Journal of Water Process Engineering 53 (2023) 103689

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Widening the applicability of most-open-valve (MOV) strategy for aeration control at full scale WWTPs by combining fuzzy-logic control and knowledge-based rules

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A R T I C L E I N F O

Keywords:
Aeration control system
DO control
Energy saving
Fuzzy-logic
Pressure control
Supervisory control

A B S T R A C T

An adaptation of a pressure-based most-open-valve control strategy to be applied in aeration control systems of any full scale Wastewater Treatment Plant (WWTP) is described in this paper. This control strategy minimises aeration energy consumption by leading the aeration system to work under the minimum pressure level that is possible given the air distribution system design characteristics and the effluent criteria. Several fuzzy-logic-based control loops are used in the different levels of a supervisory control architecture where knowledge-based rules are also applied. Results obtained in the implementation of this control strategy in three WWTPs with different configurations showed the capability of fuzzy algorithms to maintain dissolved oxygen concentration and pressure always close to setpoint values. Average electrical energy savings of 25 %, 22 % and 16 %, where achieved, respectively, in each WWTP, quantified as kWh per kg of removed COD.

1. Introduction

Activated sludge systems in Wastewater Treatment Plants (WWTPs) usually consist of several stages where anaerobic, anoxic and aerobic reactors are combined to remove organic matter, ammonia, nitrate and phosphate. Some plants are designed with a fixed configuration of these different types of reactors, while others can vary from aerobic to anoxic/anaerobic by closing an aeration control valve.

Dissolved oxygen (DO) concentration is the most important operating parameter in aerobic reactors. Oxygen is required mainly for organic matter removal and ammonia oxidation, but DO concentration values are also important for optimising other processes that can take place in activated sludge systems, such as simultaneous nitrification-denitrification, biological phosphorus removal (accumulation as polyphosphate in the aerobic stage). Furthermore, aeration is an energy intensive process and accounts for around 50 % of the total energy consumption in a conventional WWTP [1]. Hence, control of aeration systems becomes essential not only for minimising energy consumption in a WWTP, but also for achieving more stringent effluent discharge criteria on ammonia, nitrate and phosphorus.

Aeration systems can be different from one plant to another, but the most common system used nowadays consists in several diffusers grids that are connected to a group of aeration equipments (either blowers or turbo blowers) through a network of air pipelines. Each diffusers grid usually has a valve to regulate the amount of air to be introduced through the diffusers. Aeration control systems are being applied since the 1970s, when the use of on-line DO sensors was well established in many WWTPs [2]. Since then, many improvements have been obtained overall in Instrumentation, Control and Automation (ICA), as well as aeration equipment (diffusers and blowers). The control hardware has also improved significantly, allowing the incorporation of artificial intelligence to the control algorithms, such as fuzzy-logic and knowledge-based rules. Furthermore, the relatively high response time of the oxygen consumption process together with the recent improvement in communication networks allow that control actions can be taken in a time frame that can be managed by a SCADA (Supervisory Control And Data Acquisition) application installed in a central computer.

The increasingly stringent effluent discharge limits have boosted the use of automatic control systems in WWTPs, even for small to medium size facilities, due to the benefits obtained in energy savings and process

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https://doi.org/10.1016/j.jwpe.2023.103689
Received 7 November 2022; Received in revised form 1 March 2023; Accepted 24 March 2023
Available online 4 April 2023

stability. As stated before, efficient nutrient removal processes in activated sludge systems are also dependent on a proper DO concentration control. For nutrient removal and energy minimisation purposes, supervisory control loops are usually incorporated as upper control layers to decide the DO setpoint in each aerobic reactor. Recently, variable DO setpoint controllers have been developed and applied at full scale facilities with different objectives such as: meeting the affluent ammonia discharge limits [3], enhancing the oxygen transfer rate for energy and cost reduction [4], avoiding proliferation of nitrite oxidation bacteria and reducing N_2O emissions for partial nitritation-anammox reactors [5], and improving the simultaneous nitrification-denitrification process [6]. To achieve a good performance of these upper layer controllers, a reliable aeration control system able to maintain DO always close to DO setpoint is crucial.

Regarding control algorithms, several approaches have been used since the 1970s. The basic level of aeration control consists in maintaining the desired DO concentration in spite of the disturbances associated with the load fluctuations. It is usually achieved by manipulating the air flow rate supplied to the bioreactors by regulating either the speed of the aeration equipments or the opening degree of the airflow valves [7]. Different classical feedback controllers have been widely applied (on-off control, proportional-integral (PI), proportional-integral-derivative (PID)).

However, biological reactors in WWTPs are complex dynamic and nonlinear systems, which are never in a steady-state; hence, high control performance with linear controllers (such as PID), is difficult to be achieved. For this reason, unconventional control strategies have been widely evaluated and are being applied to full scale systems as an alternative to linear controllers [8,9]. In particular, controllers based on fuzzy-logic [10] have been discussed since the 1980s due to the capability of fuzzy-logic to provide an intuitive formal representation of the process and the possibility to include operator experience and process knowledge in the controller [11]. Fuzzy-logic introduces robustness in control of dynamic non-linear systems and facilitates control tuning by plant operators, since the fuzzy-rules are written in the language of process experts and operators. Nevertheless, the publications dealing with DO fuzzy controllers report mainly either simulations or pilot-scale investigations [12–15]. As stated in Bertanza et al. [11], the full-scale applications of fuzzy controllers for DO control are still scarce in the scientific literature.

Regarding advanced control systems applied to aeration systems, different architectures have been commonly used, but the most extended one is a cascade control of the DO concentration through two different approaches: air flow-based or air pressure-based control systems. In air flow-based systems, the movement of one valve affects the air flow in other reactors since changes in one valve affect the system pressure. To overcome this problem, pressure-based control can be used. Hence, in theory, by maintaining a constant system pressure, changes in valve position and flow at one location will not change air flow at other locations. However, maintaining a constant pressure high enough to supply the required air flow rate to all the reactors, including the high demanding ones requires high energy consumption, since excess blower discharge pressure wastes power. Thus, pressure-based control systems typically use a supervisory control to change pressure setpoint commonly based on valve positions and DO demands. One option to minimise the pressure loss over the air supply valves is to use the most-open-valve (MOV) principle [16]. The MOV systems were developed in the late 1990s [17,18]. These systems aim at having the valves as much open as possible, which minimises air pressure drop in the valves and makes possible to run the blowers at a lower pressure while supplying the same amount of oxygen, thus minimising energy consumption. To achieve this situation in aeration systems, once a control valve is completely open, it is designated most open and it is not allowed to close even if DO concentration is higher than the setpoint. In these cases, the pressure setpoint is decreased to reduce energy consumption. A comprehensive description of this control strategy can be found elsewhere [19]. Thus, the use of MOV theory to minimise energy consumption in the overall aeration system has been also incorporated to the current control systems, when DO concentration in different aerobic reactors is independently controlled with the same group of blowers [20,21].

In this paper, a fuzzy-logic-based aeration control system complemented with a set of knowledge-based rules is described and several full-scale applications are presented to illustrate the benefits of such combination. This controller is based on the MOV principle to minimise aeration energy consumption. The paper shows the performance results of three different WWTP configurations: a plug-flow biological reactor with two lines in parallel, 6 biofilter-type reactors in parallel, and a carrousel-type reactor with two lines in parallel. In all cases the control system has been implemented in a software application which is installed in the control PC (Personal Computer) of the WWTP and connected to the sensors and actuators via Open Platform Communications (OPC) protocol.

