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Adaptive control of the oxidation ditch reactors in a wastewater treatment plant

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SUMMARY

This paper describes the application of adaptive predictive expert (ADEX) control methodology to the oxidation ditch reactor in the wastewater treatment plant of Ceutí (Murcia, Spain) and evaluates the performance of the ADEX control system against that of the previous control system operating the plant. After a basic description of ADEX control methodology, the ditch reactor is described, as well as the control objectives and the control strategy, which focused on energy consumption reduction. The results of the application of the ADEX control system show significant improvement compared with the previous control system in terms of higher stability and precision of controlled variables, reduction of energy consumption of the plant, and better quality of the effluent water. Copyright © 2012 John Wiley & Sons, Ltd.

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KEY WORDS: adaptive control; predictive control; expert systems; wastewater treatment; energy optimization

1. INTRODUCTION

The biological phase of a wastewater treatment plants (WWTPs) present significant process control challenges due to the multivariable, nonlinear, and time-varying nature of this kind of process, which in addition is generally submitted to stochastic and discontinuous perturbations [1]. Thus, optimization of the control system performance presents a great potential for improving the operation of WWTPs with respect to better effluent quality and energy savings.

Biological processes in WWTPs are therefore difficult to control efficiently with conventional PID-based control systems [2]. More advanced control approaches, also based on PID controllers and focussed on the dissolved oxygen control problem, have been presented in the literature. A gain scheduling PID control system is described in [3] and a parameter-scheduled proportional-integral (PI) control scheme is proposed in [4]. The performance of these solutions depend on the reliability of the plant model used to tune the control parameters and may deteriorate under plant dynamic changes.

Model predictive control solutions for the same kind of problem can be found in [5–9]. These solutions were only implemented and tested on simulation models or on pilot-size plant, and because of the time-varying nature of the biological process, also have the drawback of being fixed parameter solutions.

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This paper presents the application of adaptive predictive expert (ADEX)‡ control methodology [10, 11] to the biological phase of a waste water treatment plant in Ceutí, Murcia (Spain). ADEX controllers were applied within the context of a control and optimization strategy, designed to operate within the admissible range for the control variables and to optimize process performance. This strategy was particularly focused on the dissolved oxygen control to improve efficient quality and on reduction of energy consumption, because 52% of the total plant energy cost is consumed in the biological process. Section 2 of this paper introduces ADEX methodology, which is basically a new generation of adaptive predictive control (APC) [12]. The biological process is presented in Section 3 and the previous control system design and performance are described in Section 4. Section 5 describes the new control and optimization strategy, and Section 6 presents the experimental results obtained by the new control system and the details of its implementation. These results are discussed and compared with those of the previous control system in Section 7. Section 8 presents the conclusions.

2. ADEX METHODOLOGY & IMPLEMENTATION

2.1. Basic concepts

Adaptive predictive expert methodology integrates APC and expert control in order to provide a control solution able to apply expert control when required and APC when possible, thereby optimizing the global process operation. ADEX combines APC with expert control by defining domains of operation for each of them in an integrated setup. The evolution of process variables determines if APC or expert control should be applied to the process according to the corresponding domain of operation.

The adaptive predictive (AP) domains are those in which the dynamic cause-effect relationship between the input and output process variables can be identified in real time by means of a time-varying model driven by an adaptive mechanism. In these domains, APC can be applied, and the process operation is thus optimized.

Adaptive predictive expert enables the application of expert control in certain domains of operation where manual control can provide a more robust and efficient control than APC. Operator experience is used to develop the rules imitating manual control intelligence that will drive the process output from the expert domain towards the AP domains.

2.2. ADEX controller

The block diagram of an ADEX controller is presented in Figure 1. The expert block on the top of the figure identifies the domain of operation and determines the application of APC or expert control as briefly described in the following.

When an ADEX controller is operating in an AP domain, it uses the *driver block* to generate a desired trajectory that starts from the current process output value and has to reach the set point swiftly and without oscillations. One way of achieving this is by filtering the step from the current process output to the set point with a second-order model with critical damping and static gain equal to 1 such as:

$$y_d(k+j|k) = \sum_{i=1}^{2} \alpha_i y_d(k+j-i|k) + \sum_{i=1}^{2} \beta_i y_{sp}(k+j-i), \tag{1}$$

where $y_d(k+j|k)$ is the value at time $k+j$ of the desired output trajectory projected at time k, $y_{sp}(k+j-i)$ is the setpoint value at $k+j-i$, and the parameters α_i and β_i correspond to those of a second-order model. Being $y_d(k-i|k) = y_p(k-i)$ for all $i \geqslant 0$, where $y_p(k-i)$ is the process output at time $k-i$.

‡ADEX is a trademark of Adaptive Predictive Expert Control ADEX S.L.

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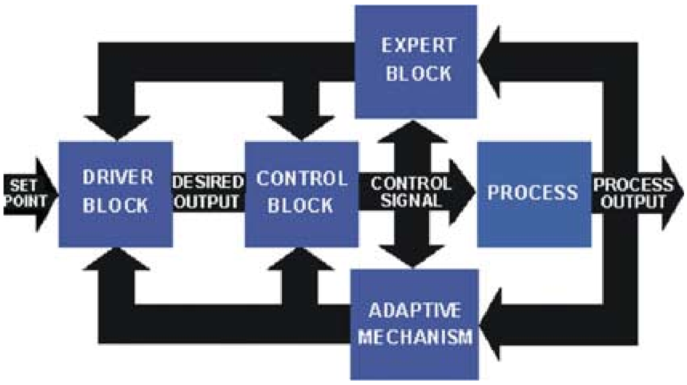

Figure 1. Adaptive predictive expert controller block diagram.

