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Robustness enhancement study of augmented positive identification controller by a sigmoid function

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ABSTRACT

The dissolved oxygen concentration in the wastewater treatment process (WWTP) must remain in a specific range while the factory operates. The augmented positive identification (PID) controller with a nonlinear element (sigmoid function) is proposed to assure stability and reduce uncertainties in the wastewater direct reuse/recycling model. The nonlinear controller gains (PID controller with sigmoid function) for uncertain wastewater treatment processes are tuned using the particle swarm optimization (PSO) technique. The proposed robust method for controlling wastewater treatment processes has good robustness during model mismatching, reduces treatment time compared to traditional positive identification (PID) controllers tuned by PSO, is easy to apply, and has good performance, according to simulation results.

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1. INTRODUCTION

In wastewater treatment plant (WWTP), dissolved oxygen concentration has a direct impact on the performance of the WWTP [1]. In order to obtain wastewater with a substrate concentration within the legal standard limit values (below 20 mg/l), quantitative feedback theory (QFT) technology control is used [2], [3]. Variable operating regimes were allowed within large limits. General rain, normal rain, and drought were the three basic regimes evaluated. A QFT controller that assures excellent properties for the three regimes is indicated [4]. Significant development has been made in the field of control technology in recent decades, particularly in the control of dissolved oxygen and the procedures of comparative evaluation of wastewater treatment plant control systems [5], [6].

In the rule structure of an internal model, in an activated sludge process (ASP) based wastewater treatment, virtual reference adjustment feedback is used to regulate dissolved oxygen emissions and substrate concentration [7], [8]. The methodology of data-driven proved to be easier to implement and provided a better result compared to continuous-time proportional integral (PI) controllers with two degrees of freedom [9]. A resilient positive identification (PID) controller can guarantee stability and be robust and economical in model mismatch circumstances [10]. The fractional order proportional-integral (FOPI)controller design scheme for the aeration model of the 2nd order activated sludge wastewater treatment process plus process aeration control activated sludge wastewater treatment time delay performance [11], [12]. The radial basis function neural network-based PID (RBFNNPID) algorithm in gradient descent technique suggests and simulates an adaptive PID algorithm based on the radial basis function (RBF) based on the neural network (NN) for the optimal control of dissolved oxygen in a sludge activation process, the comparison of the performance simulation results for the conventional PID with the RBFNNPID control algorithm to keep dissolved oxygen concentrations show that the RBFNNPID better performance results can be achieved. The RBFNNPID control algorithm has good tracking, anti-interference, and excellent robustness performance [13]. A fuzzy predictive control law is used as a control strategy for the treatment process of wastewater [14]. A PID controller is used in a hybrid controller, as well as a fuzzy logic controller (FLC) and a fuzzy-PID supervised, in which the PID's parameters are updated using a fuzzy system [15].

A metaheuristic search technique that employs process simulation blocks in a black-box approach is used to build a heuristic control strategy for non-linear multivariable systems, with the location and range of the search region changing adaptively during the algorithm's iterations [16], [17]. The recommended self-organizing radial basis function (SORBF) regulating dissolved oxygen concentration in a WWTP may change its structure dynamically to maintain forecast accuracy. It is based on the self-organizing radial basis function model predictive control (SORBF-MPC) approach, which uses a self-organizing RBF neural network model for predictive control [18]. For WWTP, the simplification model is created by simplifying the activated sludge model; it is an approach to synthesizing H∞ resilient PIDs, and the ideal PID controller parameters bound by H∞ requirements are adapted using an evolutionary algorithm to the various disturbances; the simulation shows that the closed-loop WWTP meets a variety of H∞ criteria, has good tracking capabilities, and can withstand noise disturbances [19]. In a fractional order PID controller using the multi-objective optimization function, the weighted integral time absolute error of individual loops is added together, and the performance rejection is validated by analyzing the response for set point change and interruption [20]. Through MATLAB simulations, a well-tuned baseline multi-loop PID controller was compared to the fuzzy inference baseline sliding methodology and showed that it could simultaneously regulate fuel ratios to appropriate levels under varying airflow disturbances by adjusting the mass flow rates of the port fuel injection (PFI) and direct-injection (DI) engines [21].

The complexity and non-linearity of WWTP represent a significant challenge in developing viable processes for control technologies. Wastewater treatment processes are non-linear and, due to influencing factors, show many uncertainties that make selecting the structure and parameter model difficult. The set point of the dissolved oxygen in the control system is adjusted according to the influent system [1]–[3].

This work proposes a wastewater treatment system with an augmented PID controller. The dissolved oxygen level for the organic substrate is controlled by using a non-linear element (sigmoid function). The algorithm of particle swarm optimization (PSO) is utilized to obtain the gains of the PID controller and the augmented part; the robustness of the PID controller is increased by using the augmented element.

