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**RAPID COMMUNICATION**

# Control of a wastewater treatment plant using relay auto-tuning

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**Abstract**−Efficient performance of a wastewater treatment plant largely depends on optimal process control. Owing to their complexity and nonlinearity, such processes are difficult to control. In this study, relay auto tuning method is analyzed to design of a proportional integral derivative controller for the activated sludge biological process. The process is estimated as a first-order process with time delay. The key control variable in wastewater treatment is the concentration of dissolved oxygen during the aeration process. The influence of higher order harmonics on the system critical values is considered during the design using preload relay and a modified two-step relay. The system performance was evaluated for both servo and regulatory mechanisms. In addition, the designed controller was tested in the presence of noise for the robustness analysis.

Keywords: ANAMMOX, Relay, Auto-tuning, Activated sludge process, PID control, DO control

## INTRODUCTION

A control system is designed to regulate a process at the specified operating conditions, along with the regulation of environmental and product quality protocols, in order to increase the combined profitability and efficiency of the system. Optimal control of a wastewater treatment plant (WWTP) has high computational time and operating-maintenance cost requirements owing to the highly complex and integrated process units. The optimal control of any system largely depends on the selection of control valves, sensors, and transmitters. The proportional integral derivative (PID) controller is a crucial part of industrial control, owing to ease in implementing, tuning and availability along with the satisfactory performance.

Efficient performance of the PID controller can only be ensured if the controller is tuned according to the process specifications. The dissolved oxygen (DO) concentration is considered the most critical control parameter for biological processes, as it directly affects the growth and inhibition of microbial species. The DO concentration varies depending on the influent concentration, and it is directly related to the air flow rate, which in turn affects energy consumption and the operating cost of the process. Tuning the controller involves selection of appropriate proportional, derivative, and integral gains. Tuning the controller is heuristic and time-consuming and numerous methods are available for controller tuning, including pole placement methods, internal model control (IMC), relay auto-tuning, and optimization based analytical methods [1,2]. A number of automated relay tuning methods have been developed recently. Various aspects of the auto-tuning method are reviewed by many researchers [3-10]. Auto-tuning, consisting of a conventional relay or modified relay, is widely used for linear and nonlinear process control. Saturation relay [11], asymmetric relay with an additional lead element [12], asymmetric relay [13], relay with multiple switching [14], relay with hysteresis [15] and discrete time with general minimum variance [16] are used for the identification and control of stable systems. The implementation of auto-tuning techniques for wastewater treatment plants has not received much attention. For ease in industrial implementation of the relay auto-tuning technique, auto-tuners are available from several vendors, including ABB, Honeywell, and Siemens. Most of the methods presented in the literature for aeration control involve the design of advanced controllers.

A nonlinear single-input single-output (SISO) model predictive control (MPC) based on oxygen dynamics for control of DO was developed [17] and improved using fuzzy predictive control [18]. The challenges faced during aeration control were addressed [19]. A rule-based feedback feed-forward controller to determine the set point for DO was widely used for the control purpose [20]. The feed-forward control determines the DO set point based on the nitrification capacity, while the feedback loop analyzes the influent ammonia concentration to determine the set point of the DO. A sub-space identification method was used to develop a DO model for the control of WWTP and was compared with MPC controllers based on the overshoot and settling time [21]. A comparison method study for tracking oxygen concentration using a nonlinear model predictive control with an adaptive model reference control [22] and model based optimization technique for determination of DO concentration and controller parameter based on gain scheduling [23] was carried out. An investigation on methods for optimization of the aeration time and an MPC controller for set point tracking based on a linearized model was conducted [24]. Using the Ziegler-Nichols and the relay technique, a PID controller to regulate the air flow rate in a system in real-time was designed [25]. A combined model of a blower with MPC to regulate the concentration in an activated sludge model [26] and fuzzy controller to control the DO concentration [27] was implemented. The con-

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troller behavior is the same as for a controller designed using gain scheduling. A linear air flow distribution control strategy to regulate the amount of DO in the bioreactor was analyzed by measuring the DO at the start and end of a WWTP with four aeration zones [28].

This study focused on the auto-tuning method, in which knowledge of the system response to a specific frequency is employed. Section 2 briefly discusses the relay control strategy, the issues associated with implementation, and the measures proposed to overcome these difficulties. The subsequent section describes the controller design for the biological process using the auto-tuning technique. Here, the activated sludge process is considered. A simulation study was also conducted to evaluate the system performance.

## RELAY CONTROL STRATEGY

With recent development in technology, the use of Ziegler-Nichols [29] technique for designing controller has gained popularity in industrial process control, and it has been automated by Åström and Hägglund using an on-off relay [30]. The Ziegler-Nichols method is a heuristic method for determining the critical points of a system, whereas the auto-tuning method produces the limit cycles in a single attempt. The auto-tuning method tunes the controller depending on system stability analysis along with the limit cycles. Limit cycles are used for determining critical points.