2. Control system description

2.1. Core algorithm

The main objective of the developed control system is to maintain the desired oxygen concentrations in the different aerobic chambers, which are aerated with the same set of blowers, minimising the blowers discharge pressure and therefore the energy consumption. The control system considers as aerobic chambers all the aerobic parts of activated sludge reactors including necessarily one DO probe, and at least one diffusers grid equipped with the corresponding control valve.

The developed control system consists of two hierarchical control layers: the supervisory control and the process control layers (see Fig. 1). In the process control layer several independent fuzzy-logic-based control loops were developed for two process variables: dissolved oxygen in each one of the aerobic zones and blowers discharge pressure in the air pipelines. The DO controllers manipulate the air valve opening according to DO concentration in each aerobic chamber; while the pressure controller manipulates the air flow rate provided by the aeration equipment (AE) regardless of the type of aeration equipment that exists in the plant. For instance, when aeration equipment consists in a set of blowers, the pressure controller modifies the rotational speed of the blower by a frequency converter to reach the blowers discharge pressure setpoint, whereas for turbo blowers with variable diffuser vanes, the pressure controller modifies the vanes position.

This control system allows maintaining different DO setpoints for different chambers to enhance nitrogen removal via concurrent nitrification-denitrification. It is possible because each control valve is opened or closed according to the DO concentration in the basin, and the pressure controller maintains the pressure close to the setpoint modifying the aeration capacity of the AE. The role of the pressure controller is to prevent valve movement in each chamber from disturbing the rest of the system.

DO setpoints can be set manually by plant operators or automatically, since the developed control system can be linked to a supervisory control system that modifies DO setpoints according to other operating parameters related to nutrient removal such as ammonium concentration or desired nitrification degree.

2.2. Lower layer control loops

As commented before, in the lower layer, two kind of fuzzy-logic-based control loops are used for maintaining DO concentration and blowers discharge pressure. The source of knowledge to build these fuzzy controllers comes from the expert knowledge of plant operators. The main differences between the fuzzy controllers are the input and output variables since similar rules are used in the inference engine. For the DO controller the input variables are the error at the control time

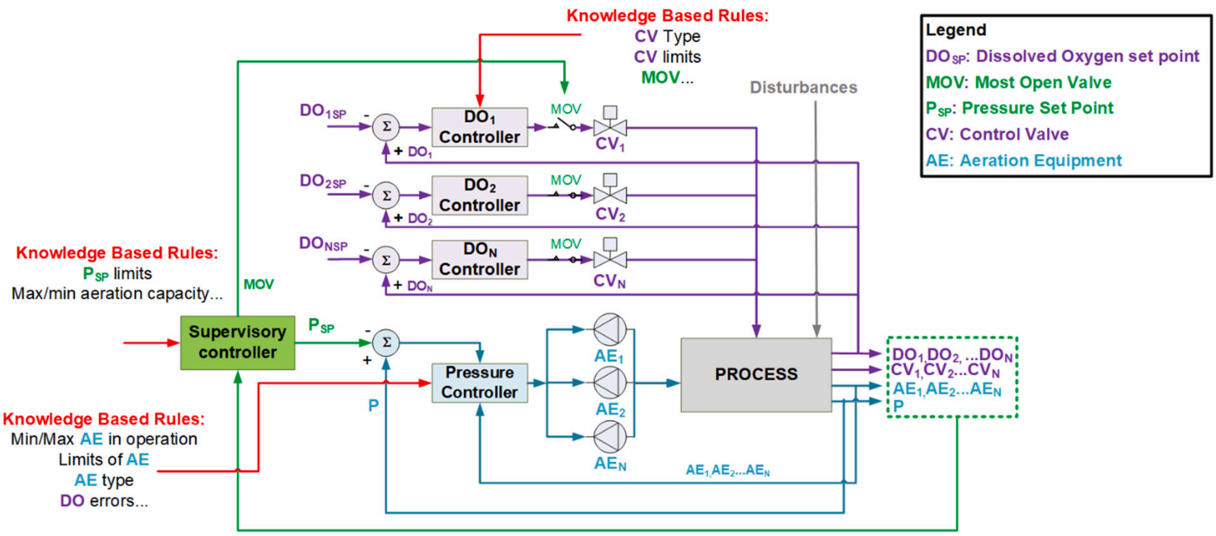

Fig. 1. General schematic flow diagram of the control system.

(DO error) and the difference between the error at the control time and the error at the previous control time (ΔDO error), while the output variable is the increment of the valve opening (Δvalve). For the pressure controller the input variables are the error at the control time (P error) and the difference between the error at the control time and at the previous control time (ΔP error), while the output variable is either the increment of the frequency in the frequency converter (ΔHz), which in turns modifies the rotational speed of the blowers, or the increment of the vane position of the turbo blowers. The different fuzzy sets used for the different input/output variables are defined in Table 1.

For the so-called fuzzification step, all the input variables are converted into the linguistic variables (fuzzy sets) shown in Table 1, by using "Gaussian-type" membership functions, which are defined by the following equation:

$$\mu(p) = exp\left(-\frac{(p-c)^2}{2\cdot\sigma^2}\right) \tag{1}$$

where p is the numerical value of the variable; and c and σ are the centre and amplitude of the Gaussian membership function, respectively.

Since all the aforementioned control loops are defined with the same structure and the same number of input and output variables, the inference engine for each controller (DO controller, blowers discharge pressure controller, and pressure setpoint controller) is defined by the same set of rules shown in Table 2. The output linguistic variables are obtained by applying these rules and using the Max-Prod operator, i.e. following the Larsen's fuzzy inference method [22]. Thus, for each rule the following operator is applied:

Table 1
Fuzzy sets defined for the different control variables.

Variable	Number of fuzzy sets	Label of the fuzzy sets
DO error	4	Large Negative, Small Negative, Small Positive, Large Positive
ΔDO error	3	Negative, Zero, Positive
Δvalve	4	Large Negative, Small Negative, Small Positive, Large Positive
P error	4	Large Negative, Small Negative, Small Positive, Large Positive
ΔP error	3	Negative, Zero, Positive
ΔHz	4	Large Negative, Small Negative, Small Positive, Large Positive

Table 2
Fuzzy control rules defined for the different control loops inference engine.

Rule number	Error	ΔError	Output variable
1	Large Negative	Positive	Large Positive
2	Large Negative	Zero	Large Positive
3	Small Negative	Positive	Large Positive
4	Small Positive	Negative	Large Positive
5	Small Negative	Zero	Small Positive
6	Large Positive	Negative	Small Positive
7	Small Positive	Zero	Small Negative
8	Large Negative	Negative	Small Negative
9	Large Positive	Positive	Large Negative
10	Large Positive	Zero	Large Negative
11	Small Positive	Positive	Large Negative
12	Small Negative	Negative	Large Negative

$$\mu_{rule,i} = \prod_{1}^{j} \mu_j \tag{2}$$

where j represents each of the input fuzzy sets involved in the rule i, μ_j represents the value obtained in the fuzzification of the j input fuzzy set.

Similarly, in order to establish only one output fuzzy set value when the consequences of different rules are the same, the following operator is applied:

$$\mu_k = Max(\mu_{rule,i}) \tag{3}$$

where μ_k represents the value of each one of the output fuzzy sets and $\mu_{rule\ i}$ represents the value of the different rules whose consequence is the output fuzzy set k.