2. WASTEWATER TREATMENT PROCESS

For the process of wastewater treatment, three main regimes related to weather conditions are considered: rain, normal, and drought to control the level of dissolved oxygen in the tank to ensure the allowable level of organic substrate. Three main regimes are considered with restrictions due to extreme situations and the variation of the parameter model due to process variables (e.g., temperature). The following is a second-order transfer function that can be used to depict the process as illustrated in (1) [22],

$$G_n(s) = k_n \frac{(s+a_n)}{(s+b_n)(s+c_n)} \tag{1}$$

where, n is integer number representing the regime type. Table 1 represents the transfer function parameters for three regimes with upper and lower limit (min and max) values for each parameter.

Table 1. Wastewater processes parameters [23]

Regimes	Parameter k_n	Parameter a_n	Parameter b_n	Parameter c_n
Rain (n=1)	K1[9.5 10.5]	a_1[2.0 3.5]	b_1[1.5 2.0]	c_1[0.3 0.4]
Normal (n=2)	K2[10.511.5]	a_2[3.0 4.5]	b_2[1.0 1.5]	c_2[0.4 0.5]
Drought (n=3)	K3[9.0 10.5]	a_3[4.5 5.5]	b_3[0.5 1.0]	c_3[0.3 0.4]

3. PID CONTROLLER

The proposed conventional PID controller's transfer function to increase the dynamic system's response is given by (2) [24],

$$\frac{Q(s)}{E(s)} = \text{K1} + \frac{\text{K2}}{s} + \text{K3}\ \frac{K4\ \text{s}}{s+K4} \tag{2}$$

where K1, K2, K3, and K4 are proportional, integral, derivative, and filter gains are the four types of gains respectively. A sigmoid function is added to the typical PID controller yields the nonlinear PID controller. The control signal is illustrated in (3),

$$u(t) = \left(\frac{2}{1+e^{-K5Q(t)}} - 1\right) \tag{3}$$

where K5 is the sigmoid function's gain and $Q(t)$ is the standard PID's output. Figure 1 shows the nonlinear PID controller construction. The design of PID controller need to tune the controller parameters (gains) to satisfy the desired specifications for the output response, therefore, PSO algorithm is used as an optimal tuning method for PID gains.

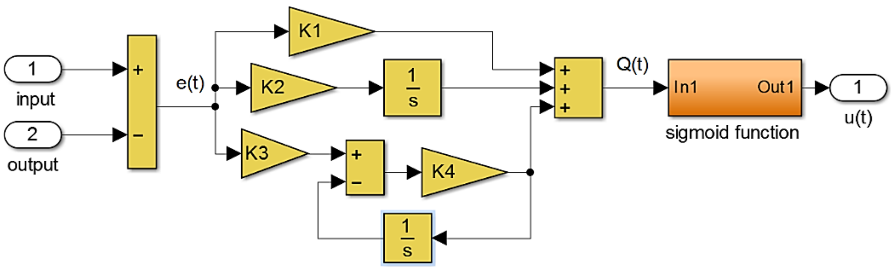

Figure 1. Augmented PID controller structure

4. PARTICLE SWARM OOPTIMIZATION TECHNIQUE

The recognized PSO algorithm's equations are shown as [25], [26],

$$V_{i,j}^{(p+1)} = W * V_{i,j}^{(p)} + c1 * R_1 * \left(\text{Pbest}_i - X_{i,j}^{(p)}\right) + c2 * R_2 * \left(\text{Gbest}_i - X_{i,j}^{(p)}\right) \tag{4}$$

$$X_{i,j}^{(p+1)} = X_{i,j}^{(p)} + V_{i,j}^{(p+1)} \tag{5}$$

$$i = 1, 2, \dots, m \; j = 1, 2, \dots, L$$

where m, L, and p are the number of particles, variables (parameters), and iteration respectively, $\mathrm{V}_{\mathrm{i,j}}^{(\mathrm{p})}$, $\mathrm{X}_{\mathrm{I,j}}^{(\mathrm{p})}$ are the velocity, position of i^{th} particles at iteration p, X^{p+1} is updated position, V^{p+1} is updated velocity, $\mathrm{P}_{\mathrm{bst}_\mathrm{i}}$ is the position of best i^{th} particles, $\mathrm{G}_{\mathrm{bst}}$ is the best particles of the population, W is the weight factor, $c1, c2$ are constants, R_1, R_2 are a random numbers.