The desired trajectory is fed into the *control block*, which uses a discrete linear model to calculate the process inputs that are predicted to lead the process along the desired trajectory. The operation of the control block at every control instant k is illustrated, by way of a simple single-input single-output example, through the following sequence of operations:

(1) The process output $y_p(k)$ is measured, and the incremental process output $y(k)$ is calculated between two consecutive control instants

$$y(k) - y_p(k) - y_p(k-1) \tag{2}$$

(2) Considering a second-order AP model structure with no measurable disturbances, the computation of the a-priori estimate of the incremental process output $\hat{y}(k|k+1)$ is given by

$$\hat{y}(k|k-1) = \sum_{i=1}^{2} \hat{\alpha}_i(k-1)y(k-1) + \sum_{i=1}^{3} \hat{b}_i(k-1)u(k-1). \tag{3}$$

The AP model parameters $\hat{\alpha}_i(k-1)$ and $\hat{\beta}_i(k-1)$ estimate the process dynamics at time $k-1$ and the values $u(k-i)$ are incremental process inputs obtained by

$$u(k-i) = u_p(k-i) - u_p(k-1-i), \tag{4}$$

where $u_p(k-i)$ is the input applied to the process at the instant $k-i$.

The estimation error of the incremental process output is therefore

$$e(k) = y(k) - \hat{y}(k|k-1). \tag{5}$$

(3) The parameters of AP model (3) are calculated by an adaptive mechanism which is described later.

(4) The incremental control signal $u(k)$ is calculated to make the predicted increment of the process output at $k+1$ equal to the corresponding desired process output increment, $y_d(k+1|k) - y_p(k)$, by means of

$$u(k) = \frac{1}{\hat{b}_1(k)} \left[y_d(k+1|k) - y_p(k) - \sum_{i=1}^{2} \hat{\alpha}_i(k) y_(k+1-i) - \sum_{i=1}^{3} \hat{b}_i(k) u(k+1-i) \right]. \tag{6}$$

The incremental predictive control law (6) considered in this example uses a one-step-ahead control strategy, that is, the basic strategy of predictive control. The prediction horizon in this case is therefore equal to 1.

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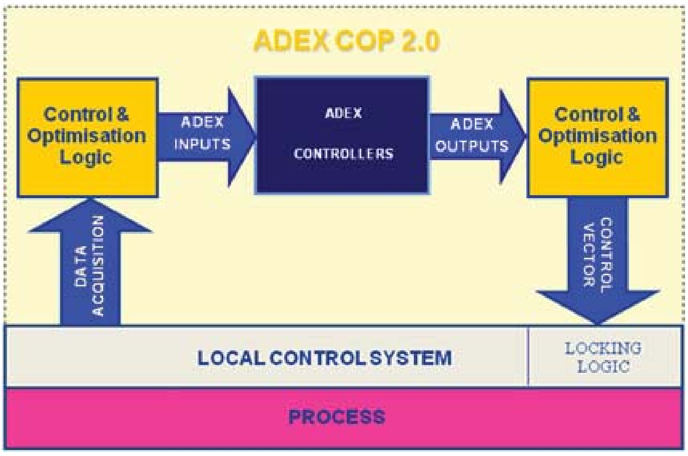

Figure 2. Functional diagram of adaptive predictive expert control optimization platform.

(5) The control signal $u_p(k)$ is computed by

$$u_p(k) = u(k) + u_p(k-1). \tag{7}$$

(6) Application of control constraints: the control signal can be limit-checked in an absolute and/or incremental manner.

The *adaptive mechanism* adjusts the model parameters using gradient parameter algorithms that minimize the prediction error (the difference between the real and the predicted process output) for each process output variable and thus adapts the controller to the changing process dynamics. Also, the adaptive mechanism triggers the driver block to recalculate the desired trajectory at each control instant, adapting it to the actual process output value.

When an ADEX controller is operating in an expert domain, the expert block will determine the application of expert control. The control block will then compute the control signal based on rules that imitate a human operator's intelligence, in a similar way to the well-known fuzzy logic/expert systems. The main control objective in this case is to drive the process output towards the AP domain.

2.3. *Implementation of the ADEX system*

The ADEX system considered in this paper was implemented using a **C**ontrol and **O**ptimization **P**latform called ADEX COP [11, 13], a Windows-[§] based application which was linked to the local programmable logic controller (PLC) via OLE for process control (OPC). A functional diagram of ADEX COP is represented in Figure 2.

Adaptive predictive expert control optimization platform enables the design and execution of control and optimization schemes (COS) that integrate ADEX controllers. The platform is designed to operate in parallel to the local control system, virtually without having to modify the local control logic.

The operation of the ADEX system implemented in the ADEX COP platform included the following steps at each control instant

- Acquisition of the relevant variables for the ADEX system operation from the local control system via OPC.
- From these variables, the COS of the ADEX system are executed to calculate the control variables to be applied to the process without having to modify the logic of the local control system.

[§]Windows is a trademark of Microsoft Corporation.

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- Finally, the calculated control variables are sent via OPC to the local control system which was prepared to send these control signals to the process. In the event of a communication failure in OPC, a locking logic would revert to the locally generated control signal thereby ensuring total integrity in the process.

In this way, the ADEX system applied to the WWTP was independent of the local system and the modification mentioned previously (the locking logic) was minor.

3. PROCESS DESCRIPTION

Figure 3 represents the biological process of the WWTP of Ceutí, designed for a wastewater flow of 8000 m^3/day. This process consists of two oxidation ditch reactors working in parallel, where the incoming wastewater joins a flow of water under treatment that moves in a circular motion in each reactor. This flow of water is submitted to a cyclic operation, including two consecutive phases: *nitrification* and *denitrification*.