Finally, the output linguistic variables are converted into the corresponding numerical control actions in the so-called defuzzification step. Here, in order to obtain a single output value (P) from the output fuzzy set, the Height Defuzzifier method was employed [23], applying the following equation:

$$P = \frac{\sum_{i=1}^{n} c_i\cdot\mu(p_i)}{\sum_{i=1}^{n}\mu(p_i)} \tag{4}$$

2.3. Supervisory control

The supervisory control is responsible for:

- Setting the MOV chamber: The location of the MOV is assigned to the aerobic chamber with both the highest oxygen deficit (the maximum difference between DO setpoint and DO measurement) and the control valve completely open. Control valves are considered completely open when their opening degree reaches an established level that is defined according to the characteristic curve of the valve.
- Setting the pressure setpoint in the air distribution system: The supervisory control continuously modifies the setpoint for the pressure controller by means of a fuzzy-logic-based control loop according to the dissolved oxygen concentration in the MOV chamber. This way the discharge pressure level is always the minimum required to distribute the air along the system maintaining the desired DO levels. The input variables of this control loop are the DO error and the ΔDO error from the aerobic zone with the MOV. The same fuzzy sets shown in Table 1 are used for the input variables in this upper layer control loop. The output variable is the increment of the pressure setpoint (ΔP setpoint), which is described by the following four fuzzy sets: Large Negative, Small Negative, Small Positive, Large Positive. The fuzzy control rules used are those shown in Table 2.
- Adapting the control actions obtained from the process layer controllers according to the WWTP characteristics: the supervisory control system includes a set of knowledge-based rules that modify the control actions from the process layer controllers according to the aeration demand dynamics, the WWTP layout, the aeration equipment, the characteristic curve of the valves, and system boundaries. These rules are explained below.

2.3.1. *Knowledge-based and boundary-based rules considered in the supervisory control layer*

The following knowledge-based and boundary-based rules allow adapting the developed control system to different treatment schemes and aeration systems.

- Control valve position lower bound: To assure an appropriate mixing degree in the aerobic zone a lower bound for each control valve is defined. The supervisory control avoids each control valve to be closed beyond this limit.
- Characteristic curve of the valves: to ensure proper performance of the DO controller regardless of the control valve type, the valve opening increment is corrected according to the characteristic curve of the valve (linear, quick opening, equal percentage…).
- Pressure level upper bound: to avoid mechanical problems in the aeration system, the pressure setpoint is limited to a maximum value, which should be stablished by plant operator. If pressure exceeds this upper bound, the control system opens the control valves to release air pressure and if necessary, switches off AE.
- Maximum/minimum number of aeration equipments in operation: plant operator sets the maximum number of AE that can be simultaneously switched on. This rule avoids sudden increases in air pressure and energy consumption when oxygen remains below the setpoint due to external disturbances (very high influent load due to industrial discharges, oxygen probe failures, …)
- Supervision of pressure setpoint variation: Pressure setpoint cannot be increased when both, the AE are operated at their fixed maximum capacity, and pressure setpoint is higher than the measured value. In the same way, pressure setpoint cannot be decreased when both, the AE are operated at their fixed minimum capacity, and pressure setpoint is lower than the measured value.
- Aeration levels hierarchy: when different AE are available in the WWTP, different aeration levels are defined. Each aeration level is characterised by the specific number and type of AE that are simultaneously switched on, jointly with their minimum and maximum aeration capacity. When the defined maximum/minimum aeration capacity is reached and maintained for more than a predefined time interval, being the pressure value lower/higher than pressure setpoint, a higher/lower aeration level respectively, is needed.
- Conditions for level change: To avoid AE being unnecessarily switched on/off, two conditions are stablished to allow the aeration level change. Before switching on a new AE, the supervisory control system verifies that these two conditions are fulfilled: (1) oxygen concentration is below an error band during a defined time interval; and (2) time since last AE start/stop is higher than a predefined time interval. In the same way the system only switches off an AE when oxygen is over a predefined error band and time since last AE start/stop is higher than a predefined time interval. All these parameters (error bands and time intervals) can be modified by plant operators.
- Operation mode of AE: The operator can choose the criteria for the selection of the blower to be connected/disconnected when all the previous conditions for aeration level change are fulfilled. It can be done by operating hours or by a specific hierarchy.

3. Full scale application

In order to evaluate the control system performance under different conditions, the developed control system was implemented in three Spanish full scale WWTPs with different treatment schemes: a plug-flow biological reactor with two lines in parallel (WWTP #1), 6 biofilter-type reactors in parallel (WWTP #2), and a carrousel-type reactor with two lines in parallel (WWTP #3). Although control algorithms are always the same, parameter calibration and knowledge-based rules allowed adapting the overall control system to each specific case. In this section, the main characteristics of the three WWTP as well as the details of the control system adaptation to each plant are presented.

3.1. *WWTP #1*

This WWTP is treating wastewater from 110,000 p.e. The biological treatment of this WWTP consists of two lines of activated sludge reactors following a modified UCT scheme (see Fig. 2). Each line is divided into one anaerobic chamber (16 % of the total volume), two anoxic chambers (20 % each) and one aerobic chamber (44 %). Each aerobic reactor has two diffuser grids and is equipped with two DO probes. Therefore, two aerobic chambers can be defined in each activated sludge reactor. The aeration system includes 5 blowers of different aeration capacity (5214 Nm^3/h for AE-1, AE-2 and AE-3, and 2284 Nm^3/h for blowers AE-4 and AE-5). All of them are equipped with a frequency converter. The following aeration levels have been defined: Level 1 (1 small blower), level 2 (2 small blowers), level 3 (1 big blower), level 4 (1 big blower and 1 small blower) and level 5 (2 big blowers). Only these 5 levels were defined because a maximum of two simultaneous blowers was established to avoid overpressure in air pipelines. When the aforementioned conditions for level change are fulfilled the control system increases or decreases the aeration level.

3.2. *WWTP #2*

This WWTP is treating wastewater from 33,900 p.e. The biological treatment of this WWTP consists of six lines of two-stage (anoxic-aerobic) tricking filters (BIOFOR® from Degrémont Technologies Ltd.) (see Fig. 3). Each aerobic BIOFOR has one DO probe and one diffuser grid equipped with a control valve and an air flow meter (FIT). Therefore, six aerobic zones can be defined in the system. The aeration system includes 4 blowers of same aeration capacity. All of them are equipped with a frequency converter. Since only three blowers can be simultaneously switched on, three aeration levels were defined.

3.3. *WWTP #3*

This WWTP is treating wastewater from 45,200 p.e. The biological treatment of this WWTP consists of two oxidation ditches in parallel,

