2018 22nd International Conference on System Theory, Control and Computing (ICSTCC)

A hierachical Plant wide operation in wastewater treatment plants: overall efficiency index control and event-based reference management

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***Abstract*—In this paper, a hierarchical control strategy is proposed to improve the WWTP performance from a plantwide perspective. An integral performance index (N/E index) is defined to measure the removal efficiency as the ratio between the nitrogen eliminated in the biological rectors (KgrN) and the energy (KWh) required to remove that amount of nitrogenated compounds. That index is controlled by an upper level PI controller that changes the dissolved oxygen (DO) set point of the lower level PI control loop. When the DO concentration is driven to excessively low limits, the N/E index set-point can be unreachable. Under this situation, the nitrogen elimination can be negatively affected. Therefore, it is not desirable to keep the plant in this situation for a long time. Therefore, an event-based controller is implemented to adapt the N/E index set-point to realistic values preventing long operation periods with the lowest DO concentration.**

Keywords—Wastewater Treatment Plants, PID control, plantwide control, hierarchical control strategies

I. Introduction

The operation of wastewater treatment plants (WWTPs) is a challenging task due to the complexity of the biological processes and the variable influent profile. The WWTPs are designed to produce environmental benefits rather than economic profits. Moreover, strict effluent quality requirements are imposed by European Directives. Then, it is important to develop control strategies that improve the operation of the WWTPs from a plantwide perspective [1-4].

The use of automatic control methods is an appealing solution to increase the efficiency of wastewater treatment plants [5-11]. The incorporation of automatic control strategies is slow in the wastewater treatment industry, the main reasons are the complexity of the biological processes and the lack and the expensiveness of the measurement equipment. Furthermore, the WWTP industry is conservative, which make difficult to test innovative control solutions on real plants [9], [10], [11].

Another solution that supports the development of innovative control strategies for WWTP is the use of benchmark models which allow different users to test their control structures and algorithms on the same platform. A first model is the Benchmark Simulation Model No. 1 (BSM1) [12]. The BSM1 represents only water treatment units and presents three different influent patterns, based on the rain conditions that may arise. The Benchmark Simulation Model No. 2 (BSM2) [13] integrates water and sludge treatment units. The WWTP behaviour is evaluated over a period of one year considering an influent profile that includes all the possible rain events that can occur in one-year period.

Economic objectives are important for the optimization of WWTPs operation, but, some other objectives need to be considered to provide decisions with a plantwide perspective [2], [4]. For instance, the efficiency in the elimination pollutants and the rational use of the biogas from sludge digestion [3]. In the process industry, hierarchical structures are typically employed to optimize the process operation. These strategies carry out, in an upper level, a real-time optimization (RTO) of the set-points that are sent to the basic control level

Regarding the operation of WWTPs, several works have demonstrated the advantages of the implementation of hierarchical structures to dynamically based on advanced control techniques to adjust the set-points of the basic control loops (aeration, dissolved oxygen control, ammonium control) in the activated sludge process [5], [6], [7], [8]. Nevertheless, it is known that, in practice, the usual control strategies applied in WWTPs are based on simple PI controllers and the objective of the control scheme is the regulation of the key variables at a constant set point [9], [10], [11], [12]. Therefore, a sound solution that can be applied in real practice is the optimization of the operation using PI, PID based hierarchical structures [3], [14].

In this work, process efficiency metrics are used to carry out a global evaluation of WWTP performance. The BSM2 platform [13] is used to represent the WWTP. The BSM2 include the most important processes of a WWTP which make easy to capture the interactions between the sludge and water lines. A hierarchical control strategy consisting on two cascaded PI is proposed to improve the global WWTP performance.

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The control problem is focused on the definition of an integral efficiency index for a typical WWTP operation, the index is the ratio between nutrient removal (Nitrogen) and energy required to remove that amount of nitrogen. The determination of the DO set-points will be on the basis of the mentioned global efficiency performance index. This index will be kept close to a desired operational value by means of a PI controller. Therefore, the overall plant operation scenario is defined just in terms of PI controllers.