The used parameters in this work are: $n = 12, L = 4$ for conventional PID controller, $L = 5$ for nonlinear PID controller, $c1 = 1.1, c2 = 1.2,$ $W = 0.9 - \left(\frac{0.4}{80}\right) * iteration\ number$, and maximum iteration number equal to 80. The utilized fitness of integral time square error interactive technology and smart education (ITSE) is,

$$\text{FIT} = \int_0^T t\, e^2(t)\, \mathrm{d}t \tag{6}$$

where, e is the error signal between the output response and the desired response.

5. RESULTS AND DISCUSSION

Simulation for a wastewater treatment process can be classified into two phases: the tuning of controller parameters and the control phase. The PSO algorithm is used as an optimal tuning method for PID gains. The MATLAB/SIMULINK program for wastewater treatment process (normal regime for lower limit), conventional PID controller, and fitness function is illustrated in Figure 2. The changes in conventional PID gains and fitness value according to iteration number for a normal regime with a lower limit using the PSO algorithm are depicted in Figures 3 and 4, respectively. Table 2 shows the typical PID controller gains tuned by the PSO algorithm for different regimes.

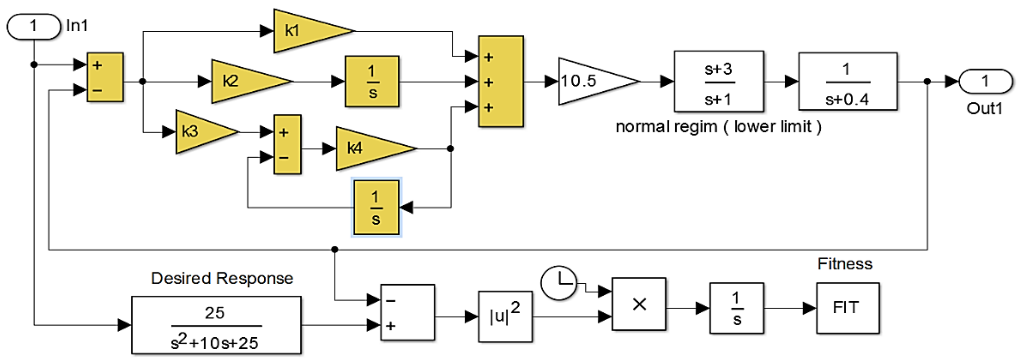

Figure 2. Wastewater process with conventional PID controller and fitness function

