

# Oxygen control in a wastewater treatment plant using adaptive predictive controllers

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**Abstract**—The article describes an implementation of a control system based on adaptive predictive (AP) controllers in control of dissolved oxygen in the pools of a wastewater treatment plant. Biological reactors are non-linear processes with relatively large time delays and time-varying dynamics and as such pose great difficulties to conventional controllers such as PID. The article also describes improvements in energy consumption reduction with the implemented control system.

## I. INTRODUCTION

In the last decades, numerous wastewater treatment plants have been installed in Europe and throughout the world. A typical wastewater treatment plant consists of a mechanical, biological and a chemical phase. This article addresses control of oxygen and energy optimisation in the reactors of the biological phase. A biological reactor is used for biological oxidation treatment of the wastewater with the help of microorganisms by injecting of air flow using air blowers.

Biological processes are very complex from the point of view of control. The controlled variables (dissolved oxygen) depend on a set of factors. On the one hand, such processes are multivariable and non-linear, on the other hand, their cause-effect relationship is time-varying and depending on factors such as temperature and water charge. As such, biological processes represent great problem for conventional controllers such as PID.

Another important issue is energy consumption. The motors of the air blowers have the power of various hundreds of kilowatts, depending on reactor capacity, and as such represent the biggest energy consumer in the plant. Consequently, beside a stable and precise control of dissolved oxygen, another objective of the control system is to optimise the energy consumption of the plant.

Considering the control problems described above, it is evident that for control of a biological reactor a controller is required that can predict process variables and not merely react to error as is the case in conventional controllers. At the same time, the controller has to detect changing process conditions and adapt to them by modifying its parameters. Furthermore, a complementary logic should be built to be in charge of searching an optimal operating point of the process.

This article describes a practical implementation of the

adaptive predictive expert control methodology in oxygen control in a wastewater treatment plant. In the following chapter the adaptive predictive control methodology is described. Further on, a description of the biological process is given. Next, a comparison of adaptive predictive control with PID control is made. Finally, the energy consumption issues are addressed and conclusions are drawn.

## II. ADAPTIVE PREDICTIVE CONTROLLERS

The modular diagram of the adaptive predictive controller is shown in Fig. 1. The first block is the *driver block*, which generates a desired trajectory for the process value, based on the setpoint and actual value of the setpoint. The desired trajectory has the following form:

$$y_d(k+j) = \sum_{i=1}^p \alpha_i y_d(k+j-i) + \sum_{i=1}^q \beta_i u(k+j-i) \quad (1)$$

$j = 1, 2, 3, \dots$

The desired trajectory is then fed to the *control block*, which contains a predictive model. The predictive model is a linear discrete model of the following form:

$$\hat{y}(k+j) = \sum_{i=1}^n a_i \hat{y}(k+j-i) + \sum_{i=1}^n b_i u(k+j-i) \quad (2)$$

$j = 1, 2, \dots, \lambda$

Where  $\lambda$  is the prediction horizon (number of control periods where the sequence of outputs can be predicted by the model). Using this model, the control block calculates the control variable that is supposed to drive the process (controlled) variable to the value defined by the desired trajectory by the end of the prediction horizon. The value of this control variable is applied to the process via actuators. The actual process variable is fed to the *adaptive mechanism* block, where it is compared to the value predicted by the control block and therewith the prediction error is calculated. Based on this error, the adaptive mechanism modifies the model parameters of the controller. The adaptive mechanism also changes the desired trajectory according to the new starting point.

Above there is the *expert block* whose functionality is defined by a set of rules that intervene in control variable when the process variable is far from the setpoint (outside the control domain).

The hardware and software platform for the adaptive predictive controllers are MS Windows with Labview environment. The connections to the process are realised via PLCs and an OPC server.

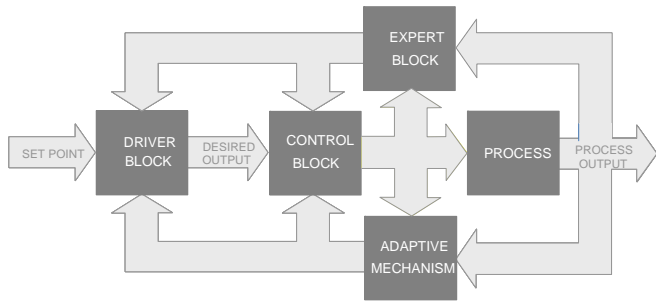


Fig. 1. Modular scheme of the adaptive predictive controller.