One of the key points of controlling the proposed efficiency index is the definition of its desired value. As the plant operating conditions (load influent, temperature, etc) experience large variations from one day to another, it may be possible that the efficiency could not be attained because it may require dissolved oxygen values that are outside the recommended limits. In such case, as the dissolved oxygen level is the manipulated variable, the system would saturate, and the plant operation would remain on that point for undesirable time. This is not desirable from the point of view of the plant treatment and nutrient removal. Therefore, such situation should be considered. In order to adapt to these changing situations, an index set-point adaptation mechanism is proposed in this paper. On the basis of the measured dissolved oxygen levels, the system detects if the plant is going to work in a "out of oxygen". An event detector is defined that drives an event based on such situation and drives the set-point to a less exigent point. This generates a moving reference value for the efficiency index. This value will vary between two defined values and its adaptation will be done in terms of the plant of accepting to work with higher oxygen levels.

II. WWTP DESCRIPTION AND DEFAULT CONTROL STRATEGY

WWTP scenario is defined in terms of the BSM2. The layout of the plant is presented in Figure 1.

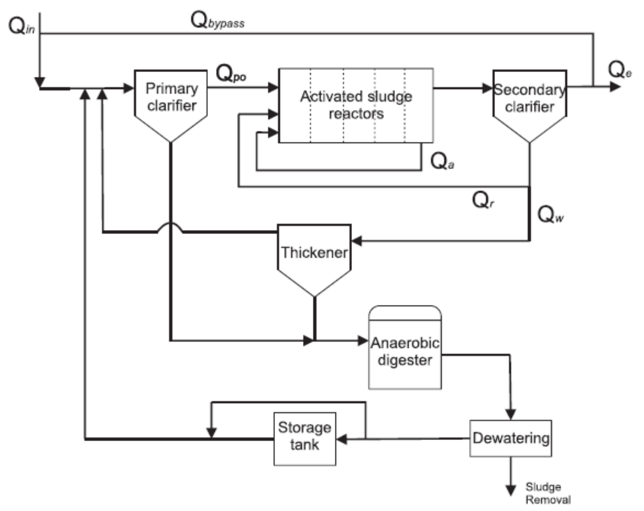

Fig. 1. BSM2 plant layout

The BSM2 [13] is a simulation benchmark that includes the activated sludge process described by BSM1 [12], a primary clarifier and the units for the treatment of the sludge wasted from the secondary settle (thickener, anaerobic digester, dewatering and a storage tank before recycling the remaining sludge to the water line). It includes the entire cycle of a WWTP, so the simulation period and the corresponding influent profile for disturbances assessment have been extended to one year, taking into account rainfall effect and temperature seasonal variations.

A. *Default control strategy*

The default control strategy proposed in the BSM2 platform for the activated sludge process is a PI control loop for dissolved oxygen (DO) in the aerated tanks. This strategy consists on the control of the dissolved oxygen concentration (DO) in the fourth aeration tank that simultaneously manipulates the oxygen transfer coefficient (*KLa*) of the three reactors that comprise the aeration zone. A PI controller computes the oxygen transfer coefficient for the 4th reactor (KLa_4), whereas KLa_3 and KLa_5 are calculated considering a gain of 1 and 0.5 respectively ($KLa_3=KLa_4$, $KLa_5=0.5\ KLa_4$). The dissolved oxygen is controlled to a set--point value of 2gr/m3. Additionally, an external carbon source with a concentration of 400000gr/m3 (usually methanol) is added to the first reactor in the anoxic zone with a constant flow of $2m^3/d$.