In auto-tuning method, a relay is introduced instead of a PID controller in the feedback control loop and is used to perturb the system. Mathematically, a relay is sum of the square wave of odd frequencies. It has been observed that when a lag of $\pi$ radians is generated between the output and input, the closed loop system produces sustained oscillations with the ultimate period ($P_u$) commonly known as the limit cycles. The relay output is given in Eq. (1), and the control system with the relay as the feedback controller is shown in Fig. 1.

$$u(t)=\frac{4h}{\pi}\left[\sin(\omega t)+\frac{1}{3}\sin(3\omega t)+\frac{1}{5}\sin(5\omega t)+\cdots\right] \tag{1}$$

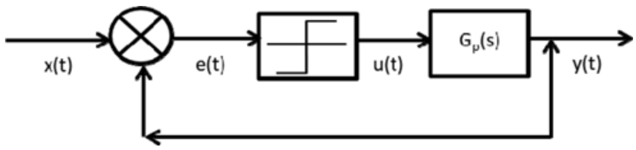


**Fig. 1. Block diagram representation of a control system with a relay as the feedback controller for a positive gain system.**

The direction of the relay input depends on system gain. For positive and negative steady state gain systems, the relay definitions are given in Eq. (2) and Eq. (3), respectively:

$$u=\begin{cases}+h & e(t)>0\\ -h & e(t)<0\end{cases} \tag{2}$$

$$u=\begin{cases}-h & e(t)>0\\ +h & e(t)<0\end{cases} \tag{3}$$

Using Fourier series analysis and describing function analysis, the relationship between the height of the relay, h, the limit cycle amplitude, a, and system ultimate gain, $K_u$, can be expressed as follows:

$$K_u=\frac{4h}{a\pi} \tag{4}$$

For the Fourier series analysis, the assumption considers that the system has characteristics similar to a low pass filter. This assumption states that the fundamental frequency sinusoidal wave can pass through the system and is obtained as the output. On the other hand, many researchers have noted that the shape of the limit cycle waveform is not always sinusoidal, and it varies with changes in the process time and dead time constants. In a system having characteristics of first-order process with time delay (FOPTD), the shape of the waveform shifts from a triangle to a rectangle form as the $D/\tau$ ratio increases [31]. 27% deviation in the ultimate gain from its original value was observed for a system with a high $D/\tau$ ratio,

**Table 1. Methods to reduce the effect of higher order harmonics**

| S. No. | Method | Description |
|---|---|---|
| 1. | Modified relay feedback | A non-linear element, containing higher order harmonic part, is introduced along with the describing function |
| 2. | Six step relay | The proposed method reduced the third order and fifth order harmonic effect |
| 3. | Saturation relay | Saturation relay is characterized by relay height (h) and relay slope (k). The relay slope (k) plays important role in generation of limit cycles |
| 4. | Biased relay method | The method combines biased relay with Fourier analysis theorems |
| 5. | Twin channel relay | An additional relay parallel to conventional relay is inserted in the system that acts on integral of process output |
| 6. | Two channel relay | The technique involves the conventional relay feedback test followed by two-channel relay feedback test. Two channel consists of proportional path and integral plus relay path |
| 7. | Preload relay | Preload relay is a combination of ideal relay and a gain element in parallel |
| 8. | Modified relay method | Combined ten pulses to generate one period of relay. The ten pulses are combined based on the optimum solution of a constrained non-linear optimization problem |
| 9. | Modified relay method | Relay is considered as linear combination of sub relays of different frequency and gains |

whereas for a system with a lower D/$\tau$ ratio, the value deviated up to −18% [32]. This signifies that higher order harmonics affect the controller performance.

To obtain the exact values of critical points and minimize the higher order harmonic influence, describing the function along with a nonlinear element is used during the relay feedback analysis [33]. A six-step relay can be introduced to reduce higher order harmonics influence on the ultimate gain [34]. Saturation relay [11], biased relay [35], and a two-channel relay [36] can be applied to identify the ultimate gain value. Table 1 lists the methods employed to modify the conventional relay auto tuning system. An equation was proposed by modifying the Fourier series study of the process response, y(t), to take effect of harmonics into account [37]. The advantage of the method [37] is that no extra experimentation or simulation is required for implementation, unlike for other methods. The application of the method in the real time scenario depends on the divergence of the limit cycle waveform from sine curve behavior and the transient dynamics. The combination of a relay in parallel with the gain (known as a preload relay) to increase accuracy [38], a combination of ten pulses to obtain the limit cycles [39], and a combination of sub-relays with different frequencies to include the effects of higher order harmonics [40] was introduced for the determination of ultimate gain value.