### III. DESCRIPTION OF THE BIOLOGICAL PROCESS AND CONTROL OBJECTIVES

#### A. The biological process

The biological process is schematically shown in Fig. 2. The process consists of 6 biological reactors (only 4 of them were in operation). An average flow of wastewater into each reactor is 500 m<sup>3</sup>/hour.

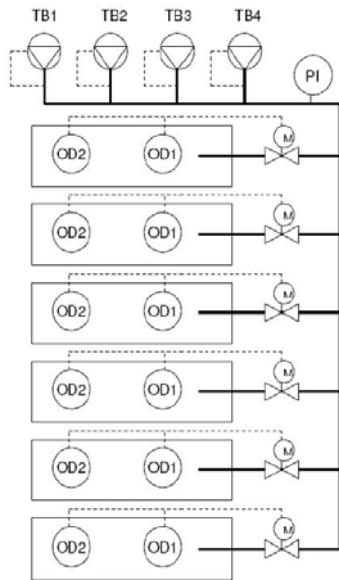


Fig. 2. Schematic representation of the biological reactors.

The air necessary for oxygenation in the reactors is produced by 4 blowers and delivered to the reactors through a common conduit. Each reactor has a corresponding automatic butterfly valve, which determines the quantity of air entering into the reactor. The air pressure (measured by the installed pressures sensor) in the common conduit is controlled by the blower diffusers. Each reactor is equipped with two dissolved oxygen sensors – one at the entrance

(OD1) and another one (OD2) at the exit. Furthermore, an air pressure sensor is installed in the common conduit.

#### B. Control issues

The following issues are associated to the control problematics:

- *Biological dynamics of the system:* It is experimentally known that there is a certain optimal oxygen level for the reproduction of the bacterial flora that eliminates water pollution. Because of different state of the bacterial flora and changing water pollution, the cause-effect relationship between injected air and dissolved oxygen is permanently changing.
- *Different working point of the process:* working conditions are constantly changing, mostly due to various inflows and pollution levels.
- *Lack of information about the state of the process:* the only information about the process variables usually are oxygen, flow and pressure measurements.
- *Interactive nature of the process:* the air to each of the 6 reactors is provided from a common conduit.
- Changes in valve openings in one reactor are reflected in changed flow in other reactors.

#### C. Control objectives

Considering the nature of the process and the available instrumentation, the following control objectives were defined:

- To maintain the oxygen level in each reactor at a constant level, defined by the operator in SCADA.
- To maintain an optimal level of air pressure in the common conduit that permits optimal oxygen control and at the same time minimises power consumption.

### IV. CONTROL STRATEGY IMPLEMENTATION AND COMPARISON OF RESULTS WITH PID

The control strategy implementation basically consists of two main modules: the first module comprises the oxygen control loops and the second module is the pressure setpoint optimisation logic that attempts to save energy by searching an optimal pressure setpoint.

#### A. Oxygen control

For each biological, an oxygen control loop with adaptive predictive controller has been implemented (Fig. 3). Besides the process value (dissolved oxygen in ppm) the loop takes into account the air flow as a measured perturbation.

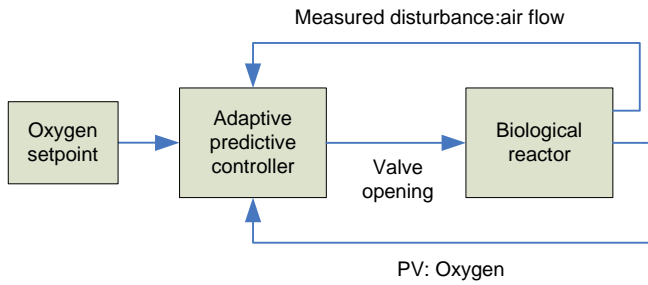


Fig. 3. Adaptive predictive control loop of oxygen.

### B. Pressure control

The pressure control is realised locally by a simple on/off controller. The control system described here sends setpoints to the local system. In order to reduce energy consumption, the pressure setpoint should be maintained as low as possible (without spoiling the oxygen control).

The following logic is used for pressure setpoint optimisation:

- *Increasing pressure.* When one of the butterfly valves exceeds a certain opening (75%), and at the same time the oxygen in the corresponding reactor is above the setpoint (setpoint+0.01), for a certain period of time (15 min), the pressure setpoint is incremented by a quantum (0.002 bar).
- *Decreasing pressure:* When one of the butterfly valves is maintained a certain opening (40%), and at the same time (15 min), the oxygen in the corresponding reactor is not considerably lower than the setpoint (setpoint-0.01), for a certain period of time, the pressure setpoint is incremented by a quantum (0.002 bar).