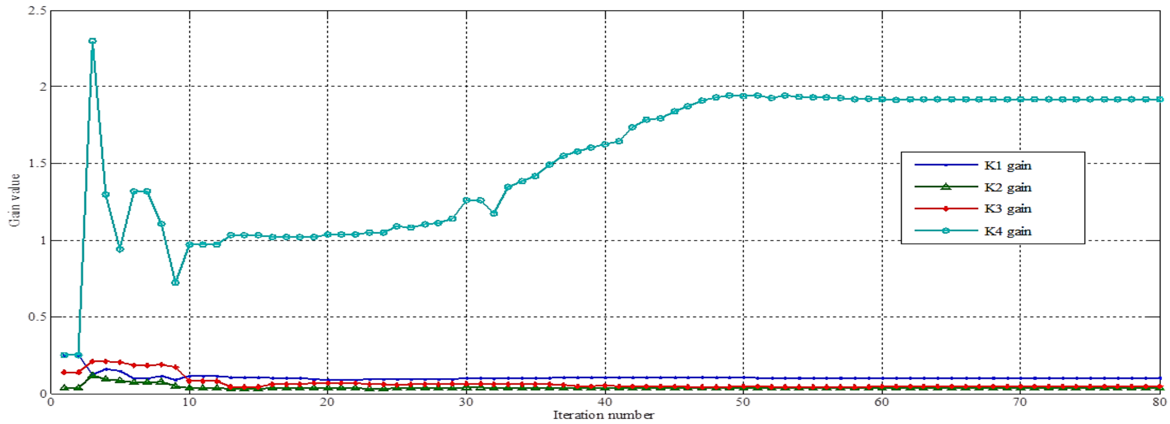

Figure 3. Tuning gains for conventional PID controller using the PSO algorithm

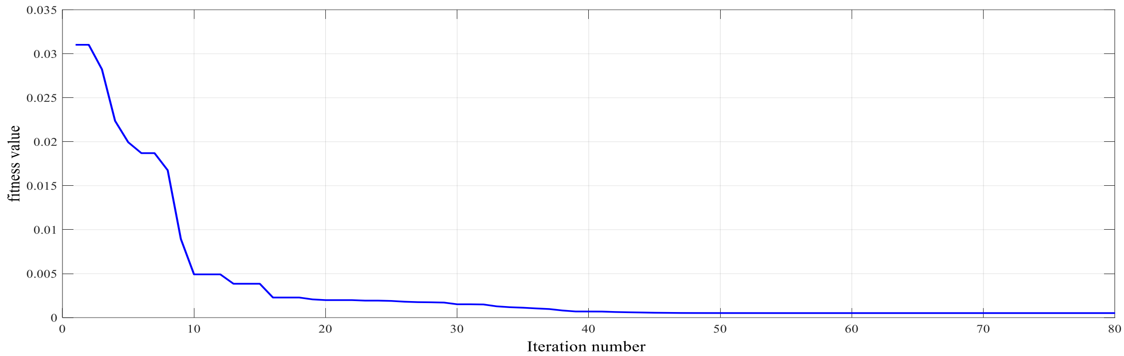

Figure 4. Changing of fitness value using PSO algorithm

Table 2. Gains of PID and fitness values obtained from PSO algorithm

PID Controller Gains	Regime at Rain	Regime at Normal	Regime at Drought
K1	0.216	0.1027	0.0504
K2	0.0639	0.0338	0.0105
K3	0.0295	0.0456	0.054
K4	0.6616	1.9175	3.0621
Fitness value	0.00077	0.00051	0.00055

The steps response of the conventional PID controller designed for the drought regime (lower limit) is illustrated in Figure 5. Figures 5-7 show that the obtained responses for the drought regime (lower limit), normal regime (lower limit), and rain regime (lower limit), respectively, are the same as the desired response, and the other responses deviate from the desired response according to the process environment. The deviation for a drought regime concerning long settling time and the deviation for a normal regime and rain are regarding settling time and large overshoot. The non-linear PID controller gains for rain regime (lower limit) tuned by the PSO algorithm are illustrated in Figure 8. The non-linear gains and fitness values for different regimes obtained from the PSO algorithm are depicted in Table 3.