## DESIGN OF PID CONTROLLER

This study considers the biological process for the treatment of wastewater, represented by the activated sludge model. A model for this process was developed [41] that accounts for both the microbial processes and the mass transfer processes through diffusion and liquid transfer at the bio-film scale and reactor-level scale. The models developed at each of these scales are linked using film theory. The process model is built and simulated in MATLAB - Simulink R2014, as shown in appendix A. The values for the process parameters are taken from literature [41] and random values are assigned as the initial conditions for all dependent state variables. Fig. 2 shows the open loop control system for the anaerobic ammonium oxidation (ANAMMOX) process.

The air flow rate is used as the manipulated variable. Mathematically, the air flow rate is represented by the oxygen mass transfer

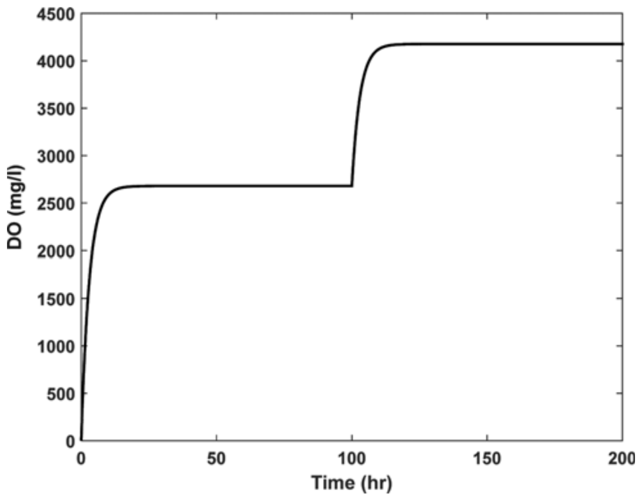


**Fig. 3. Process reaction curve corresponding to a change in mass transfer coefficient from 100 to 200 day$^{-1}$ at t=100 hr in the nonlinear system.**

coefficient, $K_La$. The controlled variable is the concentration of dissolved oxygen, and the disturbance is the rate of oxygen uptake. The nonlinear system is simulated as an open loop with a step change in the manipulated variable at time t=100 hour. The process reaction curve, shown in Fig. 3, depicts the change in transient behavior of the oxygen concentration with a change in the air flow rate. It is assumed that the system response to a step change has the shape of a first order plus time delay model.

From the step response, the process is estimated using simple formulae [42].

In the FOPTD model, $G_p(s)$ is given as follows:

$$G_p(s)=\frac{K_P e^{-\tau_d s}}{\tau s+1} \tag{5}$$

where

$$K_P=\frac{\Delta y_\infty}{\Delta u_\infty} \tag{6}$$

$$\tau_d=1.3t_1-0.29t_2 \tag{7}$$

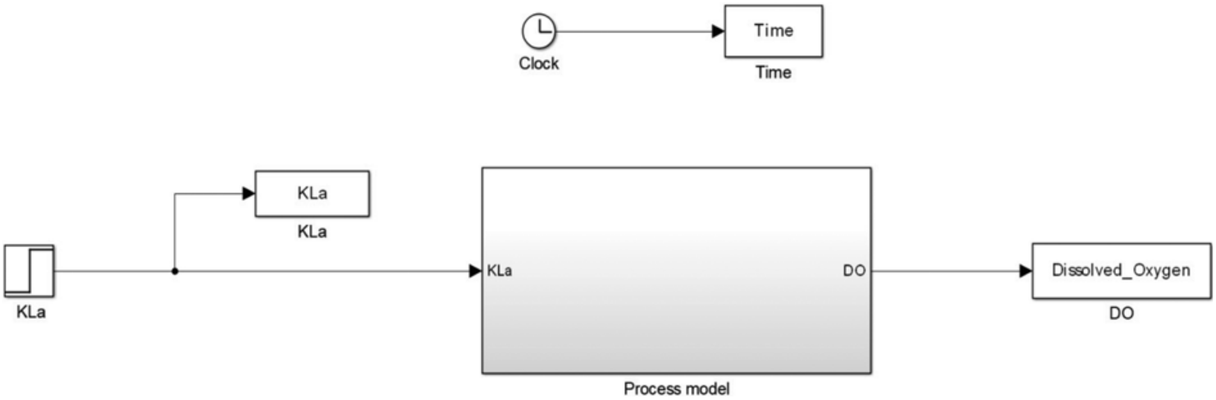


**Fig. 2. Open loop control system for the ANAMMOX process.**


**Fig. 4. Open loop control system for the FOPTD model.**


**Fig. 5. Open loop control system for the SOPTD model.**

$$\tau = 0.67(t_1 - t_2) \tag{8}$$

Here $t_1$ and $t_2$ are the times on the process reaction curve when the system responses are 35.3% and 85.3%, respectively. By analyzing Fig. 4, the process parameters can be obtained for the first-order system as $K_P$=14.97, $\tau_d$=101.08, and $\tau$=3.0820.