3.1. Nitrification

Nitrification is the process by which the ammonium ($NH4^+$) is transformed into nitrate ($NO3^-$) by the action of nitrifying autotrophic bacteria. A first group of oxidizing bacteria generate $NO2^-$ (Nitrosomomas) and a second group generate $NO3^-$ (Nitrobacter).

$$\text{Norganic} + \text{H2O} \rightarrow \text{NH4}^+ + \text{OH}^-\text{(Hydrolysis)}$$
$$\text{NH4}^+ + 1.5\text{O2} \rightarrow 2\text{H}^+ + \text{H2O} + \text{NO2}^- + \text{Energy (Nitrosomomas)}$$
$$\text{NO2}^- + 0.5\text{O2} \rightarrow \text{NO3}^- + \text{Energy (Nitrobacter)}$$

For the nitrification to take place, oxygen must be fed into the reactor because oxygen supply is a limiting factor for nitrification; this is done by injecting compressed air through a common collector which is split, in this case, into two tubes, each leading to a separate reactor, as shown in Figure 3. The air is injected into the reactors through a grid of membrane diffusers. Each reactor has an automatic gate valve used for controlling the incoming air flow rate and is equipped with a dissolved oxygen sensor and a redox potential sensor. Four blowers are ready to generate the compressed air feeding into the common collector. Two of them are of on-off type, and two are equipped with frequency converters that can regulate the power.

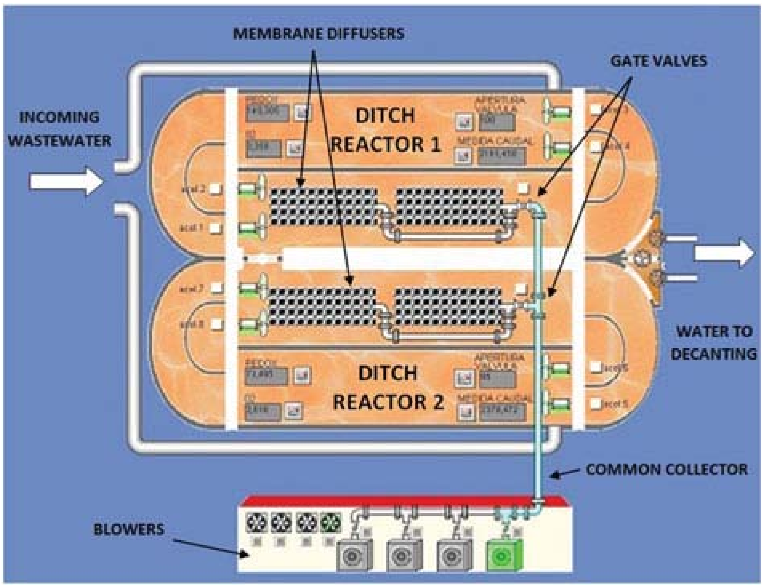

Figure 3. Biological ditch reactors of the wastewater treatment plant.

3.2. Denitrification

Denitrification is the process through which nitrogen enters the atmosphere from the water. It can formally be defined as the microbiological reduction of nitrates and/or nitrite to molecular nitrogen. However, a more extended and colloquial definition considers denitrification as a breathing process present in a limited type of bacteria.

This process varies in time and/or space, depending on the oxygen concentration and the presence of nitrates and organic matter.

The kind of bacteria responsible for denitrification are facultative anaerobes. More explicitly, these bacteria are: autotrophs bacteria (Micrococcus and Thiobacillus denitricans denitricans) and heterotrophic bacteria (Pseudomonas and Bacillus). These bacteria use oxidative metabolism using nitrate as an electron acceptor when the presence of dissolved oxygen is limited.

$$2\,NO_3^- + H_2O \rightarrow N_2 + 2.5O_2 + 2\,OH^-$$

In order that the biological reactor can denitrify in a correct way, the blowers must therefore be switched off during this whole phase.

3.3. Redox potential

The redox potential measures the ability to accept or donate electrons of the biological reactor, that is, the oxidizing or reducing capability of the biological reactor [14, 15].

One of the most relevant factors that determine the redox potential of the biological reactor (although not the only one) is the oxygen (O_2) concentration. In fact, the changes in the ammonium ion (NH_4^+) to oxidized stages (nitrates and nitrites) require aerobic microorganisms, which in turn require the oxidizing environment to grow and develop their oxidative metabolism or breathing. On the other hand, the opposite occurs when nitrate and nitrite transform into molecular nitrogen, requiring facultative anaerobic organisms in environments lacking oxygen (anoxic or anaerobic environment). In fact, the oxidative metabolism of such bacteria breathe at the expense of the nitrates and nitrites present in the reactor and are responsible for their reduction to molecular nitrogen.

In order to measure the redox potential, two electrodes are used: (1) an indicator electrode of a noble metal (gold, platinum), which has the capacity to receive or deliver electrons and (2) an inert electrode for reference. If there are oxidizing or reducing substances between the two electrodes, an electric potential between these electrodes will be produced. This electric potential enables the redox potential to be measured.

4. PREVIOUS CONTROL SYSTEM OPERATION

The operation of the process under the previous control system was as follows. Because the wastewater flow rate is currently 3000 m^3/day, only one blower is in operation. When the process was in the nitrification phase, the blower was switched on and running at full speed. The gate valve of the first reactor was constantly open at 100%, whereas the gate valve of the second reactor was open at 80% trying to compensate the different dynamic behavior of the reactors.

When the redox potential of one of the reactors exceeded an upper limit, R_{max}, the blower was turned off and the process was passed to the denitrification phase. When in this phase, the redox potential of one of the reactors fell below a lower limit, R_{min}, the denitrification phase was considered to be finished, and the blower was started again to begin the nitrification phase.