B. *Performance indices*

The control strategies tested in the BSM2 are evaluated using the performance indices proposed in the BSM2 simulation protocol. The effluent quality index is:

$$EQI = C_1 \int_{t_0}^{tf(days)} \begin{bmatrix} 2 \cdot SS_e + COD_e + 30 \cdot Nt_e \\ +10 \cdot S_{NO,e} + 2 \cdot BOD_e \end{bmatrix} Q_e dt \left[{Kg\ polution}/{d} \right] \quad (1)$$

where $C_1 = \frac{1}{T \cdot 1000}$ and T is the evaluation period and:

$$BOD_e = 0.25 \cdot \left((1-0.08)\left(X_{B,Ae} + X_{B,He} \right) \right) g/m^3 \quad (2)$$

$$COD_e = \left(S_{Se} + X_{B,Ae} + X_{B,He} \right) g/m^3 \quad (3)$$

$$Nt_e = S_{NOe} + S_{NHe} + i_{XB}\left(X_{B,He} + X_{B,Ae} \right) g/m^3 \quad (4)$$

$$SS_e = 0.75 \cdot \left(X_{S,e} + X_{I,e} + X_{B,H,e} + X_{B,A,e} + X_{P,e} \right) g/m^3 \quad (5)$$

The Influent Quality Index (IQ) is:

$$IQI = C_1 \int_{t_0}^{tf(days)} \begin{bmatrix} 2 \cdot SS_i + COD_i + 30 \cdot Nt_i \\ +10 \cdot S_{NO,i} + 2 \cdot BOD_i \end{bmatrix} Q_i dt \left[{Kg\ polution}/{d} \right] \quad (6)$$

where SS_i, COD_i, Nt_i, BOD_i are analogous to SS_e, COD_e, Nt_e, BOD_e but considering concentrations in the influent.

The concentrations and parameters involved are defined precisely in [12], [13].

Those indices are modified to consider only nitrogenated compounds:

$$EQIN = C_1 \int_{t_0}^{tf\,(days)} \left[30 \cdot Nt_e + 10 \cdot S_{NO,e}\right] Q_e dt \left[\frac{Kg\ polution}{d}\right] \quad (7)$$

$$IQIN = C_1 \int_{t_0}^{tf\,(days)} \left[30 \cdot Nt_i\right] Q_i dt \left[\frac{Kg\ polution}{d}\right] \quad (8)$$

The effluent quality limits defined within the BSM2 according with the environmental regulation are presented in table 1.

Table 1. Effluent quality limits

Total Nitrogen	< 18 grN/m^3
Chemical Oxygen Demand (COD)	<100 $grCOD/m^3$
Ammonium concentration (S_{NH})	4 grN/m^3
Nitrate concentration (S_{NO})	10 grN/m^3

The global operational cost index (OCI) described in BSM2 protocol [13] is:

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MP + HE_{net} \quad (9)$$

where *AE* represents the aeration energy in the activated sludge process, *PE* is the pumping energy in the full plant (involving all flows), *ME* is the mixing energy in the full plant, *SP* is the sludge production for disposal, *EC* is the external carbon addition and *MP* is the methane production. and HE_{net} is:

$$HE_{net} = \max\left(0, HE - 7 \cdot MET_{prod}\right) \quad (10)$$

where *HE* is heating energy necessary to heat the sludge to the digester operating temperature and MET_{prod} is the methane production (kWh/d).

III. Definition of an overal performance index for control

An index (N/E index) that represent the process efficiency as the energy (KWh) necessary to remove a Kgr of Nitrogen is presented in this work. The N/E index is computed as the ratio between the nitrogen removal obtained from eqs. 7 and 8 and the energy required by the plant to eliminate that amount of nitrogenated compounds expressed in terms of *PE*, *AE*, *HE* and *ME* as:

$$N/E = \frac{IQIN - EQIN}{PE + AE + HE + ME} \left[\frac{KgrN}{kWh}\right] \quad (11)$$

The operation of the BSM2 with the default control strategy have been tested considering an operation period of two years, but the colder week of the year have been selected to show the results. In is observed that NE index varies approximately between 0.5 and 7 KgrN/KWh in the selected operating window. Moreover, it is appreciated that oxygen concentration is kept constant by the default PI loop, but the index exhibits periodic variations that are linked with the variable influent load.