Further, the Smith method is used to estimate the process as a second order system, $G_p$, given as

$$G_p(s) = \frac{K_p e^{-\theta s}}{\tau^2 s^2 + 2\tau\zeta s + 1}$$

The process is estimated as

$$G = \frac{14.97e^{-101.08s}}{0.49s^2 + 2.8s + 1}$$

Once the process model is identified, the open loop simulation is conducted (Figs. 4 and 5) to verify the stability of the system.

To configure the controller with the help of the auto-tuning method, a negative feedback control loop system is considered, as shown in Fig. 6. The proportional-integral-derivative controller, PID, is replaced by a symmetrical relay element, and the process is simulated with the set point equal to zero. The relay height, h, is assigned a value of 0.1. As the gain of the system is positive, the switching of the relay corresponding to the error is considered from +0.1 to −0.1. The limit cycles (Fig. 7) are obtained from the simulation and evaluated. It is seen that both of the estimated models behave in the same manner. The amplitude (a) and the period of oscillation ($P_u$) of the limit cycle in the absence of noise are 1.497 and 206.4, respectively. Fig. 7 shows that the limit cycle waveform

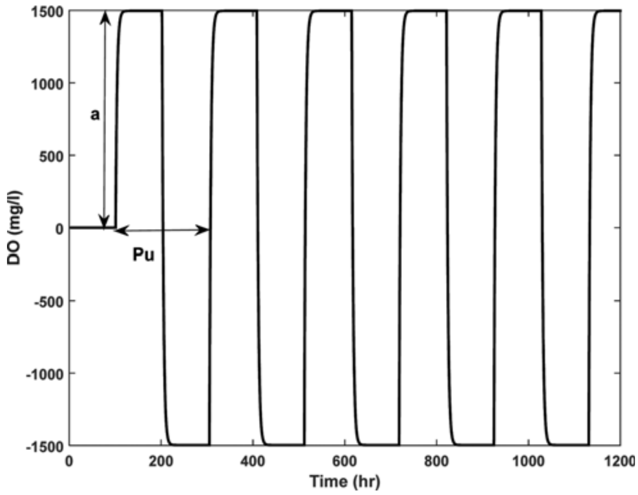


**Fig. 7. Limit cycles obtained for the FOPTD model in the absence of noise using the two-step relay.**

is approximately rectangle in shape. As explained in the previous section, this contradicts the assumption made during the Fourier series analysis. The method needs to be modified to account for the higher order harmonics effect. Here, two methods [37,38] are employed to study the effect of higher order harmonics.

Srinivasan and Chidambaram [37] devised a technique to consider the effect of higher order harmonics by modifying amplitude of the limit cycles. For implementation of this method, the conventional technique of inserting the relay into the feedback loop is employed. The proposed modification rule is as follows:

$$a^* = \frac{y(t^*)}{1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots + \frac{1}{N}} \tag{9}$$

where $a^*$ is modified amplitude, $y(t^*)$ is relay response of the process at $t^*=0.5\pi/\omega_u$ after sustained oscillations are obtained, $\omega_u=2\pi/P_u$, and N is number of higher order harmonics not filtered out through the system. The modified amplitude ($a^*$) of the limit cycle and modified ultimate gain are 2.2194 and 0.0615, respectively, when seven harmonic terms are incorporated. The improved ultimate gain ($K^*_u$) is then determined using Eq. (10) below.

$$K^*_u = \frac{4h}{\pi a^*} \tag{10}$$

Tan et al. [38] changed the relay method using a preload relay.