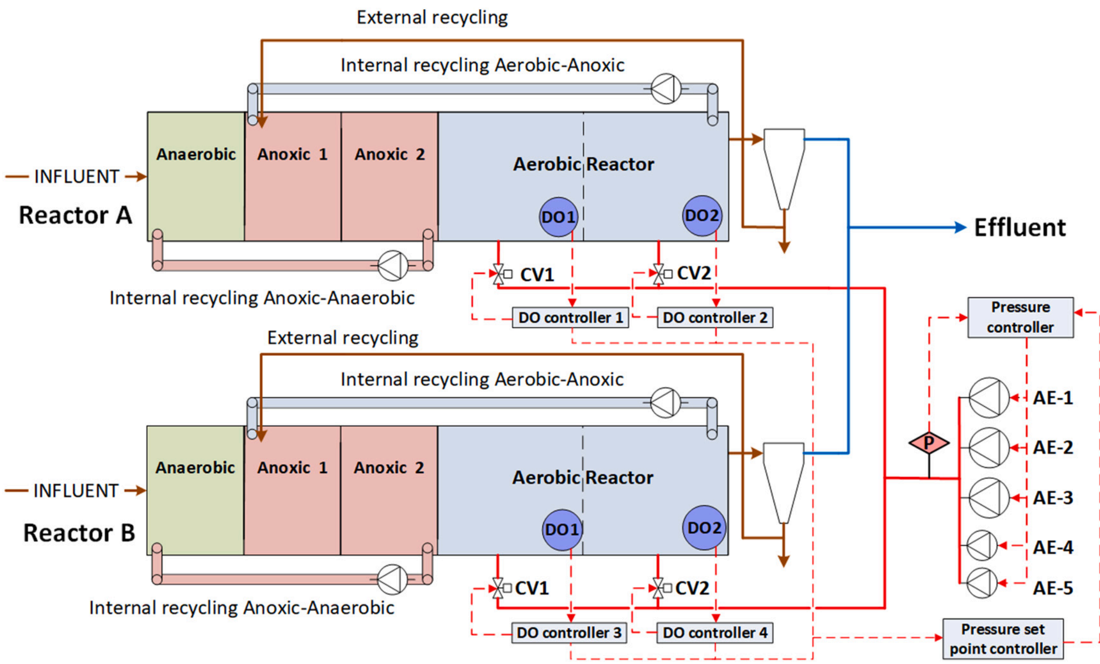

Fig. 2. Flow diagram of the aeration control system in WWTP #1.

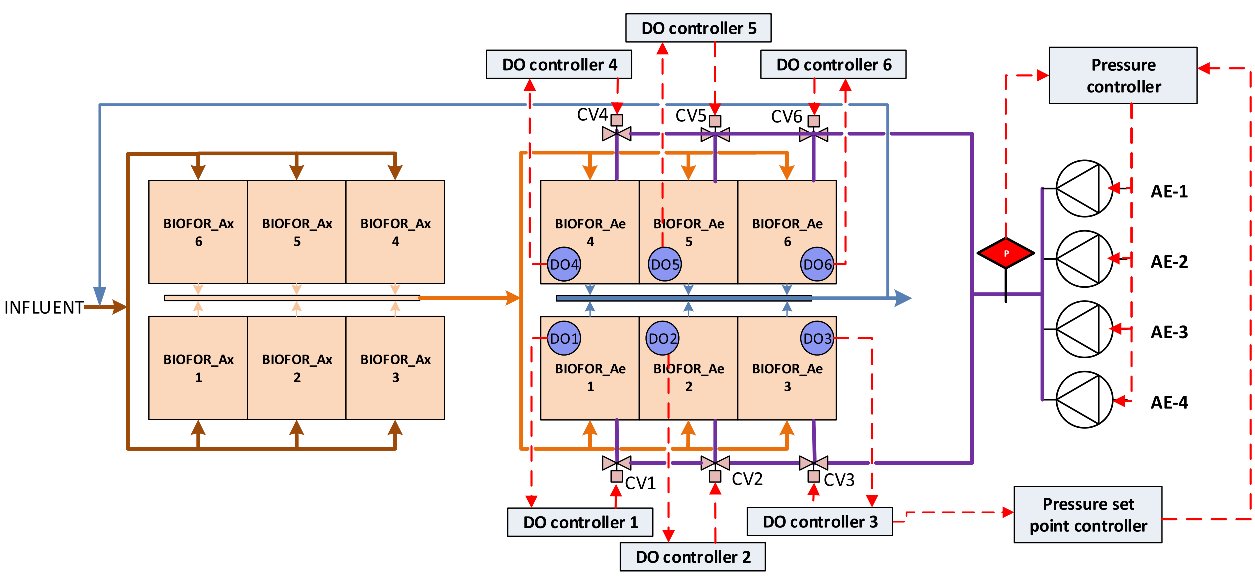

Fig. 3. Flow diagram of the aeration control system in WWTP #2.

each one with a volume of 5731 m^3 (see Fig. 4). Each oxidation ditch has two diffuser grids and is equipped with two DO probes. Therefore, two aerobic zones can be defined in each oxidation ditch, although oxygen concentration is quite similar along the reactor due to the high recycling flow rate which is typical in these systems. Since anoxic zones are difficult to obtain in these systems, low oxygen setpoints should be maintained to promote concurrent nitrification-denitrification for nitrogen removal. The aeration system includes 3 identical blowers (2 + 1) of 110 kW each. All of them are equipped with a frequency converter. In this case, only two aeration levels were defined.

4. Results and discussion

In this section, the results obtained in the three full scale implementations are presented and analysed in each plant considering the control system performance as well as the energy savings achieved after the implementation compared to the energy consumption before the implementation of the control system.

4.1. WWTP #1

The control system performance is shown in Figs. 5 and 6. Fig. 5 shows the performance of the DO controllers during the tests carried out to analyse step changes response of the developed control system. As can be seen in this figure the oxygen concentration is always close to the DO setpoint in all the aerobic chambers, even when significant modifications (up to 1.5 mg/l) in this parameter take place. The MOV is always located in the second aerobic chamber in the line A. The oxygen concentration in this aerobic chamber is maintained by modifying the pressure setpoint. As can be seen in Fig. 6a, when the setpoint is

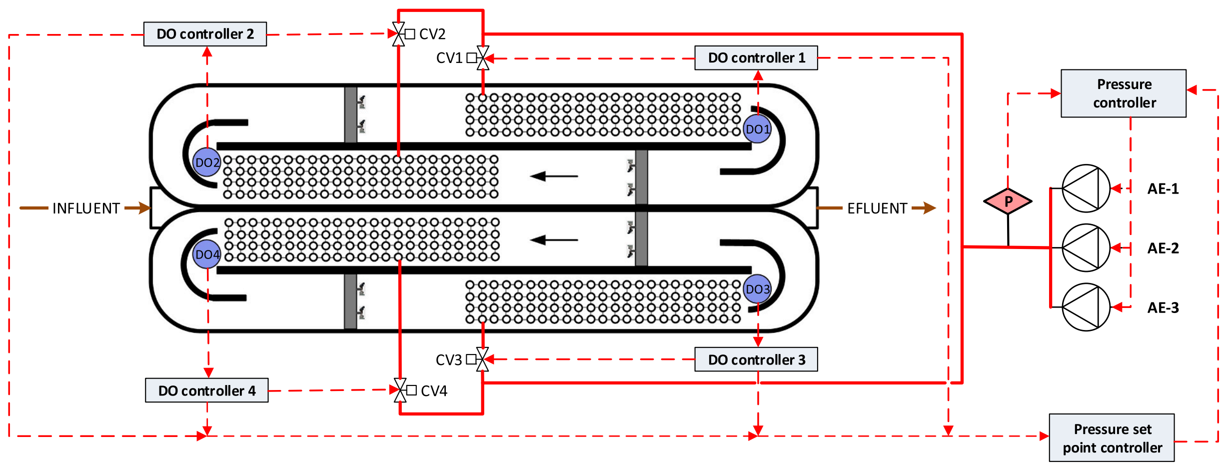

Fig. 4. Flow diagram of the aeration control system in WWTP #3.