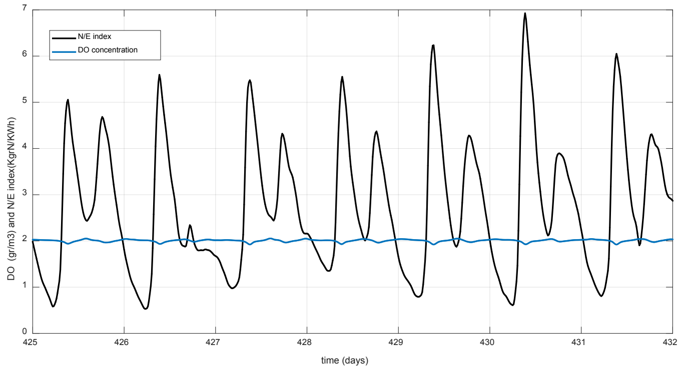

Fig. 2. N/E index values and DO concentration response obtained when using the BSM2 default control strategy

IV. Control problem formulation

The N/E index is used as an overall performance index in a hierarchical PI based control strategy. An upper level PI controller for the N/E index is implemented to provide the oxygen set point values that improve the ratio between nitrogen elimination and energy usage. The controller minimizes the difference between the efficiency index computed with the measured variables and the desired value. Thus, the upper level controller considers the nitrogen removal in the activated sludge process and the energy requirements of the full plant, which provides a link between activated sludge process and digestion process operation. This strategy was tested in [3] considering a fixed set point for the N/E index.

In this work, an event-based set-point adjustment of the N/E index is introduced to avoid operate in conditions where N/E index reference is unreachable. Due to the influent variability, there are situations where the efforts to improve efficiency leads the DO set-point to their lower bound (in this case 0.5mg/l). Then, an event-based controller has been defined to reduce the N/E index set-point to reachable values, avoiding the upper level controller to command DO set-points below the lower bound of its admissible values. The rationale of the event-based controller is based on the following operating rule: it should reduce the value of the N/E index set-point once the DO concentration achieves their lower limit, but, increases the N/E index set-point when DO concentration separates from this critical operating zone. However, if we do this operation in a continuous way, the N/E index will be continuously moving and completely following the DO dynamics. Instead, the following event-based approach is formulated. First of all, the following parameters are necessary

- Ts: Sampling time at which the event-based detector will operate.
- DO_low: Lower value for the DO that should be avoided
- Delta: Increments on the N/E set-point that should be performed at each event.
- N/E_{Max}, N/E_{Min}: Maximum and minimum values for the N/E index.

The logic of the event-based reference update is as follows:

Inputs: DO, N/E_{SP}

if (DO < DO_low)

N/E_{SP}=min(N/E_{Min}, N/E_{SP} -Delta);

else

N/E_sp=min(N/E_{Max}, N/E_{SP} +Delta);

end

This is to be executed every Ts. The N/E reference will therefore remain constant during the Ts time interval.

A schematic representation of the proposed control strategy is presented in figure 3. The upper level PI controller is followed by a first order filter with unitary gain and time constant of 0.1. The desired values of the N/E index SP are modified by the event-based controller (Adapt SP). This PI controller sends the DO SP to the lower level PI that manipulates the oxygen transfer coefficient (*KLa*) of the 4th reactor to attain the desired values of the DO concentration.

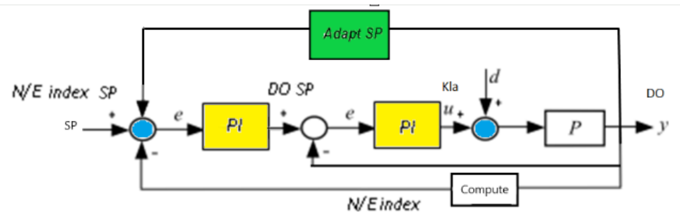

Fig. 3. Proposed control strategy: N/E control strategy with event-based set-point adjustment

V. RESULTS

The upper level PI controller is designed using this first order model following an IMC approach [15], [16]. The resulting PI controller parameters obey to the expressions:

$$T_i = T \qquad Kp = \frac{T}{\lambda \cdot K}$$

where T is the process time constant and K is the process gain.