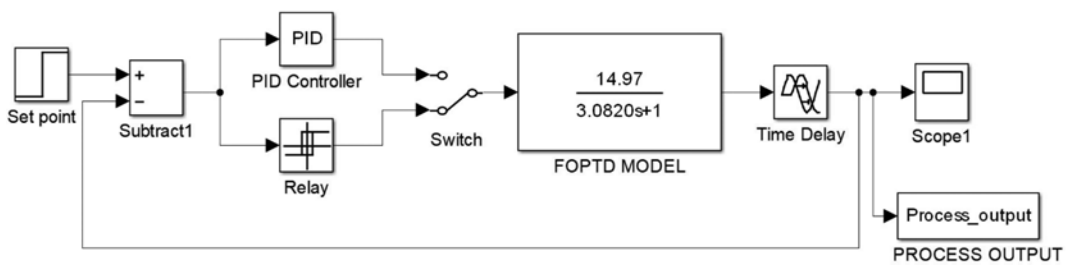


**Fig. 6. Closed loop control system for the FOPTD model.**

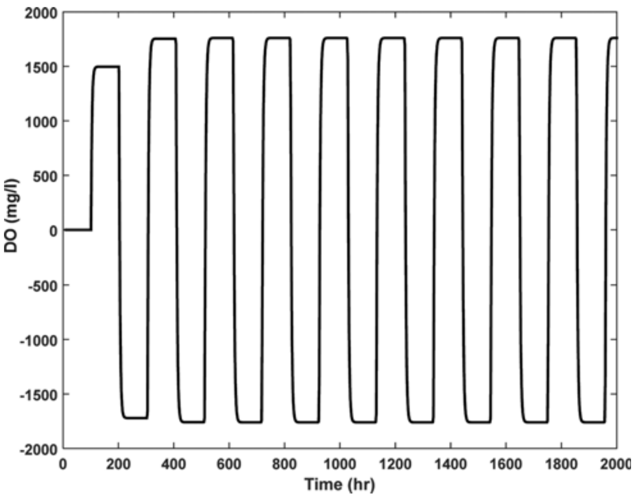


**Fig. 8. Limit cycles obtained for the FOPTD model in the absence of noise using the preload relay.**

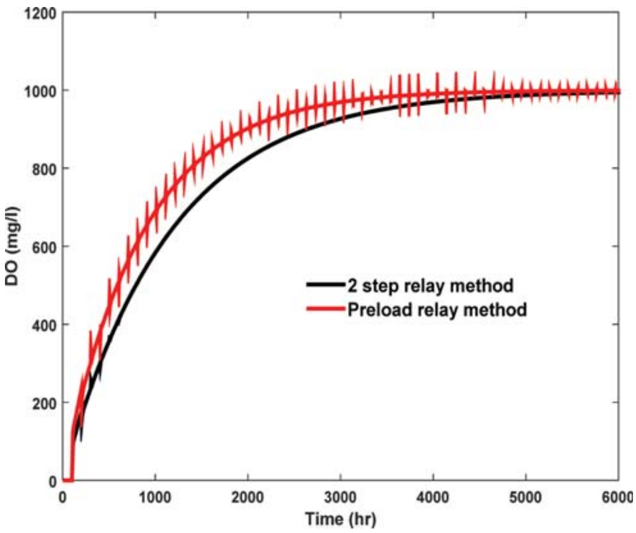


**Fig. 10. Closed loop servo response of the ANAMMOX process estimated as FOPTD system for a set point of 1,000 mg$O_2$/L.**

This increased the amplitude of the fundamental frequency over the higher order harmonics. A preload relay is a parallel combination of a two-step relay and a gain. The limit cycles produced using the preload relay are shown in Fig. 8. A gain, K, of 0.01 and relay height, h, of 0.1 are used to simulate the control loop. The amplitude (a) and the period of oscillation ($P_u$) of the limit cycle in the absence of noise are 1.761 and 206.6, respectively. The ultimate gain ($K_u$) is determined to be 0.0823 using Eq. (11).

$$K_u = \frac{4h}{\pi a} + K \tag{11}$$

Fig. 9 shows the limit cycles obtained using the two-step relay in the presence of noise. The values of $P_u$ and a are obtained as the average of the corresponding values from a minimum of five repetitive cycles. Limit cycle analysis indicates that the limit cycle amplitude (a) is 1.517 in presence of noise with a standard deviation (SD) of 0.01 and 1.476 in the presence of noise with SD of 0.02. The periods of oscillation are 205.9 and 206.7, respectively.

It is noted that the value of the ultimate gain ($K_u$=0.0607 in the presence of noise of 0.01 SD and $K_u$=0.0624 in the presence of noise of 0.02 SD) obtained using Eq. (10) in the presence of noise is close to the value obtained in the absence of noise ($K_u$=0.0615).

The PID controller is then designed based on the ultimate gain and the period of oscillations. The tuning rules for the controller tuning of a stable system based on a stability analysis have been reviewed [43]. The following tuning rules are considered for the controller tuning: $K_c$=0.1$K_u$, $\tau_i$=0.5$P_u$, and $\tau_d$=0.125$P_u$. The PID parameters obtained using the two-step relay method are $K_c$=0.006, $\tau_i$=103.2, and $\tau_d$=25.8, whereas the PID parameters obtained using

