and depends on the aeration actuating system and sludge conditions. Different approaches to modelling this function are presented in [10]. In this paper the linear model is applied:

\[
k_{L,a} = 0.00267 \cdot Q_{\text{air}}(t)
\]

Equations (9)-(11) allow to control the \( S_a \) directly by the \( n_b \). This is another very important advantage of the control plant that allows the adoption of the proposed control strategy. The implementation of multiregional PI controller requires the identification of its parameters in each operating area. As a first step (preliminary identification) the relay tuning method is used. It is the modification of Ziegler-Nichols method, proposed by [3]. It is based on the fact that limited amplitude oscillations are aroused in the system. For this purpose, the relay is used with parameters chosen experimentally (Figure 5).

![Figure 5. Preliminary identification of parameters of multiregional PI controller.](image)

As a result of simulation studies the relay parameters were determined as follows: on point 0.2, -0.2 off point, the signal value ‘0’ , 3900, the signal value ‘1’ in 2450. Subsequently based on these simulations tests were carried out to identify the relevant parameters of the controllers. The set point is giving a value corresponding to the point being considered work. It was decided to adopt the operating points of the range 0.5-2 [g O2/m3]. This allows for a uniform covering the static characteristic in a particular area of operation 1.5-2.2 [g O2/m3] and provide better quality control in the initial period of plant operation. Values obtained by this method provide only stability of control system. They are not in any way optimal and often require adjustments in order to provide additional satisfactory quality control. The final results of tuning are summarized in Table 1.
Table 1. Parameters of PI controllers

<table>
<thead>
<tr>
<th>Operating point ( S_o )</th>
<th>( K_p ) – identif.</th>
<th>( K_i ) – identif.</th>
<th>( K_p ) – tuning</th>
<th>( K_i ) – tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>5994.1</td>
<td>240</td>
<td>1.5*( K_p )</td>
<td>( K_i /1.1 )</td>
</tr>
<tr>
<td>1</td>
<td>6993.2</td>
<td>571.43</td>
<td>( K_p /6 )</td>
<td>( K_i *1.5 )</td>
</tr>
<tr>
<td>1.5</td>
<td>6993.2</td>
<td>300</td>
<td>( K_p *0.75 )</td>
<td>( K_i *0.7 )</td>
</tr>
<tr>
<td>2</td>
<td>6455.2</td>
<td>342.86</td>
<td>( K_p /4 )</td>
<td>( K_i /1.1 )</td>
</tr>
</tbody>
</table>

The next stage of this study was to design a fuzzy controllers and the adaptation of their parameters. The first step is to determine the shape and scope of fuzzy sets. The numeric space of fuzzy sets describes the \( S_o \) in the biological reactor. It was decided to choose a trapezoidal membership functions. They were created on the basis that the center is exactly the point of operation, the lower base has length 1 and the top 0.5. The exception is the last set, which goes back to its range value of 5. It is very important when taking into consideration the advantages of domain continuity of fuzzy sets in the entire operation area. List of fuzzy sets parameters is given in Table 2.

Table 2. List of fuzzy parameters

<table>
<thead>
<tr>
<th>Left lower point</th>
<th>Left upper point</th>
<th>Right upper point</th>
<th>Right lower point</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.75</td>
<td>1.25</td>
<td>1.5</td>
</tr>
<tr>
<td>1.25</td>
<td>1.75</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.5</td>
<td>2.25</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

In order to ensure appropriate control signal one should consider additive for each PI controller in the track reference speed of the output signal. It was adopted as 3150 [rpm], which is exactly half of the working range of the blower. A structure of new control system is presented in Figure 6.

Figure 6. Structure of DO tracking and aeration control.

Based on the current value of the \( S_o \), the region in which the system currently works is determined. It was made by defining the membership function values for \( S_o \). Four fuzzy sets divide operating area into sectors of about 0.5, 1, 1.5 and 2 [g O\(_2\)/m\(^3\)]. Each of these areas has its own regional PI controller. Based on the current value of the control error and the \( S_o \), the value of \( n_b \) is determined as a weighted average of output signals from each regional controllers:

\[
  n_b(t) = \frac{\sum_{i=1}^{4} w_i(S_o) \cdot n_{b,i}(t)}{\sum_{i=1}^{4} w_i(S_o)}
\]

where \( w_i(S_o) \) - weight depends on the \( S_o \); \( n_{b,i}(t) \) - value of the control signal for i-th PI controller.

The weights are on-line tuned according to the process state and have the degrees membership to each fuzzy set. As a result soft switching is achieved as a form of adaptation of the control system to the current working conditions. This implementation also allows for very rapid response to system disturbances (see section 4).

4. Simulation results

In this section the proposed control system (see section 3) was tested by simulation, based on real data records from the case study WWTP. The commercial simulation package Simba [13] was applied to modelling a biological processes at WWTP. The model of an aeration system was implemented in Matlab environment. Next, both models were coupled. Matlab package was applied to implementing nonlinear multiregional PI control strategy. The amount and composition of the influent wastewater to WWTP is varied during the day. Their variability is shown by four parameters (disturbances): \( Q_{in} \), COD, TN and TP (see Figures 7-10). Their values and variability correspond to the real values of the influent wastewater for NDG WWTP.

Figure 7. Inflow into WWTP.
In order to verify the efficiency of the proposed control system, the results are shown for two different reference trajectories of $S_o$. The range of changes was set at 1.5-2.2 g O₂/m³, which corresponds to the optimal conditions of aeration wastewater. In Figures 12 and 14 the set point $S_o^{ref}$ and DO tracking $S_o$ have been presented. Variable speed blower schedule have been shown in Figures 13 and 15.

A very important parameter disturbing the process of aeration is the respiration (Figure 11). It refers to the rate of oxygen consumption by bacteria as a result of biochemical reactions.
The control results are very good. It can be seen good tracking performance. The control error never exceeds value 5%. Moreover, the Root Mean Square (RMS) error value is 0.211 and 0.222 for trajectory 1 (see Figure 12) and trajectory 2 (see Figure 14), respectively. The obtained values of the control signal (see Figures 13 and 15) permit the physical implementation. They are set in range 1500-4800 rpm. Wide range of blower helps to accurately keep up for good tracking performance. Also the acceleration required from the actuators is small. Moreover, the blower works most of the time at the average speed. This represents a significant advantage in terms of their reliability and durability.

5. Conclusions

Control of dissolved oxygen at the wastewater treatment plant is important for economical and process reasons. The paper has addressed the tracking of a reference trajectory of dissolved oxygen concentration at wastewater treatment plant. The multiregional control strategy based on PI controllers with the Takagi-Sugeno-Kang method of defuzzification has been designed. The aeration system has been included in the overall controller design. The control system proposed was tested for case study wastewater treatment plant. The tracking performance of the overall control strategy have been investigated by simulation based on case study plant data records. Promising results have been obtained.

References