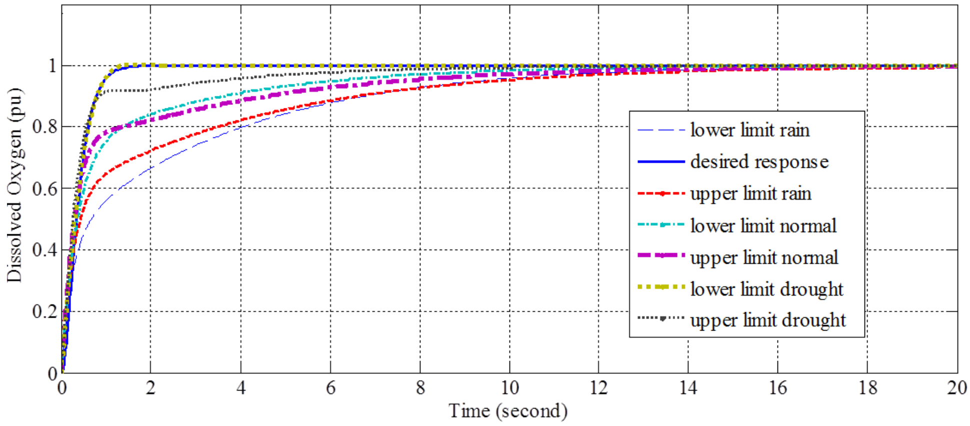

Figure 5. Step response for WWTP using PID controller for drought regime

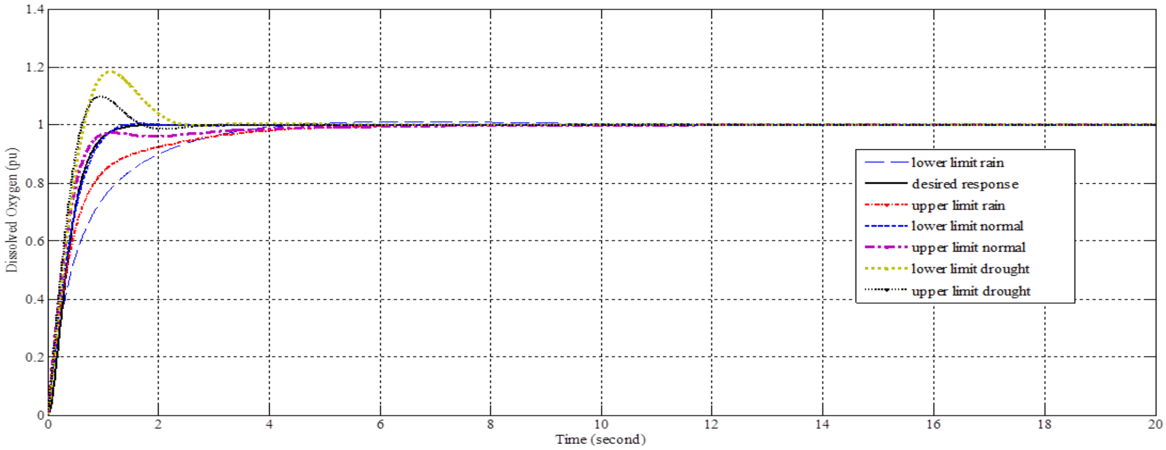

Figure 6. Step response for WWTP using PID controller for normal regime

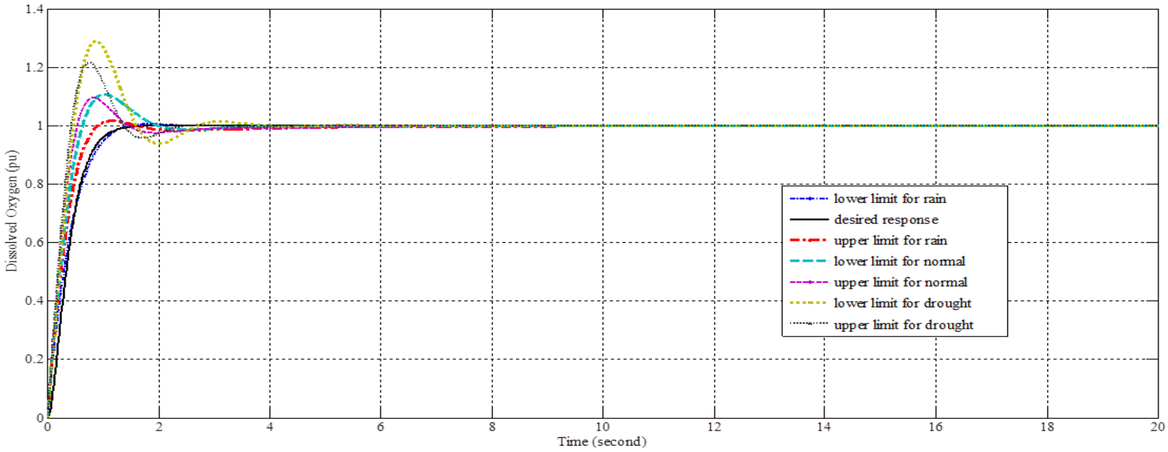

Figure 7. Step response for WWTP using PID controller for rain regime

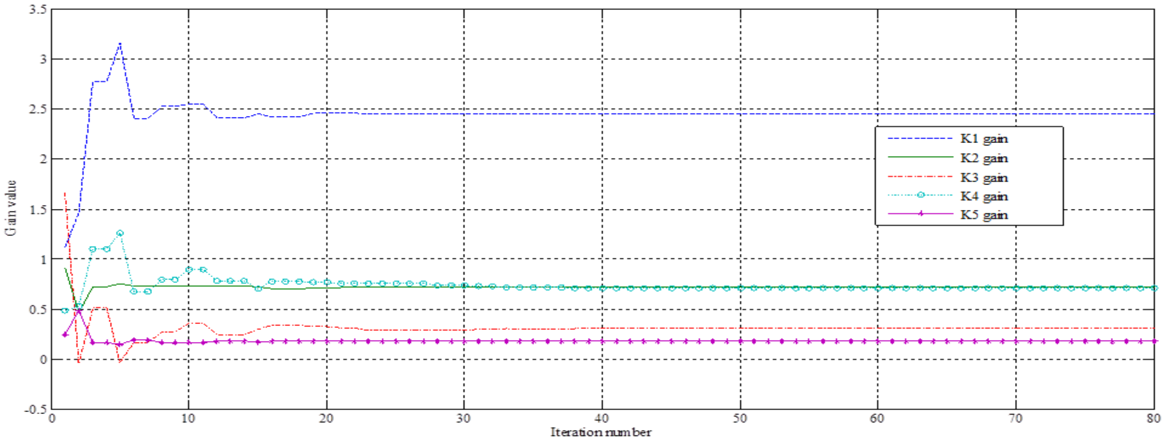

Figure 8. Gains values of nonlinear PID controller utilizing the PSO technique for rain regime

Table 3. The gains and fitness values for nonlinear PID controller

PID Controller gains	Plant at rain	Plant at normal	Plant at drought
K1	2.4523	1.2964	0.3872
K2	0.715	0.423	0.0769
K3	0.304	0.5723	0.4077
K4	0.7085	1.9233	3.0212
K5	0.1783	0.1595	0.2541
Fitness value	0.00075	0.0005	0.00039

The step response for three regimes of wastewater process with a non-linear PID controller designed for a normal regime with sigmoid function gain (K5=0.1595) is illustrated in Figure 9, which looks like the response of a conventional PID controller in Figure 6. To enhance the robustness of the controller, it is possible to increase the sigmoid function gain (K5). The enhancement of the robust response is obviously seen in Figure 10 for K5=2, and Figure 11 for K5=10. The step responses for the non-linear PID controller designed for rain and drought regimes with gain (K5=10) are shown in Figure 12 and Figure 13 respectively, which depict the high robustness of the proposed non-linear PID controller by comparison with the responses of Figure 5 and Figure 7.