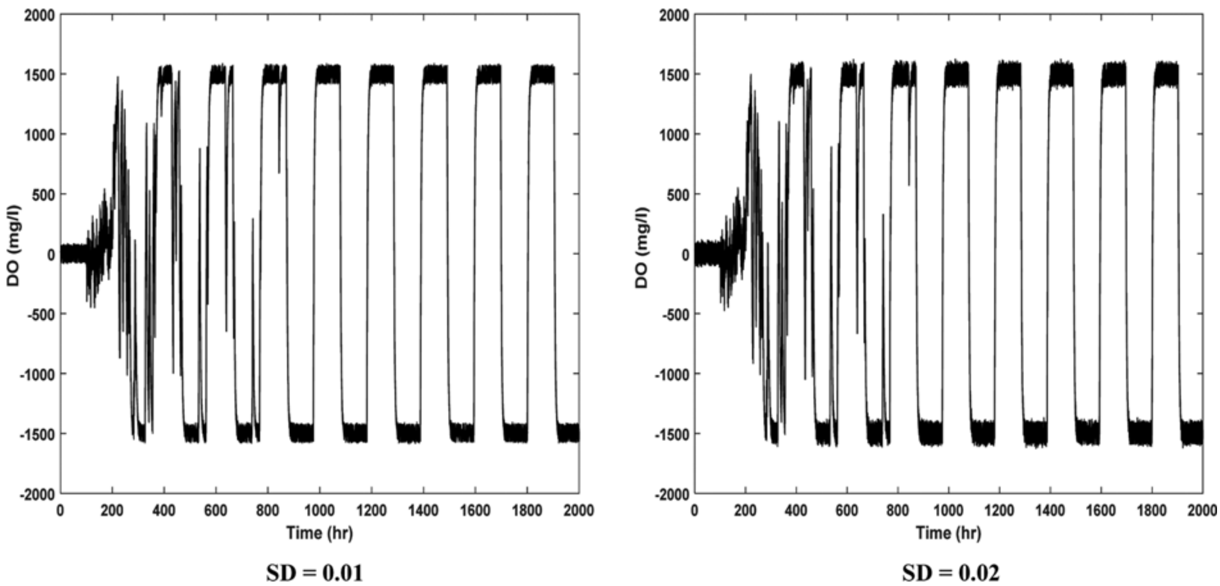


**Fig. 9. Limit cycles obtained for the FOPTD model in presence of noise with mean=0.**

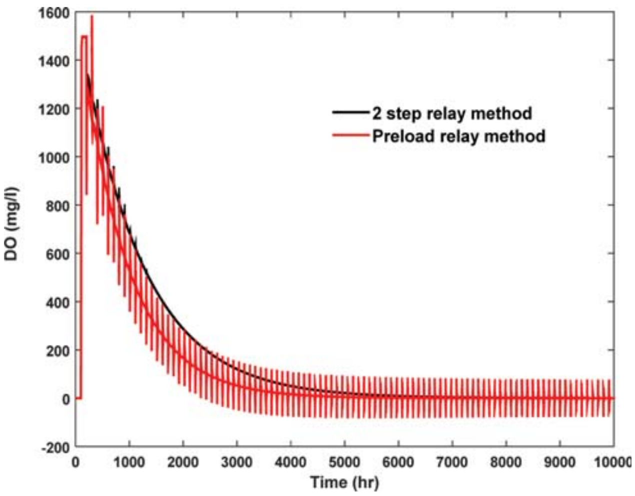


**Fig. 11. Closed loop regulatory response of the ANAMMOX process estimated as FOPTD system for a unit step change in the disturbance.**