Figure 4 shows 8 h of operation of both reactors under the previous control system of the plant.

The upper plot of Figure 4 shows the trend curves and operation limits of the redox variable in both reactors. The upper limit redox value R_{max} was set equal to 140 mV, whereas the lower limit was set at -140 mV. The lower plot of Figure 4 shows the evolution of the dissolved oxygen (DO) concentration. It can be observed that the DO during the nitrification phases exceeds 3 mg/L, which was probably higher than the value required for the necessary redox increase. This would imply that far too much air was injected into the reactors, and energy for air compression was unnecessarily wasted.

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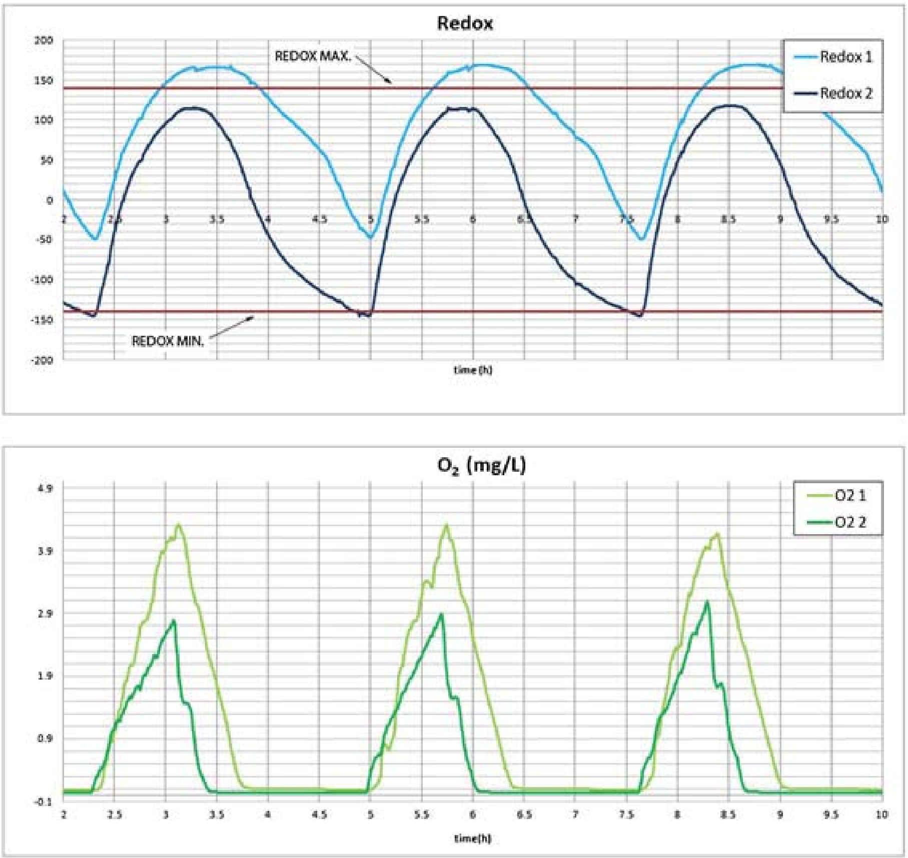

Figure 4. Previous control system operation.

The main goal of the new control system has been to maintain or improve the quality of the treated water at the same time as energy consumed in aeration is minimized.

5. NEW CONTROL STRATEGY

5.1. Fundamentals

In order to improve reactor performance, the following points had to be explored and taken into account in the control strategy of the new system:

(1) the most appropriate setting of the upper and lower redox limits,
(2) the level most suitable for the DO during the nitrification phase, and
(3) the air pressure in the common collector.

The control strategy finally defined was generic and can be applied in any oxidation ditch system with an arbitrary number of reactors. It includes discrete logic to determine the transitions between the nitrification and denitrification phases. The nitrification phase uses ADEX controllers to maintain a desired DO level in the reactors by controlling the air flow rate. Also, the air pressure is controlled in order to enable stable DO control at the same time that energy consumption is minimized. This control strategy had to operate using the instrumentation installed in the plant as explained in the following sections.

5.2. *Nitrification–denitrification logic*

The transition between the nitrification and denitrification phases is determined, as in the previous control system operating the plant, by the redox potential variable. However, in this case, a lower limit $R_{min}(i)$ and an upper limit $R_{max}(i)$ were set for each reactor i, taking into account their particular dynamic behaviors. During the nitrification phase, when the redox potential of one of the reactors exceeds its upper limit, the control system initiates the denitrification phase by cutting off the air supply (switching off the blowers) to the reactor and opening the gate valves 100% in anticipation of the next nitrification period. This is to avoid starting the blowers with the valves closed, which would damage the installation.

On the other hand, during the denitrification phase, when the redox potential of one of the reactors goes below its lower limit, the control system initiates the nitrification phase. The blowers are switched on and the gate valves open to begin controlling the DO at the desired level in each reactor, as explained in the following.

The nitrification time is limited with a maximum value t_{NitMax} in order to prevent an excessive accumulation of nitrates. In a similar way, the denitrification time is limited with a maximum value $t_{DenitMax}$ to prevent excessive accumulation of ammonia. Moreover, minimum nitrification and denitrification times (t_{NitMin} and $t_{DenitMin}$) are set to avoid the nitrification and denitrification periods being too short, resulting in the blowers starting and stopping with excessive frequency.