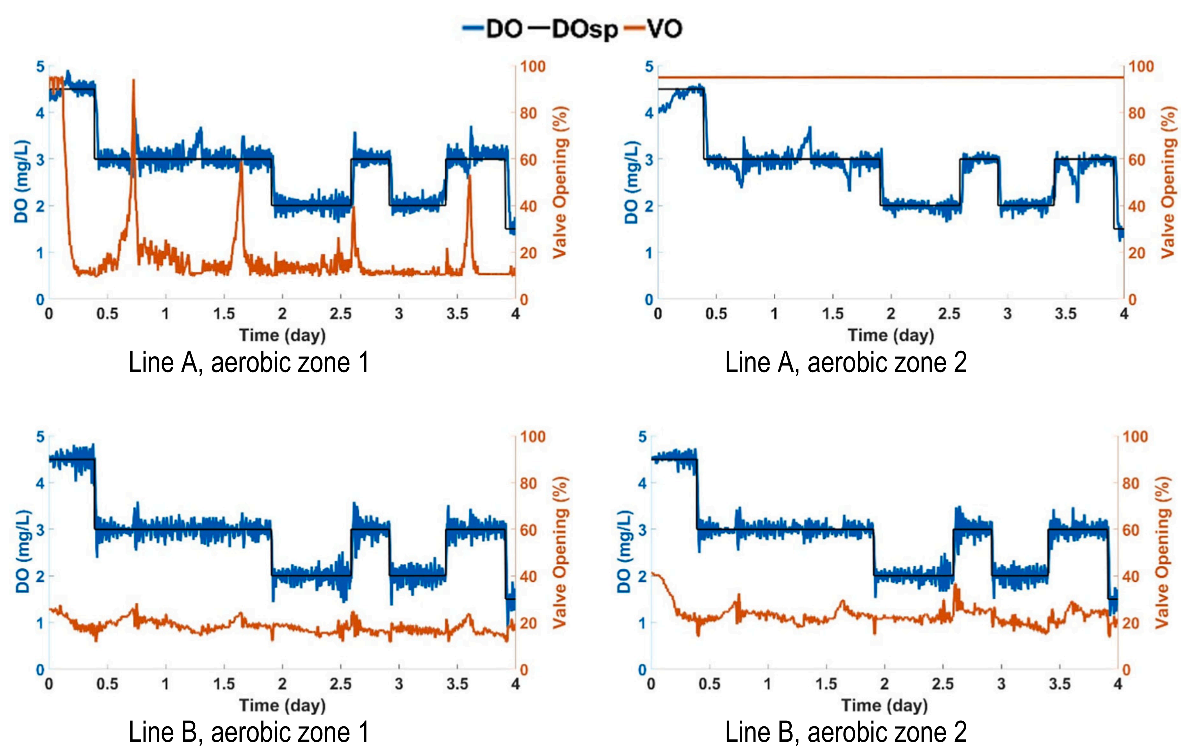

Fig. 5. DO control system performance under step changes in DO setpoint in the four aerobic zones.

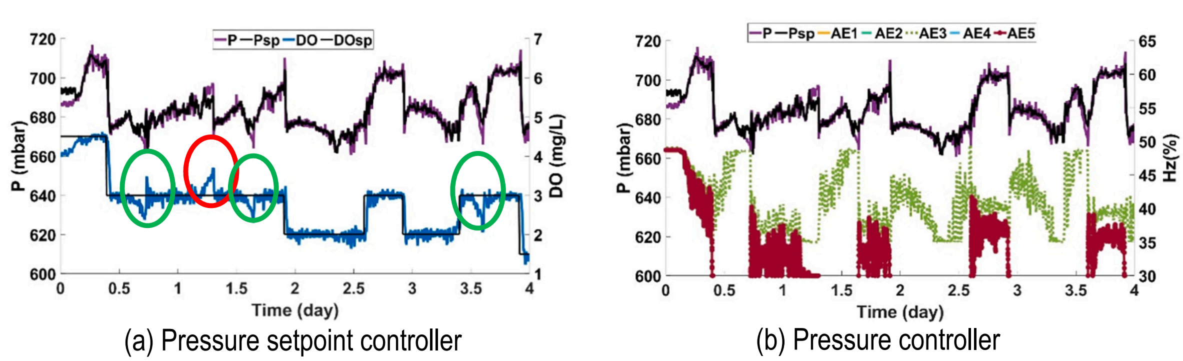

Fig. 6. Pressure control system performance in WWTP #1 under step changes in DO setpoint in the four aerobic zones.

maintained constant the variations in the pressure setpoint are smoother and are related to the variations of influent flow rate and load. However, when the DO setpoint in the aerobic zone with the MOV is step-changed a sudden variation in the pressure setpoint can be observed, which causes changes in the aeration levels. As can be seen in Fig. 6b, aeration levels are changing between level 3 (big blower AE-3) and level 4 (big blower AE-3 and small blower AE-5). During the 4 days shown in this figure, aeration level is decreased 5 times from level 4 to level 3 (the small blower AE-5 is switched off). Four of these changes are due to a step decrease in the DO setpoints. The other one takes place in the first hours of day 2 due to a decrease in influent flow rate and load. As commented before the blower is switched off when the error band in the DO setpoint of aerobic zone with the MOV is exceeded (see red circle in Fig. 6a) and the other conditions for level change are fulfilled. Aeration level is increased 4 times from level 3 to level 4 (the small blower AE-5 is switched on). Only one of these changes is due to a step increase in the DO setpoints. The other three take place during constant DO setpoints due to an increase in influent flow rate and load. As commented before the blower is switched on when all the aforementioned conditions for level change are fulfilled, including the error band in the DO setpoint of aerobic zone with the MOV (see green circles).

The developed aeration control system was integrated in a global nitrogen control system (which is out of the scope of this paper) where the DO setpoints are continuously changed according to the influent and effluent ammonium and nitrate concentrations. Fig. 7 shows the performance of the DO controllers. DO setpoints modified by this global nitrogen control system are lower (between 0.5 and 1 mg/l) during the first hours of each day due to the low influent flow rate. In the morning, when the influent flow rate increases DO setpoints are increased and maintained between 1.5 and 2.5 mg/l during the rest of the day. Despite these DO setpoints modifications, DO concentrations in all the aerobic zones are always maintained close to the DO setpoints. The MOV is always located in the second aerobic zone of reactor A. DO in this zone is controlled by modifying the setpoint of the pressure controller. DO concentrations in the other aerobic zones are controlled by modifying the corresponding control valves. The opening of the control valves in reactor A is always higher than in reactor B indicating that oxygen requirements in both reactors are different. The wastewater influent flow rate treated in reactor A was higher than in reactor B.

Fig. 8 shows the performance of the pressure control system when continuous DO setpoints modifications are taking place. As can be seen in Fig. 8c, pressure setpoint varies between 680 and 720 mbar and follows the same trend that DO setpoints, decreasing in the first hours of each day and increasing during the morning. Pressure controller is able to maintain the pressure level close to the setpoint during the whole period by changing the rotational speed of the blowers (frequency converters) and the aeration levels (when all the conditions for level change are fulfilled). As can be seen in Fig. 8a and b, all the aeration levels are covered during this period, except for level 3 which was deactivated because the aeration capacity of two small blowers (level 2) was similar to one big blower (level 3). Fig. 8b shows the changes in the aeration level for the two first days of this period. Only five/six changes per day are required to maintain the pressure close to the setpoint along the day.

Fig. 9 shows the monthly average values of specific energy consumption in the WWTP before and after the control system implementation. During the tuning period the energy consumption increased because of the different tests carried out where the DO setpoints were significantly increased to evaluate the systems performance under different aeration requirements. Once calibrated, the aeration control system achieved a reduction of 25 % in the specific energy consumption of the whole plant with no significant differences in the effluent concentrations. Before the control system implementation, DO concentration was controlled by modifying only the frequency of the blowers. Although no control valves were available for each diffuser grid, one valve for each line was manually modified by plant operators.