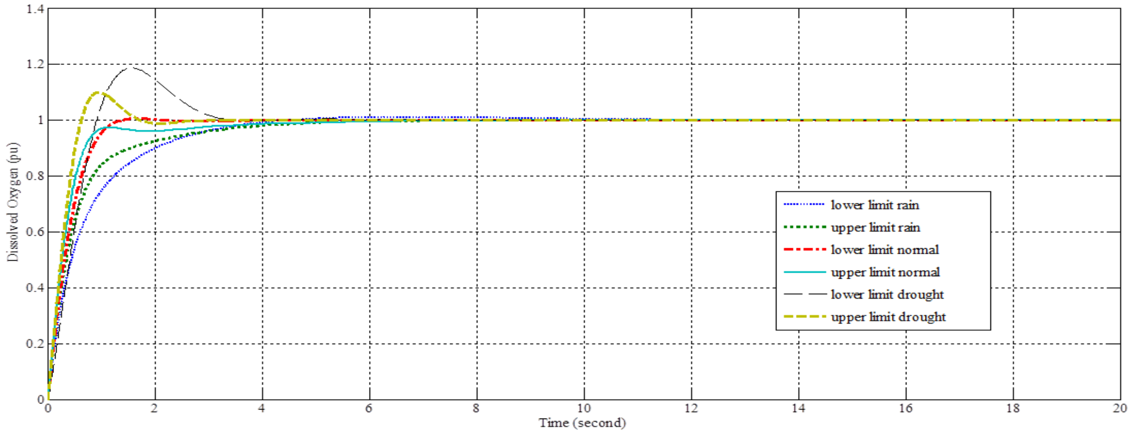

Figure 9. Step response for nonlinear PID controller of normal regime with gain (K5=0.1595)

Figure 14 represents the white noise signal that was injected into the system for the purpose of checking the robustness of the system against unwanted signals. Figure 15 shows the output responses for the control system in the regular regime using the conventional PID controller and the augmented PID controller with (K5=10) under the influence of disturbance (white noise). The response of the WWTP with a conventional controller is stable with perturbations of about ±15%, and the response of the WWTP with PID augmented by a sigmoid function of gain (K5=10) is stable. It has perturbations of about ±2%. That means the augmented PID controller has a better disturbance reduction than the non-augmented PID controller. Figure 15 shows that the augmented PID's robustness is better than the non-augmented PID controller.

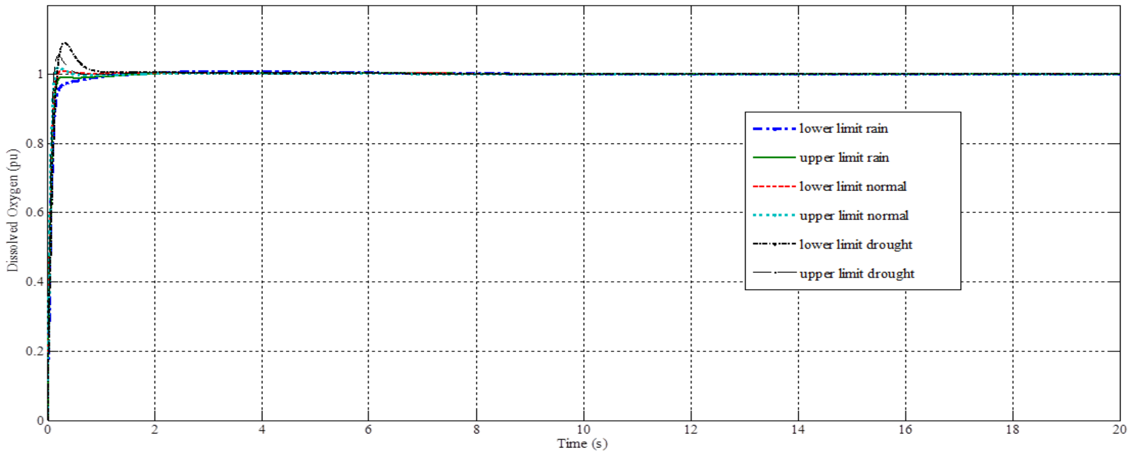

Figure 10. Step response for nonlinear PID controller of normal regime with gain (K5=2)