5.3. *Dissolved oxygen control strategy*

Dissolved oxygen concentration is a key variable in the activated sludge process [16]. The DO concentration is controlled by compressed air injected into the reactors. As mentioned before, generation of compressed air represents a significant share of the energy consumed in a WWTP. The main task of the control system is to find a good balance between the biological needs of the process and economy [17]. The DO concentration has to be sufficiently high so that the growth of heterotrophic and autotrophic organisms is not limited due to lack of oxygen, and the redox potential increases in a desired manner. On the other hand, the DO has to be sufficiently low to save energy.

Figure 5 shows the control scheme for the DO in each reactor during the nitrification phase. An ADEX controller manipulates the gate valve opening, which determines the compressed air flow into the reactor. The setpoint signal for the DO is generated by a block that makes it follow a ramp until it reaches a maximum value. The ramp slope and the maximum value are set experimentally by the operator.

The time-varying and nonlinear dynamic nature of the DO process, the high interaction between the different reactors and limits on the instrumentation, such as the 15% minimum opening of the gate valves, makes it a difficult process to control, as will be discussed in Section 6.

5.4. *Pressure control strategy*

The air flow entering each reactor depends on the gate valve opening and on the air pressure in the common collector. The control actions (closing and opening of the gate valve) of a DO control loop

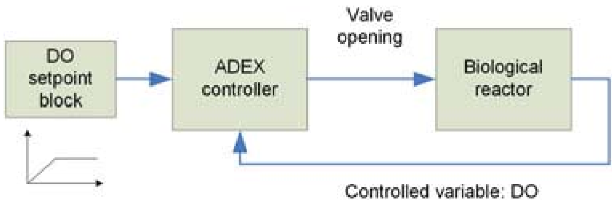

Figure 5. Dissolved oxygen control scheme.

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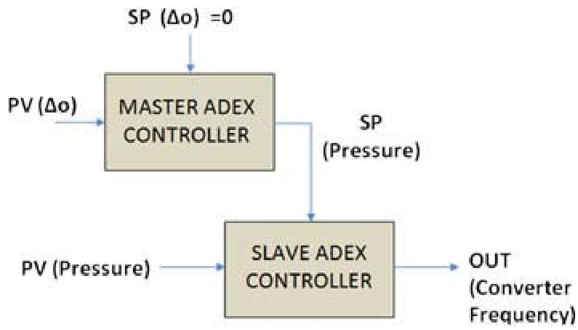

Figure 6. Air pressure cascade control strategy.

change the pressure drop across the gate valve and consequently, the air pressure in the common collector. This disturbs the air flow and so the DO control loop of the other reactor. For this reason, it would be desirable to control the air pressure in the common collector maintaining it at a constant value.

For pressure control, an ADEX controller has been applied using the frequency of a frequency converter for the blower as the manipulated variable. The goal of the optimization system is to find a balance between the energy consumption and providing sufficient air flow for oxygenation. The power consumed by a blower is defined, at each sampling instant k, by the following equation:

$$P(k) = \frac{p(k)q(k)}{\eta}, \tag{8}$$

where $P(k)$ is the power, $q(k)$ is the air flow, $p(k)$ is the pressure, and η is the efficiency of the blower. Furthermore, for each reactor (i), the flow $q_i(k)$, valve opening $o_i(k)$, and pressure drop across the valve are connected by the following relation:

$$q_i(k) = f(o_i(k))\sqrt{\Delta p(k)}. \tag{9}$$

Because f is a monotonically increasing function, in order to minimize the pressure drop at a certain air flow rate and thereby minimize consumption, it is beneficial to open the valve as much as possible. Thus, the pressure control strategy tried to find an air pressure setpoint that compelled the DO loops to maintain the valves around a certain desirable opening a.

Figure 6 shows the cascade control scheme used for the air pressure control. The process variable (PV) to be controlled by the master controller was conveniently defined by

$$\Delta o(k) = (o_{mean}(k) - o_{meand})|o_{mean}(k) - o_{meand}|/1000. \tag{10}$$

The $o_{mean}(k)$ represents the mean of the gate valve openings of both reactors. The setpoint of the master controller is zero to make the $o_{mean}(k)$ variable equal to the desired opening o_{meand}. The control action of the master controller is the air pressure set point for the slave controller. The control action of the slave controller manipulates the frequency of the blower frequency converter.

However, it is important to mention that the frequency range of the blower frequency converter had a maximum value of 50 Hz and a minimum of 35 Hz. The small range of the frequency control signal limited the performance of the air pressure control strategy, as discussed in the following sections.

6. EXPERIMENTAL RESULTS

In this section, the experimental results obtained by the operation of the ADEX system are presented. Figure 7 shows 8 h of operation of the new system in similar operating conditions to those of Figure 4.