As it is well known, the selection of the λ parameter has a direct relationship with the closed-loop speed of response. If T_{CL} is the desired closed-loop time constant, then the controller λ can be expressed in a more convenient way as $\lambda = T_{CL} \cdot T$ being T_{CL} the relationship between the open-loop and the closed-loop time constants. Therefore, a step change is applied to the DO set-point considering constant influent flow and concentration, the N/E index response to a magnitude two decreasing step change is presented in figure 4. Then, the N/E index response is approximated with the following first order model:

$$\frac{N/E\ index}{DO} = \frac{0.25}{0.2s+1} \qquad (12)$$

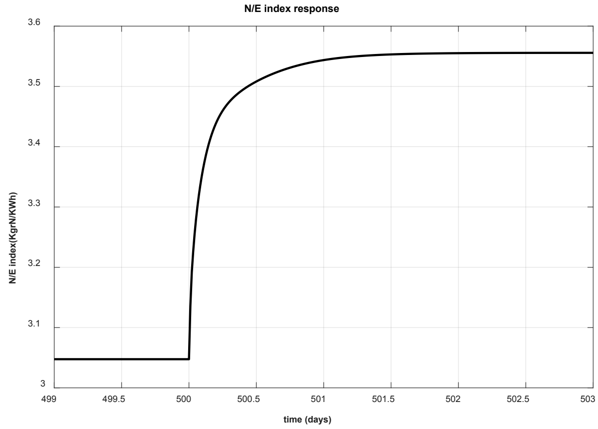

Fig.4. N/E index response

The controller parameters computed for a $\lambda = 0.8$. They are Ti=0.2 and Kp=1. An anti-windup configuration is considered.

The proposed event-based reference management strategy is implemented in the BSM2 platform to be compared with the hierarchical control of the N/E index set-point considering a constant reference and the default BSM2 strategy.

The selection of the set point for the N/E index is based on the idea of improving the average value of the index compared with the values achieved when using the default control strategy. The observation of figure 2, leads to consider 4 KgrN/KWh as an appropriated value for the constant set-point strategy.

In the case of the event-based reference management strategy, the N/E set point SP can move between 4.2 and 3.2 to take advantage of the flexibility given by the consideration of a variable reference. Sequential step changes are carry out the admitted variation range.

The simulation of the process response with the proposed strategy considering that reference can vary between their limits with steps 0.25 KgrN/KWh and a sampling time of 1 hour is presented in figure 5 and compared with the constant SP strategy and the default control strategy. It is observed the higher values of the N/E index are achieved which indicates an improvement of plant efficiency.

The movements of the manipulated variables are presented in figure 6. In figure 6, it can be observed that DO is in the lower limit (DO=0.5 gr/m^3) in most of the operating period when using the constant SP hierarchical strategy, while the variable SP strategy avoids this undesirable condition. If affects ammonium removal as seen in figure 7, lower levels of ammonium in the effluent are achieved with variable SP hierarchical strategy. The lowest levels are attained with the default strategy, but it implies an excessive use of energy.

One of the key points of controlling the proposed efficiency index is the definition of its desired value. The variable operating conditions (influent load, temperature) affect the process efficiency and the desired value could not be achieved because it may require reducing the dissolved oxygen concentration to values that are outside the recommended limits. In such case, the manipulated variable (DO) would saturate and the plant operation would remain on that point for undesirable time. This is not desirable from the point of view of the plant treatment and nutrient removal. The proposed index set-point adaptation mechanism (N/E control variable SP) detects if the plant is close to the "out of oxygen" condition. The event detector drives an event based on such situation and drives the set-point to a less exigent point, generating a moving reference value for the efficiency index. This value adaptation will be done in terms of the plant of accepting to work with higher oxygen levels.