Summing up, the optimisation procedure seeks the lowest pressure setpoint, at which even in the least favoured reactor the control system manages to maintain the dissolved oxygen at a desired level (opening the corresponding valve to a maximal value).

In continuation, a comparison of results obtained by the previous (PID) controller and the adaptive predictive control system, is presented.

### C. PID oxygen control results

The plot in Fig. 4 shows the following signals during 24 hours of operation in reactor 2. The setpoint is represented by a red line, oxygen by a green line and the

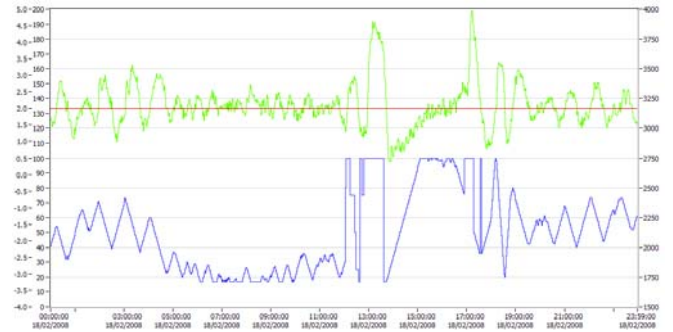


Fig. 4. PID control of reactor 2.

valve aperture by a blue line. We can observe that the PID does not manage to control the oxygen satisfactorily and in addition destabilises the rest of the reactors by introducing airflow oscillation by exaggerated valve actions.

### D. Adaptive predictive oxygen control results

The plot in Fig. 5 shows a day of operation of reactor 2 with adaptive predictive control of the oxygen. The sample time was 1s, control period 60s and prediction horizon 300s.

Comparing the response to the one shown in in Fig. 4, we can notice that the adaptive predictive controller significantly reduces the oxygen oscillations as well as the oscillations of the control variable (valve aperture). A deviation of the oxygen signal can be observed at around 7:25 pm, this drop of oxygen was caused by the stoppage of the air blower due to excess of temperature. After the blower had been restarted, the control system quickly recovered good control of oxygen.

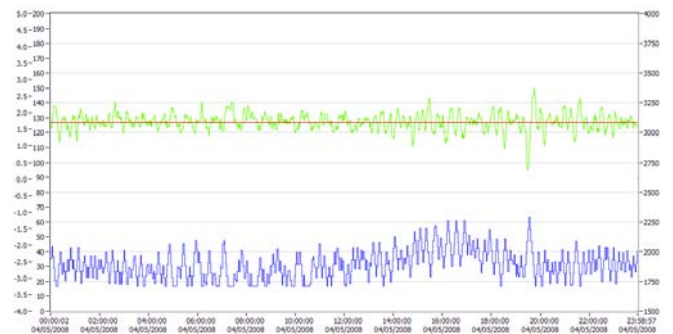


Fig. 5. Adaptive predictive control of reactor 2.

Fig. 6 shows an illustrative example of switching from AP control to PID control at around 8 am. It can be clearly seen that in the same conditions, the switch from AP to PID control significantly destabilizes the control of oxygen.

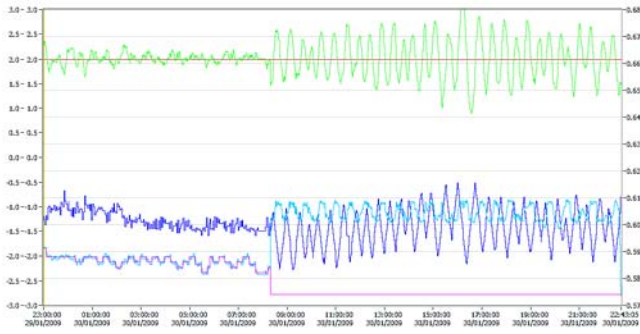


Fig. 6. Switch of control from AP to PID in reactor 2.

### E. Pressure setpoint optimisation results

The pressure optimisation strategy consists of maintaining the pressure at a minimal level that still permits satisfactory control of oxygen. Fig. 7 shows beside oxygen and valve aperture signal the signals of pressure setpoint (violet line) and pressure value (cyan line).