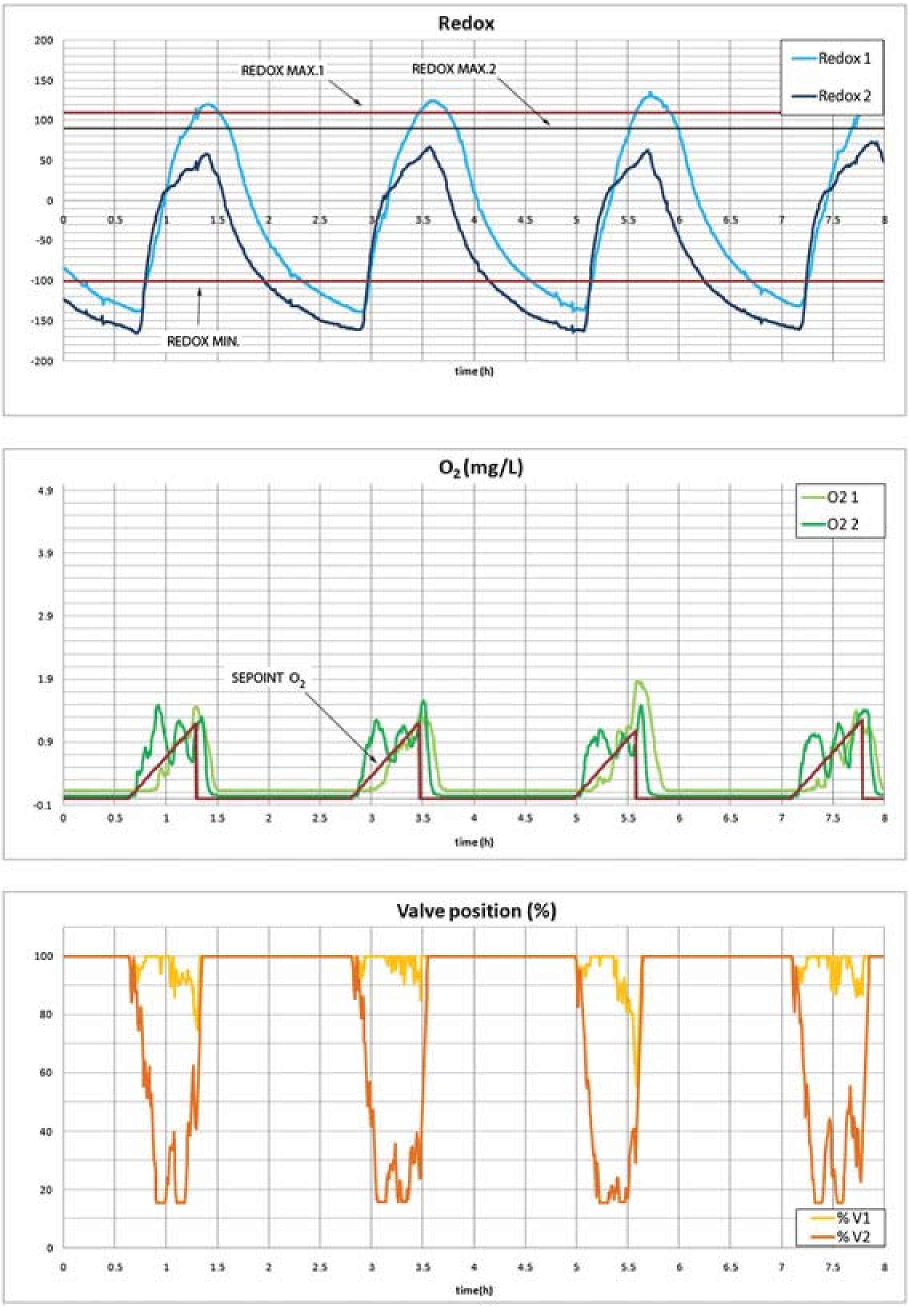

Figure 7. Dissolved oxygen control and redox evolution under new control system.

It can be observed in Figure 7 that the lower redox limit for both reactors was set in this case equal to −100, whereas the upper redox limits were set to 110 and 90 for the first and second reactors, respectively, taking into account the different biological dynamics of each reactor. The nitrification period is limited to a range between 10 and 200 min, and the denitrification period is limited to a range between 90 and 200 min. The desired mean valves o_{mean} is 80%. During the nitrification phase, the oxygen concentration set point increases with a slope of 1.83 mg/L per hour, but this set point has a maximum value of 1.5 mg/L. These values were set experimentally based upon satisfactory plant operation. As previously mentioned, the frequency converter of the blowers was limited to a range between 35 and 50 Hz and the operation of the gate valves to a range between 15% and 100%.

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As in Figure 4, the upper plot of Figure 7 shows the trend curves and operational limits of the redox in both reactors; the middle plot shows the evolution of the DO in both reactors and the common set point. The third plot shows the gate valve openings.

The ADEX controllers used during the nitrification phase to control the DO in the biological reactors, operated in an AP domain, and their sequence of calculations was basically that described in Section 2.2. These were single-input single-output controllers with a control period of 15 s and an AP model described by Equation (3), that is, two $\hat{\alpha}_i(k)$ and three $\hat{b}_i(k)$ parameters. The driver block dynamics were consistent with those of a second-order model with damping ratio equal to one and time constant equal to one control period. The performance of these controllers is illustrated by the results presented in Figures 7 and 8 and discussed in the next section.