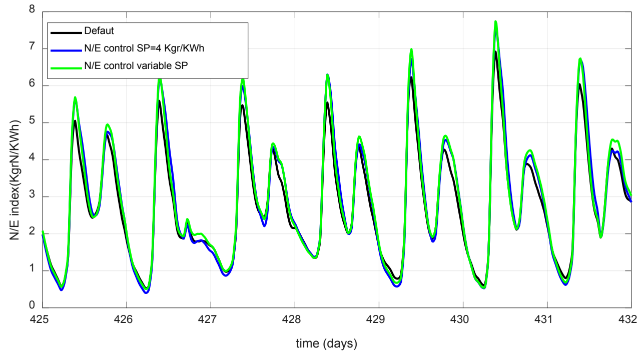

Fig. 5. Comparison of different N/E control strategies with the default control strategy

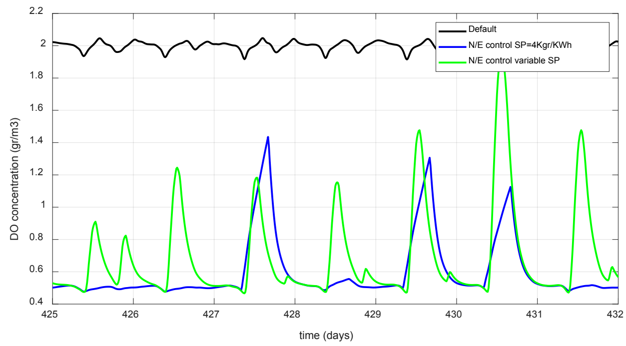

Fig. 6. Comparison of DO movements with the different control strategies

The changes of the N/E index set-point produced by the event detector are presented in Figure 8. The set-point is varied between 4.2 and 3.2 with Delta=0.25 and Ts=$1^{1/2}$ hours. The effect of the frequency and magnitude of the changes can be evaluated. Three case studies are considered, where the reference can vary between their limits with Delta 0.5, 0.25 and 0.125 KgrN/KWh at each sampling time. The sampling time is selected to cover the N/E index span in $1^{1/2}$ hours, 3 hours and 18 hours respectively. The N/E index set-point movements for the different cases are shown in figure 9.

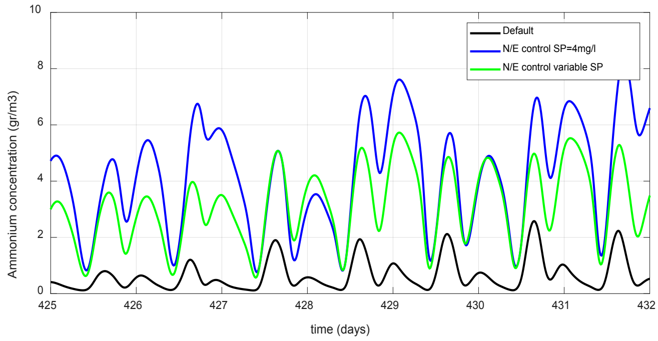

Fig. 7. Comparison of ammonium concentration with the different control strategies

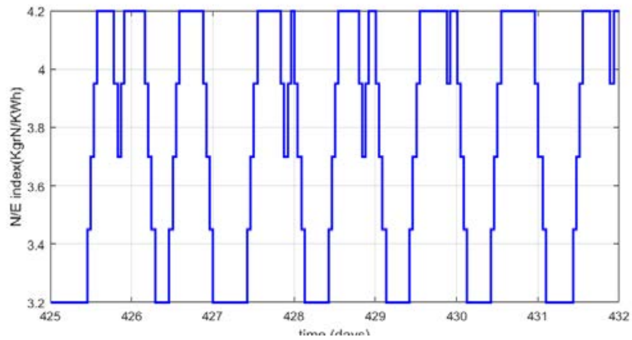

Fig. 8. N/E index variation in the variable N/E SP control strategy (a) Delta= 0.25

The comparison of computed DO set point considering different values of Delta for the N/E index set-point movements is shown in figure 10 and the N/E index control error is shown in figure 11. It is observed that slow movements of the index produce more changes in the manipulated variable (DO set-point) but also, larger control error.