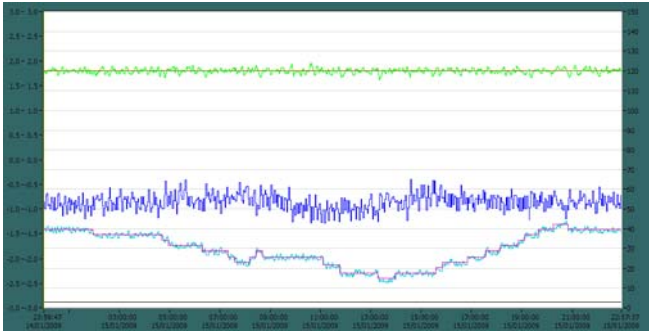


Fig. 7. Pressure setpoint optimisation – reactor 5.

We can observe in Fig. 7 that the pressure setpoint is decreasing during the first 13 hours of the day. Due to the low charge of the reactors, in all the reactors the oxygen is maintained close to the setpoints and in one or more reactors the valve is closed below a defined value. When the charge increases and in one reactor the oxygen starts to fall although the corresponding valve is maximally open (reactor 1, Fig. 8), the pressure optimisation logic starts to increment the pressure setpoint.

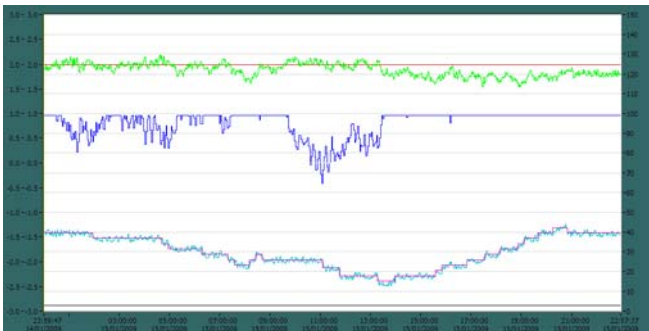


Fig. 8. Pressure setpoint optimisation – reactor 1.

## V. EVALUATION OF THE ADAPTIVE PREDICTIVE CONTROL RESULTS

To evaluate PID and AP oxygen control results, we calculated a standard deviation of the oxygen signals. The results are shown in Table 1. We can observe that in this regard the AP system introduced a significant improvement with factors between 2.13 and 6.05 in respective reactors.

### A. Oxygen control results

TABLE 1:  
STANDARD DEVIATION OF OXYGEN SIGNALS

Reactor	PID	AP	Factor
1	0.3974	0.1863	2.13
2	0.6632	0.2528	2.62
5	0.5221	0.1432	3.65
6	0.9138	0.151	6.05

### B. Energy consumption estimation

Energy consumption of the air blower motors represents a major part of the consumption of the plant (typically around 80%). For technical and economical reasons, in most of the cases it is difficult to measure the electrical consumption of the motors. An indirect method, using pressures and air-flows (available measured signals) was used.

In thermodynamics, a differential work performed by a gas is:

$$dW = p \cdot dV, \quad (3)$$

$p$  being the pressure,  $W$  mechanical work and  $V$  volume. Thus, the consumed power in each time instant can be calculated as:

$$P = \frac{dW}{dt} = p \cdot \frac{dV}{dt} = p \cdot \Phi_V \quad (4)$$

Where  $\Phi_V$  represents the air flow. The energy consumed in a time period can be obtained by integrating the power:

$$W(t_1) = \int_{t_0}^{t_1} p(t) \cdot \Phi_V(t) dt \quad (5)$$

By applying this method, we estimated the energy consumption in previous situation (PID control) and compared it to the estimated consumption of the system using adaptive predictive controllers and pressure optimisation logic. The comparison results are shown in Table 2.

TABLE 2:  
COMPARISON OF ESTIMATED CONSUMED POWERS

Reactor	PID consumption (kW)	AP consumption (kW)	Difference [%]
1	51.36	42.25	17.74
2	61.55	34.97	43.18
5	67.63	52.28	22.70
6	54.47	41.98	22.93
<b>Total</b>	235.01	171.489	<b>27.03</b>

We can see that better control of oxygen with adaptive predictive controllers combined with pressure setpoint optimisation significantly reduced the energy consumption (by more than 25 % in average). Taking into account the average energy price of 0.1 eur/kWh, an annual saving of about 55 000 was estimated.

## VI. CONCLUSIONS

Despite a very complex, time-varying and unknown process dynamics, the following results have been achieved using the adaptive predictive controllers:

- The system has stabilised the process variables at the setpoint values, eliminating the oscillations of the dissolved oxygen in the reactors, typical for the previous PID control system. One of the most direct and important consequences of a more precise and stable control of oxygen is improvement of water quality. Another consequence is an indirect influence on energy consumption reduction.
- The pressure setpoint optimisation module helped to reduce the energy consumption for up to 27%.

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