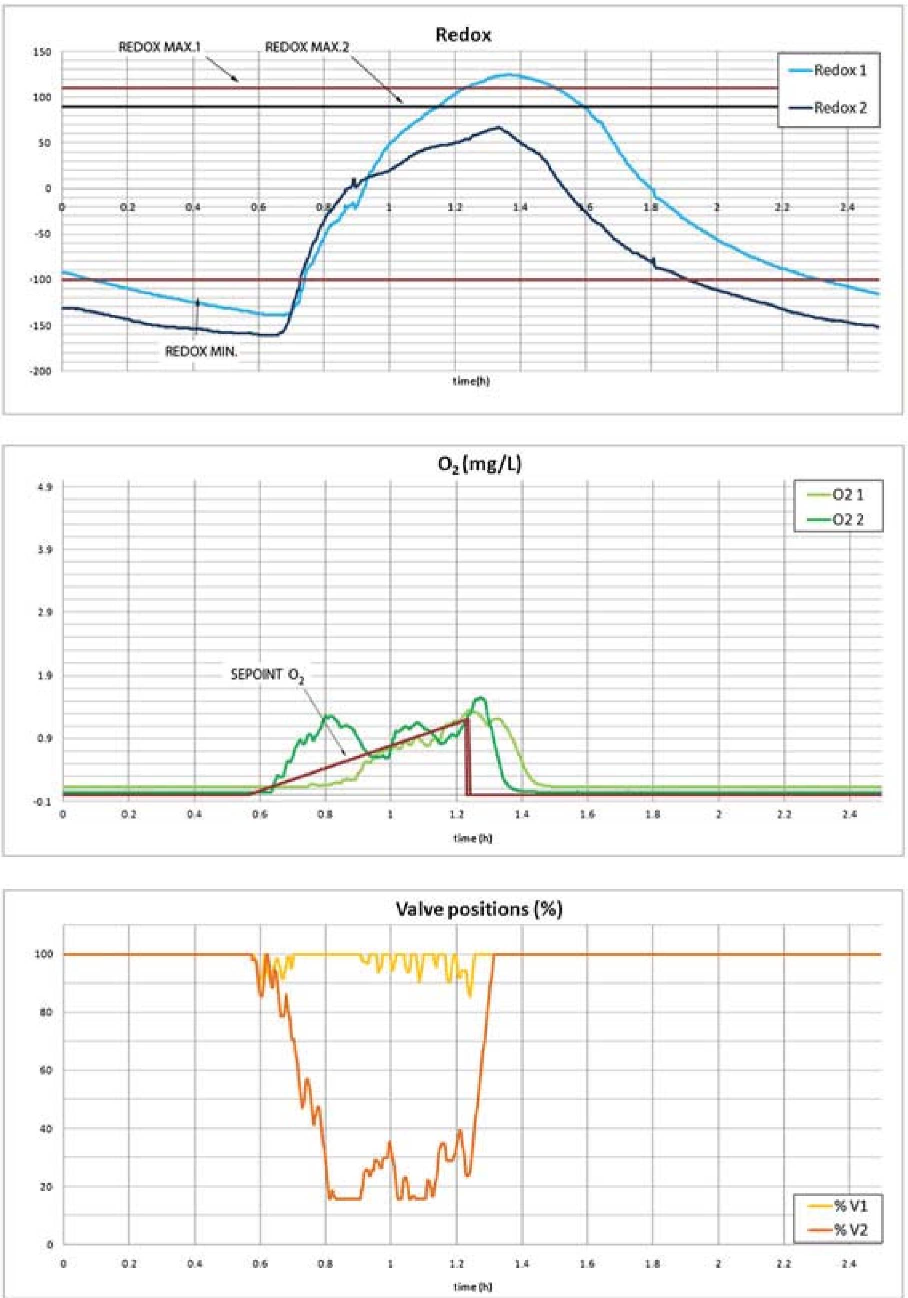

Figure 8. Dissolved oxygen control redox evolution during one nitrification/denitrification cycle.

The dynamics in one nitrification/denitrification cycle is shown in more detail in Figures 8 and 9.

The upper plot of Figure 9 shows the trend curves of the mean position deviation variable Δo and its set point; the second plot shows the pressure in the common collector and its set point, and the third, the evolution of the frequency converter of the blower.

7. DISCUSSION OF THE RESULTS

The Ceutí WWTP currently operates with a wastewater flow of 3000 m^3/day that is considerably lower than the designed wastewater flow. A single blower is therefore sufficient to provide the