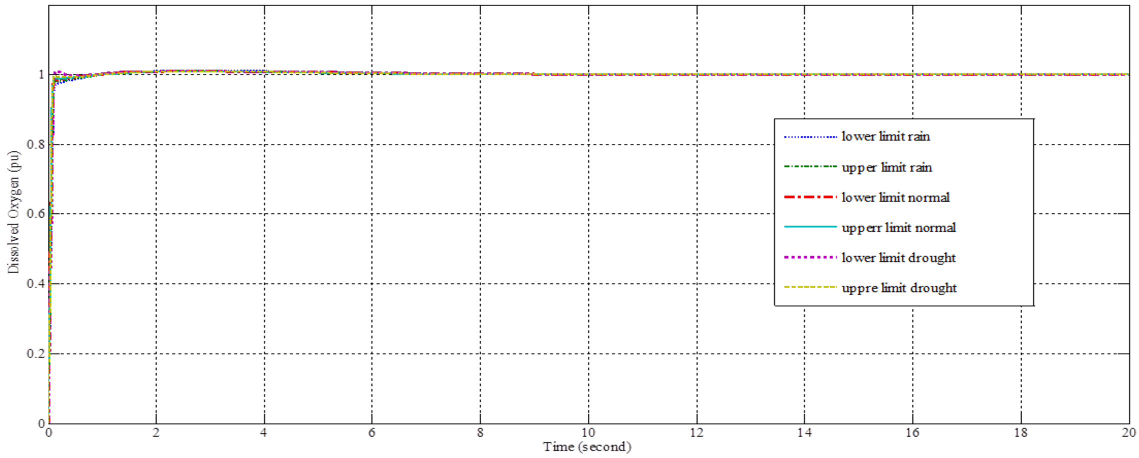

Figure 11. Step response for nonlinear PID controller of normal regime with gain (K5=10)

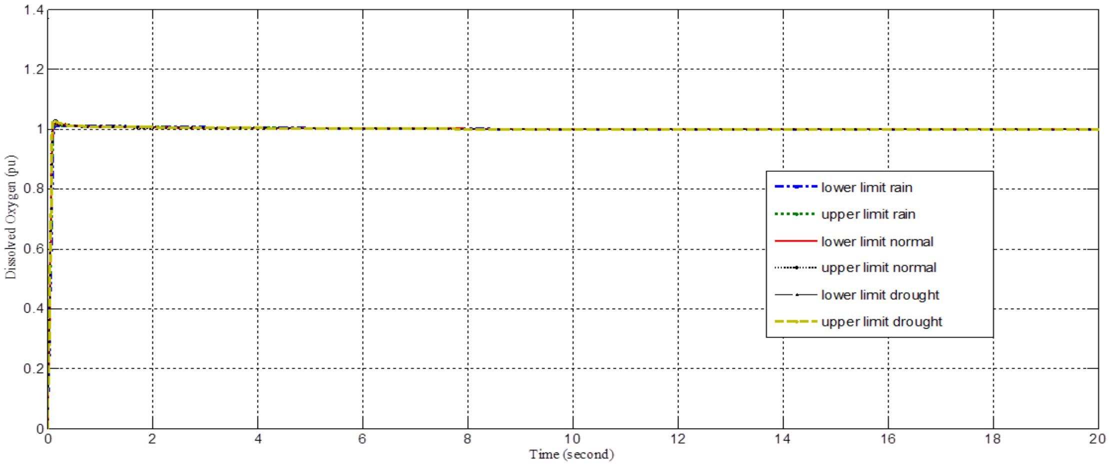

Figure 12. Step response for nonlinear PID controller of rain regime with gain (K5=10)

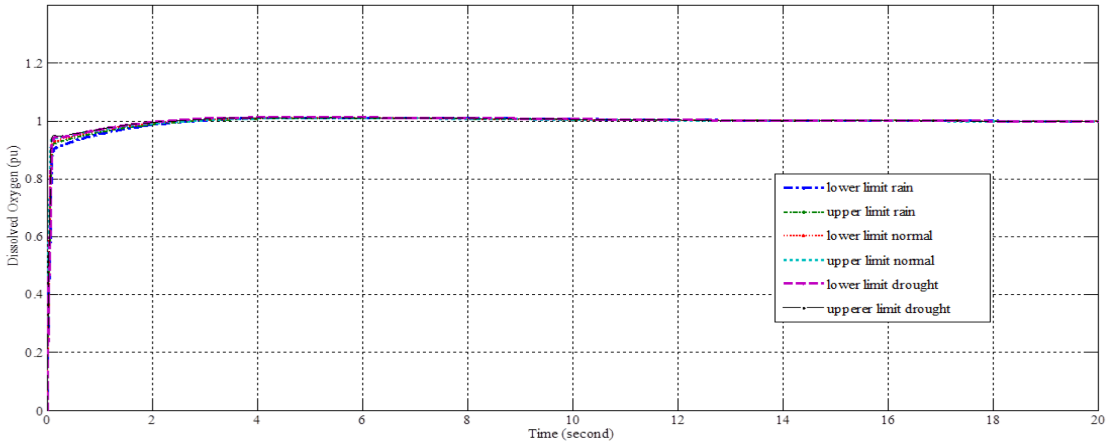

Figure 13. Step response for nonlinear PID controller of drought regime with gain (K5=10)