4.2. WWTP #2

The control system performance is shown in Figs. 10 and 11. Fig. 10 shows the performance of the DO controllers during two days. As can be seen in this figure the oxygen concentration is always close to the DO

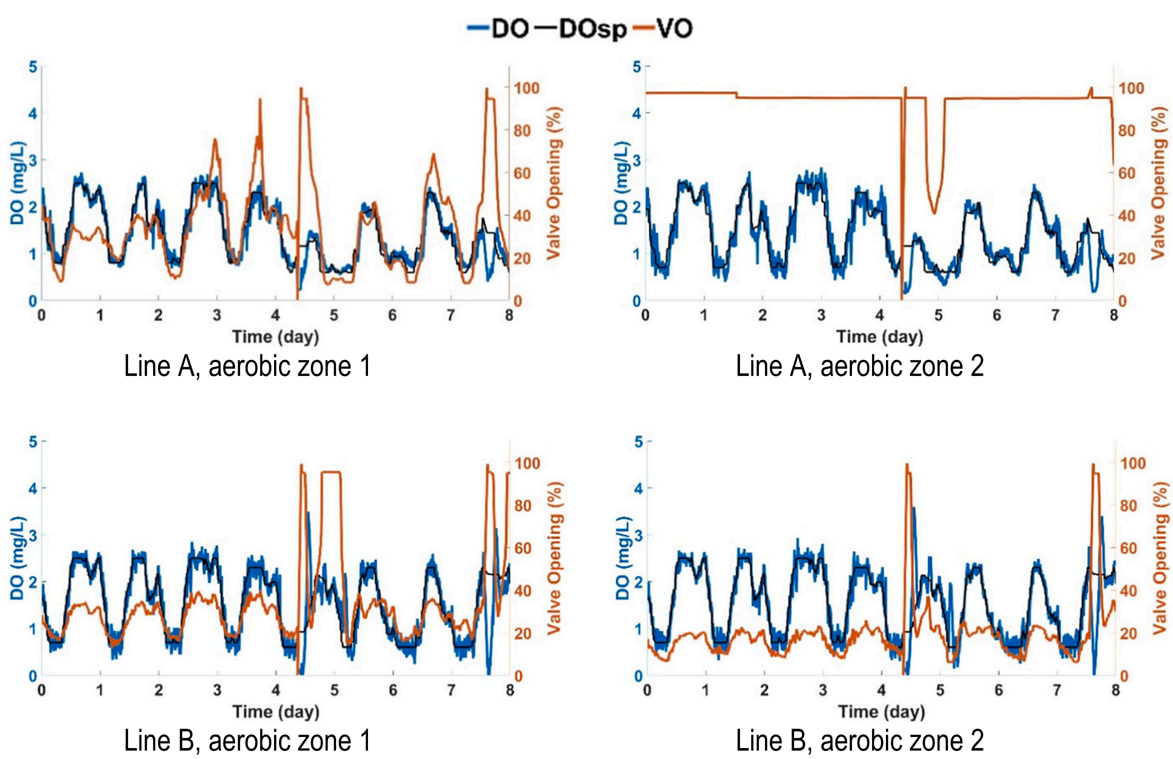

Fig. 7. DO control system performance with continuous modifications of DO setpoints.

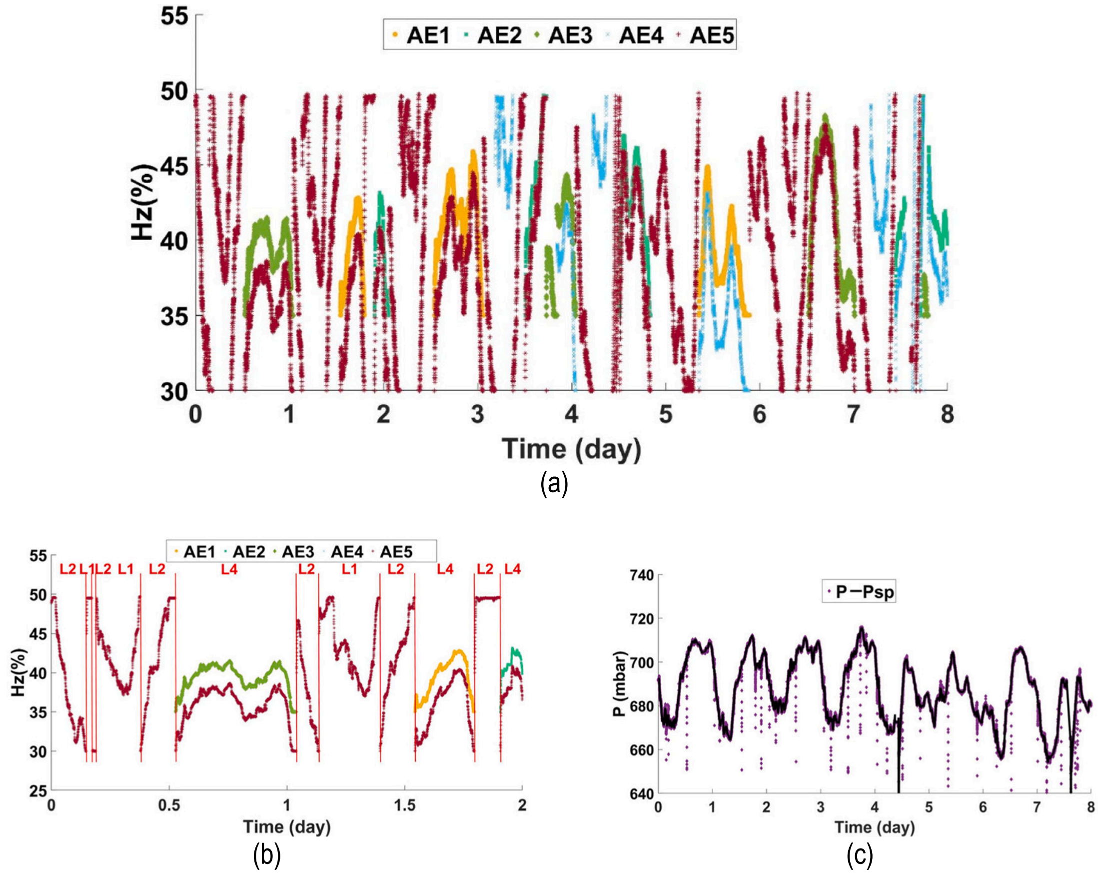

Fig. 8. Pressure control system performance with continuous modifications of DO setpoints. (a) Time evolution of frequency for all the blowers during the whole period. (b) Zoom of the first two days to indicate the aeration level changes (in red vertical lines). (c) Time evolution of pressure and pressure setpoint during the whole period.