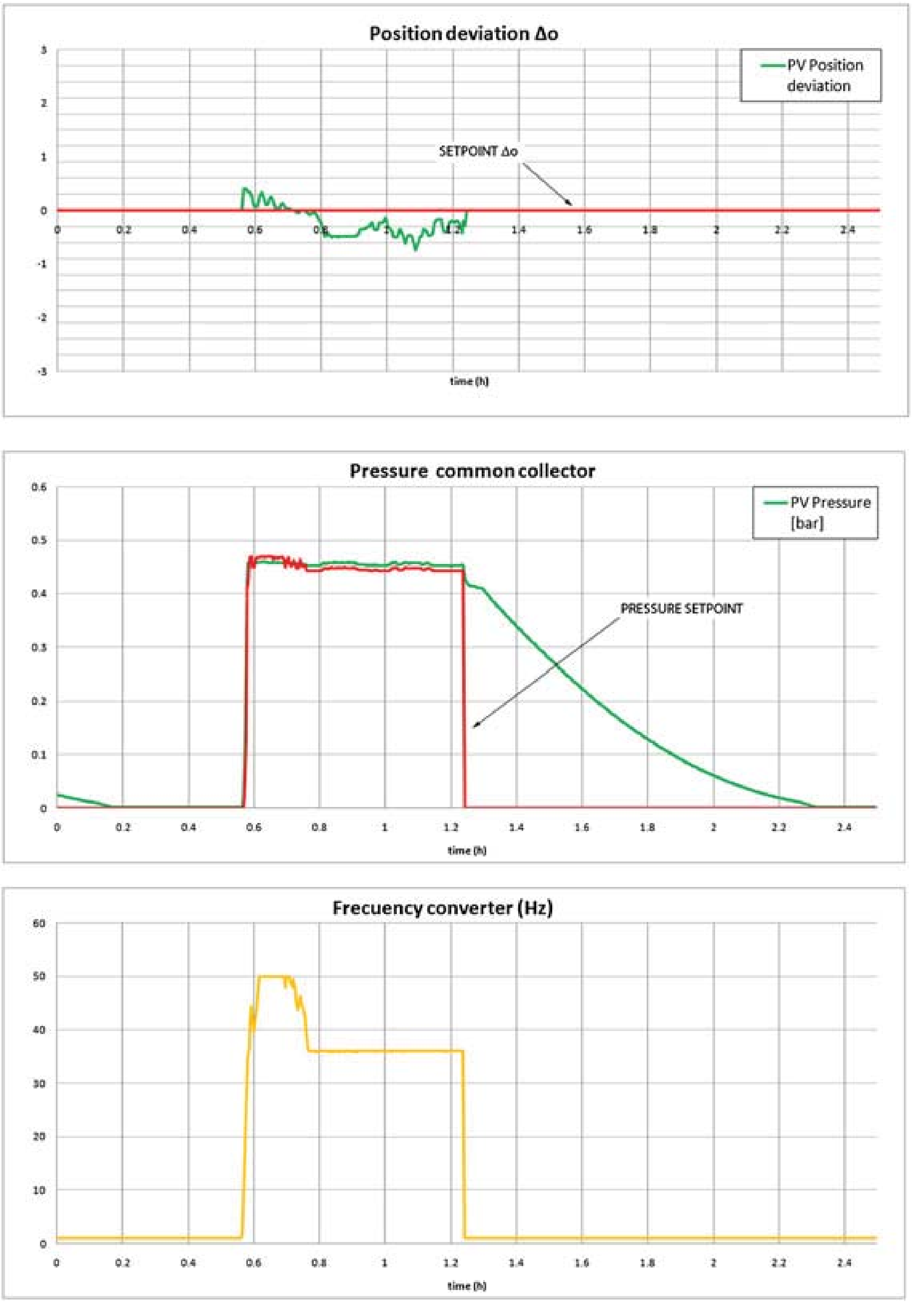

Figure 9. Pressure evolution during one nitrification/denitrification cycle.

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necessary air for oxygenation. Although reactor 2 has been in operation for a few months, reactor 1 started operating only recently, which means that each of the reactors has its own history of operation and thereby different composition of bacterial flora. The process dynamics of the reactors are therefore also different.

It can be appreciated in Figure 7 that redox limits are narrower compared with those used by the previous control system shown in Figure 4. This resulted in shortened nitrification/denitrification cycles. This was carried out after verifying experimentally that the quality of treated water was not affected by these reduced cycles, while there was a potential for energy savings in the blowers.

In Figure 7, and in more detail in Figure 8, it can be seen that in order to drive the DO along the set point ramp during the nitrification phase, the opening of the gate valve of reactor 1 was significantly greater than the opening of the same valve in reactor 2. This shows the difference in the dynamics of both reactors, basically because of the age of the bacterial bloom.

The dynamics in one nitrification/denitrification cycle is shown in more detail in Figures 8 and 9, both using the same time axes. At the beginning of the nitrification cycle (approximately at $t = 0.6$ h), the blower is started and the frequency converter applies the upper limit frequency of 50 Hz, as shown in the lower plot of Figure 9. The middle plot of Figure 8 shows that the DO in reactor 2 initially exceeds the setpoint value, and so the controller responds by closing substantially the corresponding valve position. On the other hand, the DO in reactor 1 does not initially reach the set point value, and the gate valve position remains at 100% opening until this happens. This clearly shows the different behavior of both reactors.

All together, as shown in the first plot of Figure 9, the position deviation variable Δo decreases, causing the pressure setpoint controller to lower the pressure set point, as shown in the second plot of this figure. This causes the pressure controller to decrease the frequency of the blower, reaching the lower frequency limit of 35 Hz. Although this minimum value of the frequency is maintained during the rest of the nitrification cycle, the air pressure remains above its set point, and consequently, the position deviation variable also remains negative and cannot reach the desired value of zero, that is, the mean of valve openings is equal to 80%. This shows how the limits of the frequency range for the blower deteriorated the performance of the new control system, and particularly, limited the operation of the ADEX controllers used for the air pressure control and the optimization of the gate valve position openings.

However, in spite of the inadequacies of the available instrumentation, the remarkable behavior of the ADEX controllers of the DO in both reactors must be emphasized. This behavior can be observed in detail in Figures 8 and 9. With the default initial conditions for the AP model parameters and using the structure previously described in Section 6, they were able to maintain the controlled DO variables of both reactors in a reasonable band around their set point values, without any prior knowledge of the different dynamics of the reactors and operating under a changing environment, with significant unknown perturbations, such as the air pressure itself and the biological load in each of the reactor.

Also, it is important to mention that, in spite of the differences in the dynamics of reactors 1 and 2, satisfactory control performance of the DO variables by the ADEX controllers resulted in a much more homogenous and improved treated water quality compared with the case of the previous control system.

Finally, in order to evaluate and compare the energy efficiency of the new control systems, the average daily consumed power was estimated from the volumetric air flow $\Phi_V(k)$ and pressure $p(k)$ signals:

$$Pavg = \frac{1}{24h} \sum_{0}^{\frac{24}{\Delta t}} p(k)\phi v(k)\Delta t \tag{11}$$

The calculated average power consumption with the new system was 9.72 kW, whereas 13.69 kW were consumed under the previous control system. This means that a 29% of reduction of energy consumption was achieved. This resulted in annual savings of about 10,200 €, considering a blower efficiency factor of 37%, and an electrical energy cost equal to 0.108 €/kWh.

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8. CONCLUSIONS

A new control system based on a generic adaptive control strategy was applied to the ditch reactors of wastewater treatment plant. A discrete logic to determine the transition between nitrification and denitrification phases of the reactors was combined with control strategies that used ADEX controllers for the DO and the air pressure in the common collector.

In spite of the inadequacies of the available instrumentation, ADEX controllers were able to maintain a desired DO level and redox evolution in the reactors during the nitrification phase. This was achieved without any prior knowledge of the various dynamics of each reactor and operating under changing environments, with significant unknown perturbations, such as the air pressure and the biological load.

The use of ADEX controllers made the development, implementation and operation of the new control system relatively straightforward. It was able to equalize the responses of both reactors and achieve an overall satisfactory operation of the plant, obtaining the desired water quality and avoiding hindering the nitrification/denitrification cycles, as it was the case with the previous control system. Also, a 29% energy savings was achieved by reducing the air pressure in the common collector.

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