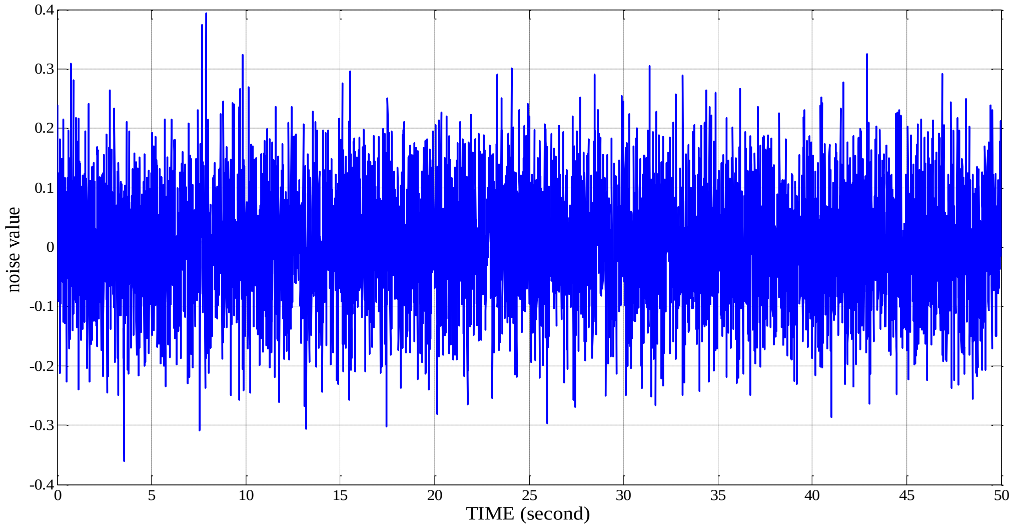

Figure 14. Injected white noise to WWTP

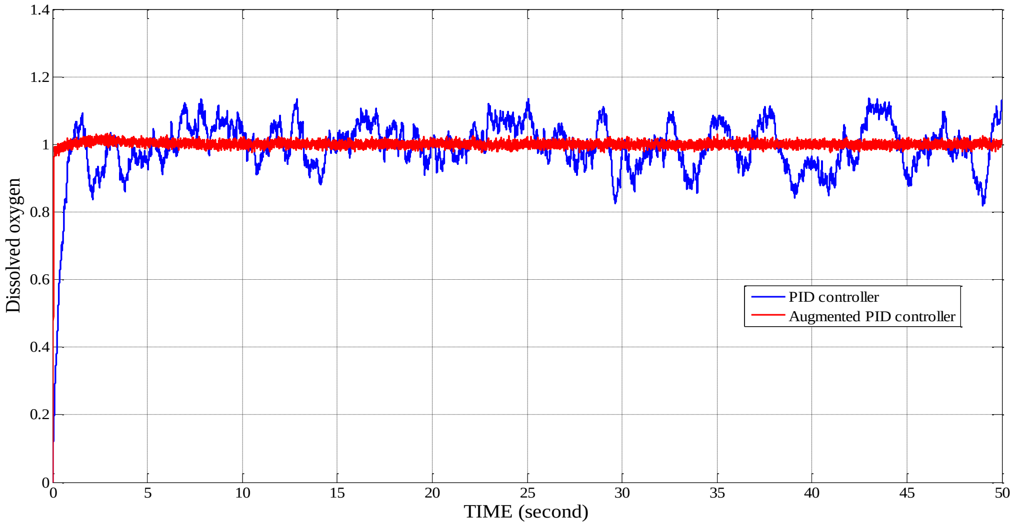

Figure 15. Step response of WWTP with augmented and non-augmented PID controllers

6. CONCLUSION

The wastewater treatment process is uncertain and non-linear. It needs a robust controller to reduce the influence of parameter uncertainty and non-linearity. A robust controller is also required to reduce the influence of uncertainties and stabilize the response of the open-loop system. The conventional and non-linear PID controller gains are found using the PSO algorithm. The wastewater treatment plant is mentioned under three different regimes, and the comparison result shows the robustness of the designed controller. The augmented PID controller has less influence from disturbance than the non-augmented PID controller. The augmentation of a non-linear function to the PID controller allows the system to become more robust than conventional PID controllers. Also, the proposed non-linear controller has the advantage of increasing the robustness by increasing the gain of the sigmoid function only.

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