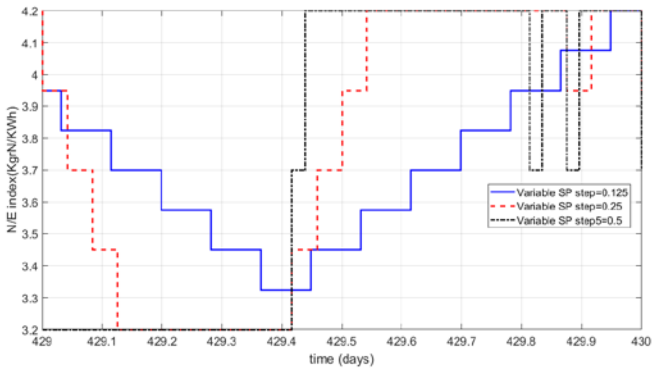

Fig. 9. N/E index variation in the variable N/E SP control strategy. Comparison of different Delta (SP step) for the N/E index set-point.

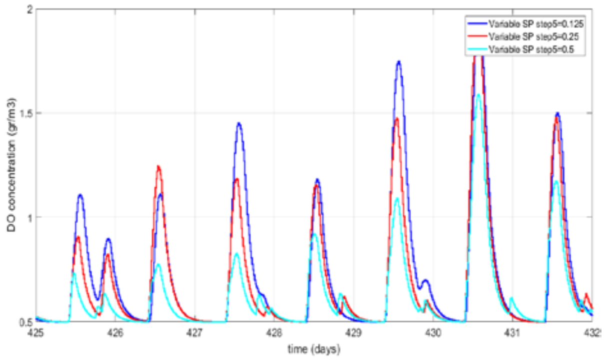

Fig. 10. DO set point variation. Comparison of different step sizes of the N/E index set-point movements

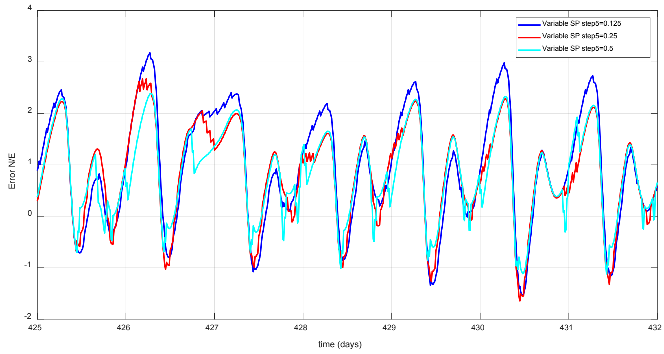

Fig. 11. N/E index error in the variable N/E SP control strategy

CONCLUSIONS

An integral efficiency index (N/E index) that measures the ratio between the nitrogen removed in the activated sludge process (KgrN) and the energy (KWh) required for eliminating that amount of nitrogenated compounds is used as an overall performance index to improve the global operation of WWTPS. A hierarchical PI based control strategy is proposed: the upper level PI controller regulates the index to a desired value using the oxygen (DO) set point as manipulated variable. To avoid the situations where the N/E index set-point is unreachable, an event-based controller is introduced to reduce the N/E index set-point to reachable values, avoiding the upper level controller to command DO set-points below the lower bound of its admissible values. The comparison of controlled process response with default BSM2 strategy and constant set-point hierarchical strategy, demonstrates that the event-based controller adapts the N/E index set-point to realistic values preventing long operation periods with the lowest DO concentration; it improves process efficiency as well as ammonium removal.

ACKNOWLEDGMENT

The authors acknowledge the support of the Spanish Government through the MINECO/FEDER projects DPI2015-67341-C2-1, DPI2016-77271-R and Dr Ulf Jeppsson, Dr Christian Rosen and coworkers for the BSM1 platform.

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