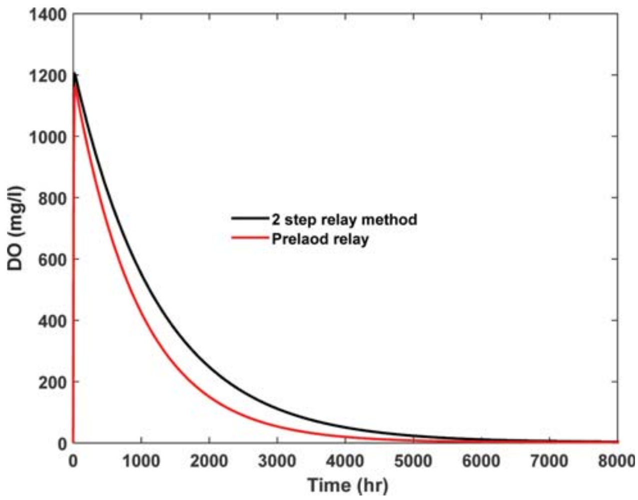


**Fig. 12. Closed loop regulatory response of the nonlinear ANAMMOX process.**

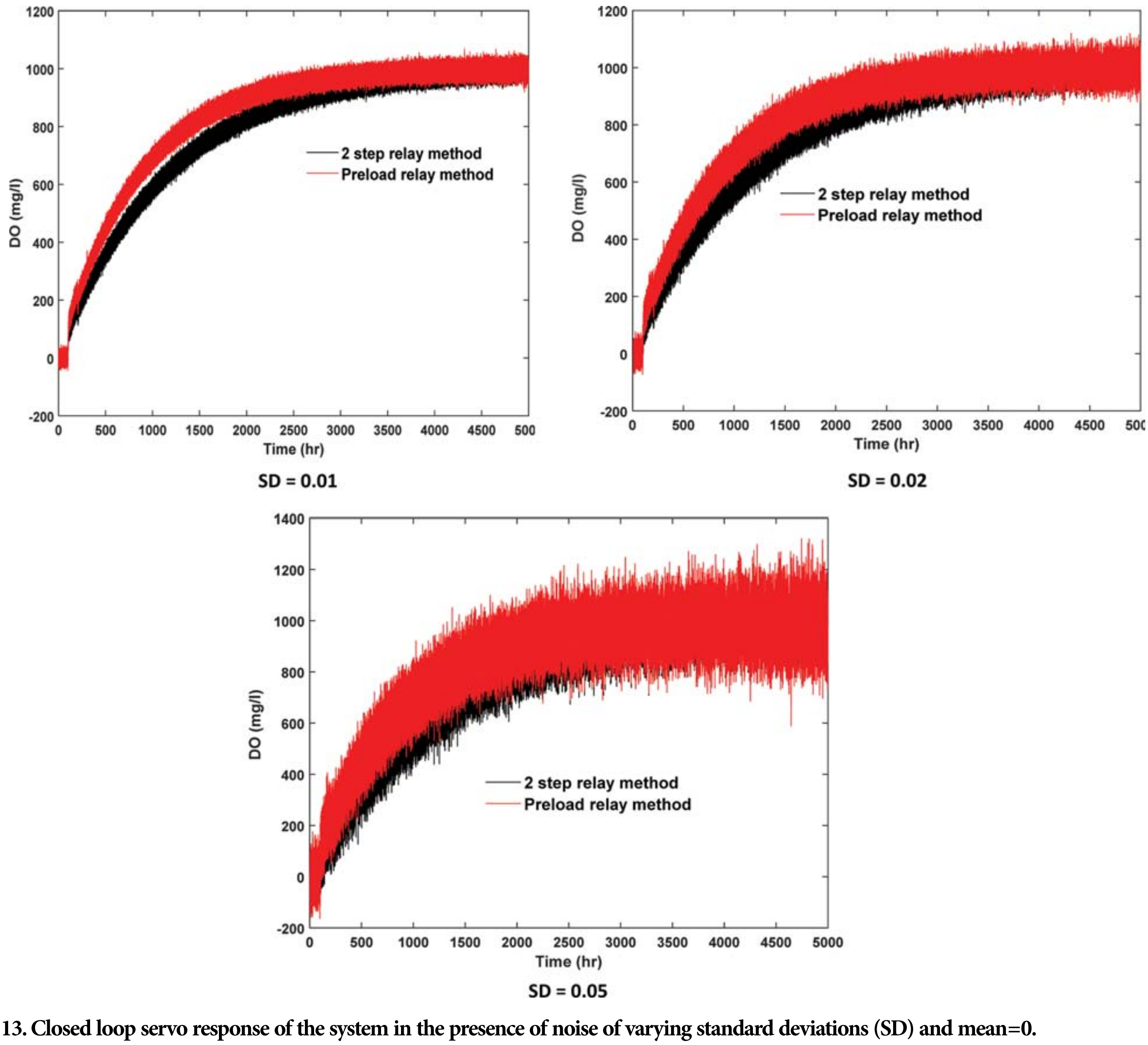


**Fig. 13. Closed loop servo response of the system in the presence of noise of varying standard deviations (SD) and mean=0.**

the preload relay method are $K_c$=0.008, $\tau_i$=103.3, and $\tau_d$=25.82. The closed loop PID Simulink is built using these parameters, as shown in Fig. 6, and is simulated for changes in set point (dissolved oxygen) and disturbance. The servo and regulatory transition behavior of the dissolved oxygen are shown in Fig. 10 and Fig. 11 for the unit change in the reference and disturbance, respectively. For servo response, the integral square error (ISE) value for the two-step relay method is 578.2, whereas for the preload relay method, the ISE is 436.4. The two-step relay method provides better performance than the preload relay. Once the controller action is verified for the linearized plant model, the nonlinear plant is simulated using the same controller parameters with a set point of 1,000 $mgO_2/l$. The set point is achieved at a faster rate with few oscillations in the process output. The regulatory response shown in Fig. 11 illustrates that although the response from the two-step relay method is slow, it provides less oscillatory response than the preload relay method. The closed loop regulatory response of nonlinear process is shown in Fig. 12. As a compromise between fast response and smoother performance, the two-step relay method proposed by Srinivasan and Chidambaram [37] is preferred for both the servo and regulatory mechanism. A comparison of the dissolved oxygen behavior in the presence and absence of the controller was studied, and the improvement achieved indicates efficiency, speed, and a minimization of steady state error.

To verify the robustness of the controller, the transition behavior of the dissolved oxygen in the presence of noise was analyzed. Fig. 13 shows the performance for a change in the airflow rate in presence of noise of varying standard deviations. At steady state, the output of the process oscillates near the set point. However, with an increase in the standard deviation of the measurement noise, the response becomes more oscillatory. The effect of the noise can be minimized with the help of a filter.