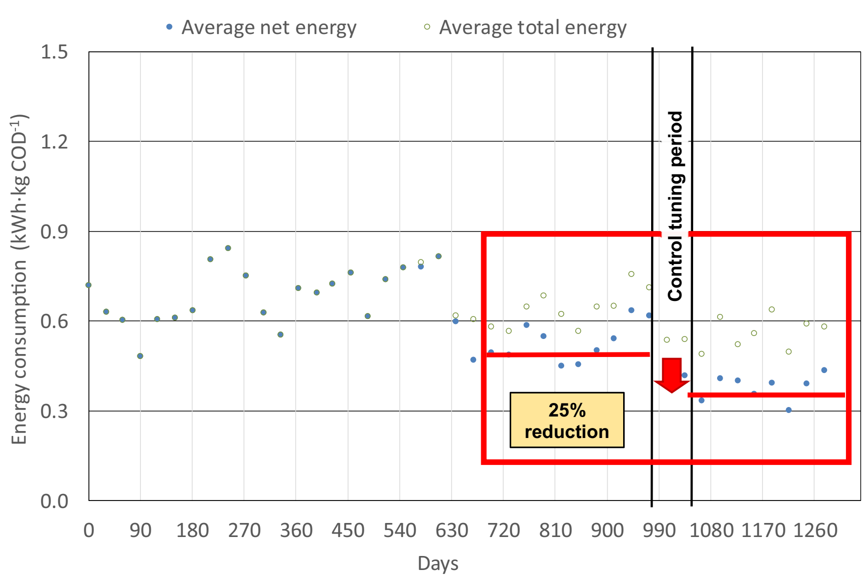

Fig. 9. Specific energy consumption in the WWTP before and after the control system implementation (monthly average). The difference between the two series corresponds to the energy produced by the co-generation system.

setpoint in all the aerobic zones. During this period, the MOV alternates between BIOFOR 2 and 3. The oxygen concentration in these aerobic zones is maintained by modifying either the pressure setpoint (when the MOV is in this zone) or the control valve. Fig. 11 shows the performance of the pressure controller. As can be seen in this figure, pressure is always very close to the setpoint, varying between 560 and 730 mbar. Aeration levels, in this case also the number of working blowers, varies from 1 to 3 during this period to maintain the pressure controlled.

A backwash is carried out for each BIOFOR filter each 2–3 days. The backwash of the 6 reactors was not carried out simultaneously. During

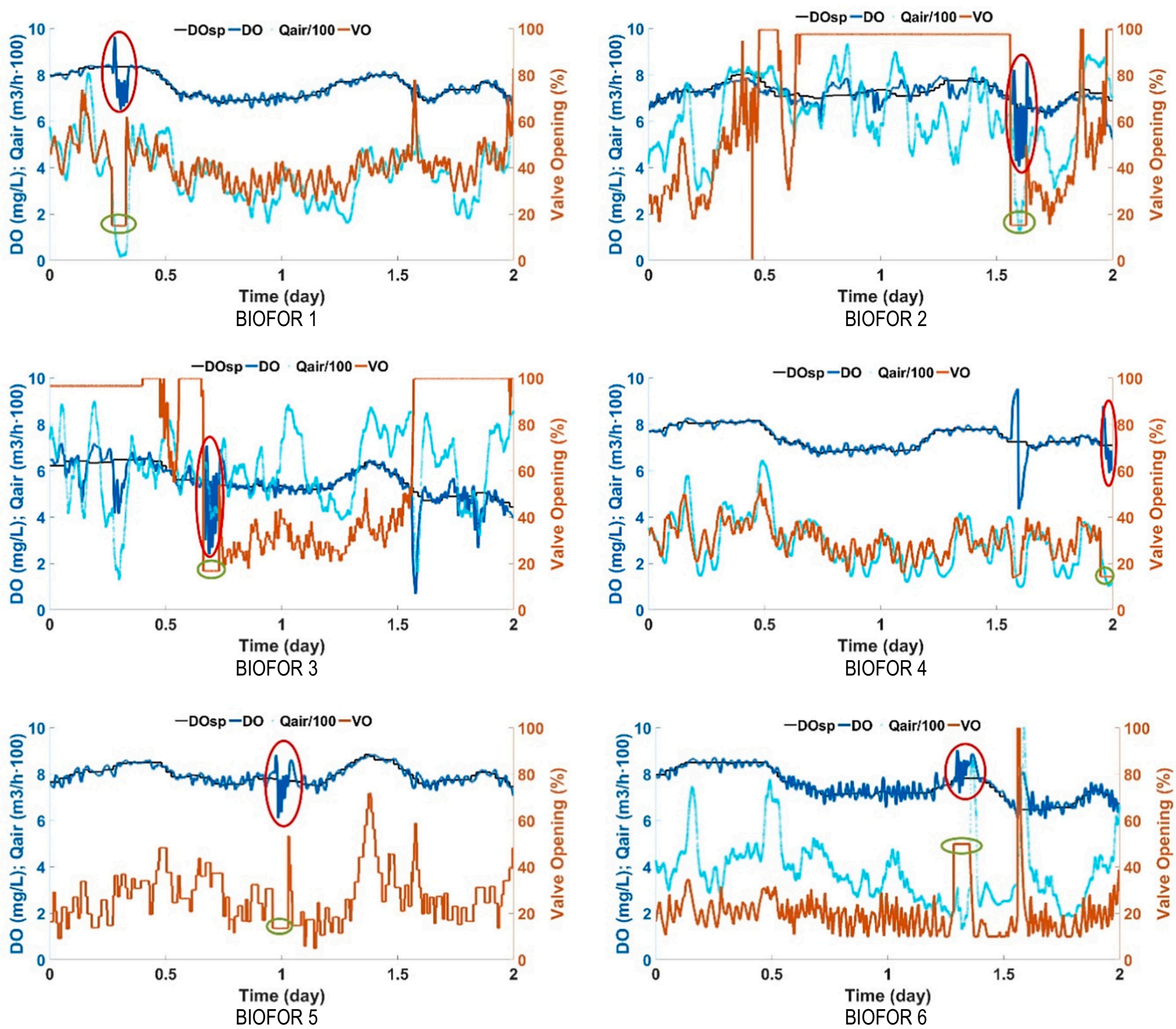

Fig. 10. DO control system performance under variable DO setpoint in the six aerobic BIOFOR.

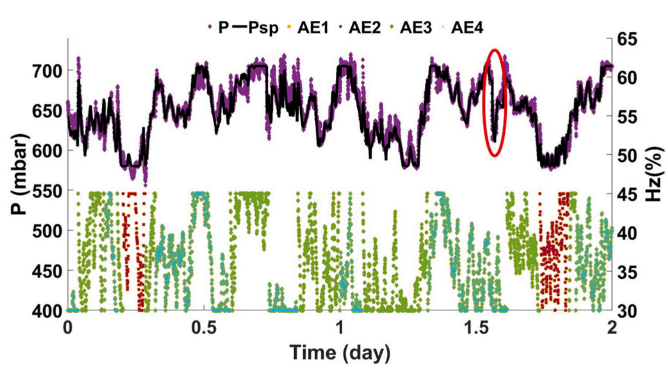

Fig. 11. Pressure control system performance in WWTP #2.

the backwash of each BIOFOR, the correspondent DO controller is switched off and the control valve remains at constant opening in a predefined value (see green circles in Fig. 10). The DO concentration during these periods is not controlled, but it rapidly reaches the DO setpoint when the backwash finishes (see red circles in Fig. 10). If a backwash event occurs in the reactor with the MOV, the control system decreases the pressure setpoint to force control valves opening until another reactor fulfils the MOV conditions (see red circle in Fig. 11).

To assure a proper BIOFOR performance, a minimum and maximum air flow rate was defined by plant operators (100 and 900 m^3/h, respectively). These threshold values must not be exceeded, even if DO concentration is far from its setpoint. Fig. 12 shows an example when minimum and maximum air flow rates are reached several times.

A reduction of 22 % in the specific energy consumption of the whole plant was achieved after the control system implementation and calibration. Before the control system implementation, the air flowrate was maintained at constant values in each reactor.

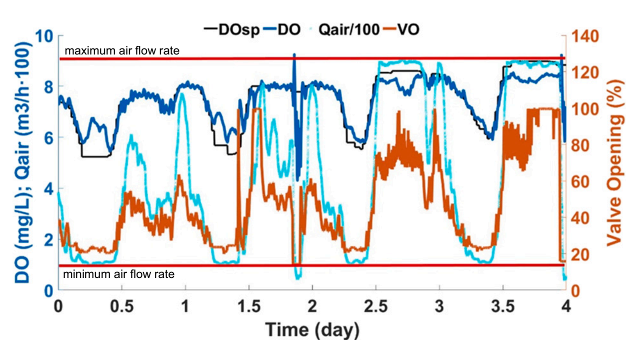

Fig. 12. Example of control system performance when maximum and minimum air flow rates are reached.

4.3. WWTP #3

The control system performance is shown in Figs. 13 and 14. Fig. 13 shows the performance of the DO controllers during two days. As can be seen in this figure the oxygen setpoints were stablished at 0.5 ppm in all the aerobic zones and DO concentration is always close to DO setpoint. The MOV is located always in the second aerobic zone in the line A. The oxygen concentration in this aerobic zone is maintained by modifying the pressure setpoint. The control valves opening in reactor A is higher than in reactor B because the air pipelines were not properly designed and blowers are closer to reactor B. In both reactors, the opening of the control valve next to the wastewater inlet is usually lower than the other one. In fact, this control valve is maintained most of the time at the minimum opening degree in reactor B. Since an oxidation ditch can be considered a completely mixed reactor, the different valve opening should be attributed to an uneven air distribution.

As can be seen in Fig. 14 the variations in the pressure setpoint are smoother than in the other WWTPs and are related to the variations of influent flow rate and load. In these systems, the influent flow is significantly diluted because of the high recycling flow rate and influent variations are equalised in the reactor. During the period shown in this figure, only one blower (aeration level 1) was enough to maintain the pressure setpoint. The frequency of the blower varied between 20 and 30 Hz.

Table 3 shows the monthly average specific energy consumption before and after the control system implementation. As can be seen on this table, this energy ratio is lower in all the months except for September. During this month, sludge thickener was overloaded, thus increasing the COD and TSS of sidestreams recycled to the aerobic reactors. An average reduction of 16 % energy consumption was obtained after the control system implementation. Before the control system implementation, DO concentration was controlled by modifying only the frequency of the blowers, i.e. without control valves.

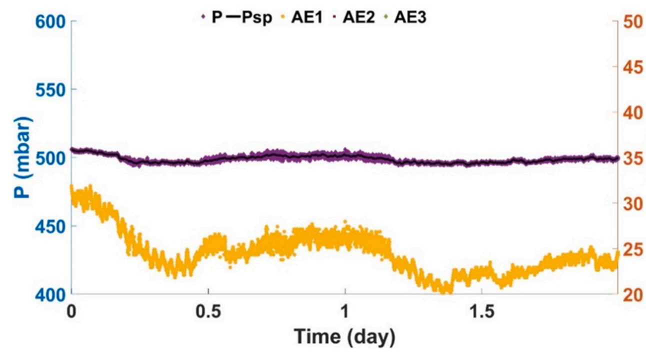

Fig. 14. Pressure control system performance in WWTP #3.

5. Conclusions

An aeration control system based on MOV strategy has been presented in this paper. With this strategy at least one of the control valves is always completely open to minimise the pressure in the air pipelines. Two hierarchical control layers (process control and supervisory control layers) which are made up of several independent fuzzy-logic-based control loops are the core of the system jointly with a set of knowledge-based rules. DO is maintained in each aerobic zone by modifying the opening of the corresponding control valve. Pressure in the air pipelines is controlled by modifying the rotational speed of the blowers. To maintain the DO concentration in the aerobic zone with the MOV, the supervisory controller modifies continuously the pressure setpoint. The knowledge-based rules limit the action of the process controllers, avoid unnecessary starts and stops of the blowers, and allow the developed control system to be adapted to different WWTP configurations. The results obtained after the implementation of this control system in 3 full scale WWTPs with different treatment schemes show the capability of fuzzy control algorithms to maintain DO concentrations always close to the DO setpoints in spite of daily variations of influent flow rate and load, step-changes in the DO setpoints or different WWTP layouts. In all cases the performance of pressure controller was excellent. Maintaining the pressure always close to the pressure setpoint is crucial to assure an appropriate performance of the control system. The MOV strategy led the blowers to be operated at the minimum discharge pressure decreasing energy consumption. Energy savings between 16 % and 25 % were achieved after the implementation of the control system in the three WWTPs presented.

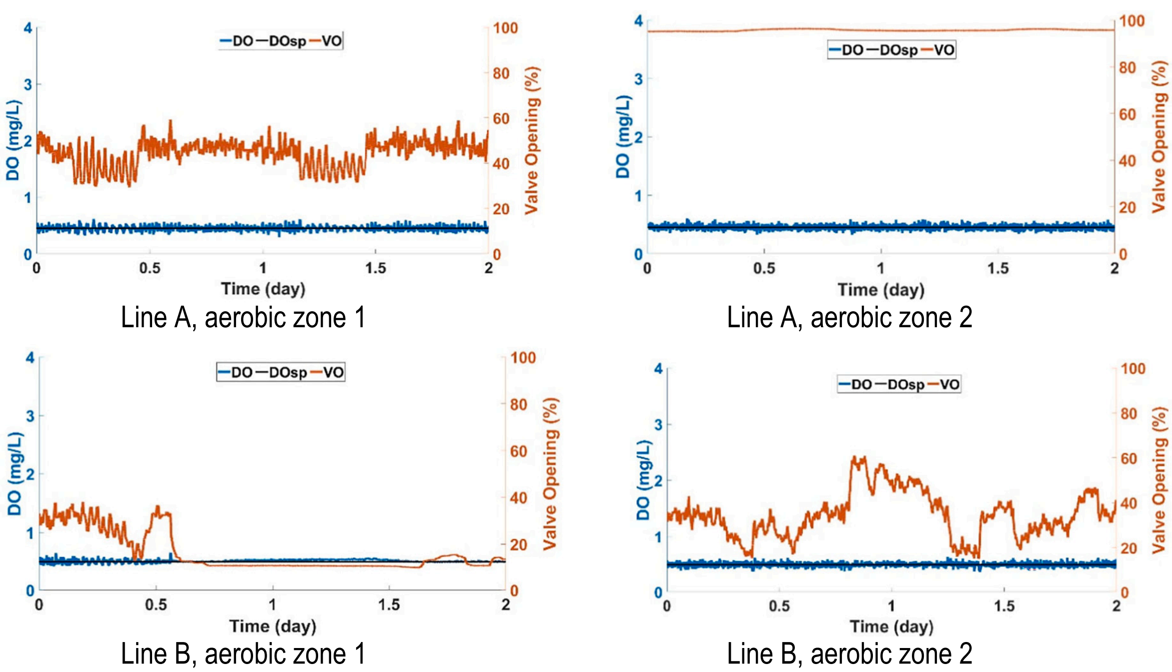

Fig. 13. DO control system performance in the two oxidation ditches.

Table 3
Monthly average specific energy consumption (kWh·kg COD^{-1} removed) before and after the control system implementation.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Before	0.570	0.600	0.564	0.539	0.533	0.606	0.478	0.491	0.361	0.487
After	0.456	0.472	0.430	0.402	0.472	0.479	0.322	0.404	0.426	0.459

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This research did not receive any specific grant from public funding agencies. The authors would like to thank plant operators who collaborated in the control system implementations.

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