## CONCLUSIONS

An efficient and simplified PID control system was designed using a simulation study to allow regulation of the dissolved oxygen concentration during the aerobic stage of a wastewater treatment process. As the activated sludge process is nonlinear and time-variant, an auto-tuning method was used to allow the controller to be tuned online according to the real-time system conditions. The results indicate that the control system provides a short rise time, zero steady state error, and less oscillatory response. Moreover, the system can reject incoming disturbance in the oxygen uptake rate. The controller was designed using the auto-tuning technique, and the effect of higher order harmonics was considered with two different methods. The Srinivasan and Chidambaram method [35] uses a two-step relay, while the Tan et al. method [38] uses a preload relay. The results show that the Srinivasan and Chidambaram [37] method gives satisfactory results for both servo and regulatory mechanisms compared to the Tan et al. method [38]. The servo response of the nonlinear system was simulated at a set point of 1,000 $mgO_2/l$. The effect of measurement noise on the limit cycles was also analyzed. It is observed that the ultimate values obtained in the latter case are close to the original values. The resulting controller is robust in the presence of noise. The main advantages of the developed control system include flexibility in changing PID values and set points based on the influence of disturbance, good disturbance rejection capability, efficient performance in the presence of measurement noise, easy implementation and lower operational costs. The results obtained from these simulations are promising, and this control system can be easily implemented on an industrial scale with the help of auto-tuners.

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## APPENDIX A

The nonlinear simulation of the process is shown in Fig. A1.

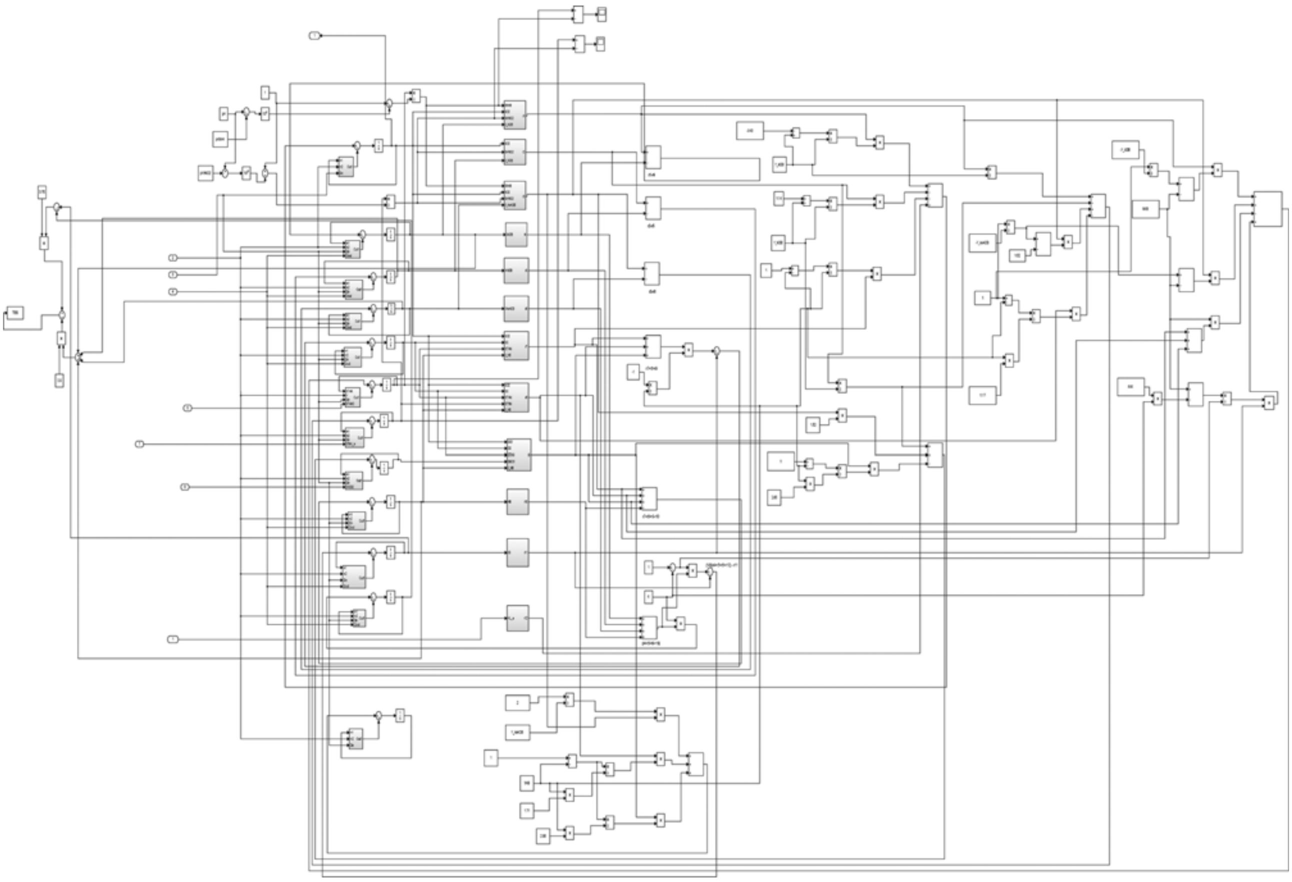

**Fig. A1. Process model in MATLAB - Simulink R2014.**