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Optimization of PID Controller For Three Tanks System By MATLAB/Simulink/Genetic Algorithm

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Abstract:
The three-tank system is used for many purposes, including industries and education, especially in engineering. Designing and tuning a suitable controller is one of the most important things in this system. The PID controller is one of the most famous controllers used for this purpose. In this article, the three-tank system is simulated using Simulink MATLAB, and different nonlinear transfer functions are used to represent the three-tank system. The ITAE error was obtained for each of the functions. The result showed that the higher the degree of non-linearity, the ITAE error increases. To obtain the minimum error and optimal parameters of the PID controller, the genetic algorithm was used for 150 generations and the number of repetitions was 50. The optimization results showed that more favorable results are obtained by using the genetic algorithm. Also, the ITAE error obtained from the genetic algorithm optimization method is much less than other optimization methods, such as the Gray Wolf.

Keywords: *Three Tank System; Genetic Algorithm; PID Controller; Optimization; ITAE Error.*

1. Introduction

All process industries aim to improve product quality and economic benefits to compete in global markets. Therefore, industrial owners are looking for ways to achieve this goal. In practice, the best performance is achieved by designing and optimizing the controllers that keep the physical parameters such as temperature, pressure, etc. that affect the process within the desired limits [1-3]. One of the topics that has attracted the attention of control systems researchers and has a wide range of applications in industries is controller design [4-6]. In almost all process industries, including oil and gas, petrochemical, paper, etc. tanks are used to store, transport and mix liquids. Therefore, optimization of controllable parameters in storage tanks plays a key role in these industries [7, 8].

The three-tank system (3TS) is widely used in educational and research fields to model industrial tanks [9]. It is also used for demonstration purposes in control engineering, test systems for fault detection and identification as well as for reconfigurable control, and investigation of nonlinear multivariable feedback control [8, 10-18].

The main problem in the three-tank system is the difficult design of the controller due to the non-linear flow and interaction between the tanks [17]. Many researchers have investigated the control of optimal conditions within a three-tank system.

2. Literature Review

Hou, Xiong [10] studied state observers for the benchmark of a three-tank water process by Matlab/Simulink simulation software tool. Their findings demonstrated an acceptable agreement with the laboratory results for the three-tank system, particularly in estimating water levels within the first tank. Voglauer, Garcia [11] operated a 3TS by combining a standard industry Programmable Logic Controller (PLC) and Matlab/Simulink in real time. Borbély [6] applied the H_2/H_∞ minimax method, extended or disturbance rejection linear quadratic (LQ) control for three tank systems using Matlab/Simulink. They compared the results of disturbance rejection LQ control with the classical LQ method and the superiority of the minimum control was shown, for large weight values obtained for the worst disturbance, the LQ disturbance rejection method becomes a classical LQ problem.

The paper presents a self-tuning predictive controller for real time control of a three-tank system. The controller integrates a multivariable state-space model and an autoregressive with exogenous input (ARX) model, with improved performance by using recursive least squares and directional forgetting [19].

Some researchers used a radial basis function (RBF) type neural network system to approximate the feedback linearization law and a Mamdani-type fuzzy inference system, and the goal was to control the liquid level in a tank for 3TS. The results showed that a more successful and stronger control is obtained compared to the results obtained using a PI controller [20]. The mean square error (MSE) in the three-tank system with a PI controller with active fault-tolerant control (AFTC) is smaller than the system with only one PI controller that compensates for the actuator error [21]. The decentralized PI controller is tuned using Gray Wolf optimizer. It shows good transient performance for the nonlinear multi input multi output (MIMO) process [22, 23]. Also, the centralized PI controller for the Three-Tank Hybrid system was optimized using methods such as Manta Ray Foraging Optimization (MRFO) and Particle Swarm Optimization (PSO). MRFO technique provides better performance compared to PSO [24]. The results obtained by Jukka showed that the model predictive controller (MPC) responds faster than the proportional plus integral (PI) controller for liquid-level control [17].

Cartes and Wu [25] investigated liquid level control within three rectangular tanks by comparing a nonconventional Proportional-Integral-Derivative (PID) controller, three different types of adaptive controllers, a direct model reference adaptive controller (MRAC), an indirect MRAC with recursive least-squares (RLS), and an indirect MRAC with Lyapunov estimation. The direct MRAC and indirect MRAC with RLS estimation performed much better than the others. Although both need the least amount of control effort, the direct MRAC has the smallest steady-state tracking error band, whilst the indirect MRAC with RLS estimation has the fastest response and convergence. Also, the developed software used both PID and fractional PID controllers using a multi agent system on several computers to model the three-tank system and fault detection, which enables adaptive control and control. It is fault tolerant and suitable for educational purposes [12]. Full mode feedback controller (FSFB) and linear quadratic controller (LQC) with pre-compensator were compared with Zeigler-Nichols (ZN) tuned proportional PID controller. FSFB controller with pre-compensator performed better [7]. Shivam et.al designed an optimal PID controller to control the level of the three-tank system. An integral error squared (ISE) based approach is used to tune the PID controller. A teacher-learner-based optimization (TLBO) technique is used to minimize the ISE. The results obtained using the ISE technique perform much better compared to other methods [26]. The researchers discussed the application of the Gray Wolf algorithm (GWO) in tuning a PID controller and the classic trial and error method (T&E). The results obtained using the GWO showed better results than T&E [27]. Also, a hybrid optimization-based PID controller and Model Predictive Control (MPC) were used for the tank system [28].

For a laboratory-scale industrial three-tank nonlinear multiple-input multiple-output (MIMO) system for liquid level control, linear and nonlinear controllers were modeled and optimized. The linear optimal controller is designed based on the Jacobian linearization of the nonlinear system. Automatic Control and Dynamic Optimization (ACADO) was used to compare and validate the nonlinear optimal controllers. The results of the two control schemes showed good performance. However, the linear controller had stronger control and less computational demand than the nonlinear design [29].

Kouadri, et al., suggested a radial basis function neural network (RBFNN) for modeling the three-tank system. Also, a hybrid DIRECT algorithm is used in learning RBFNN for nonlinear optimization. The optimization process of the RBFNN is altered slowly by considering a tuning algorithm based on a standard direct search algorithm. The experimental results indicate the effectiveness of this method and its capability to reproduce the dynamic behavior of a 3TS under different conditions [14].

Marwa et.al studied an optimization method based on the genetic algorithm to identify the parameters of the three-tank system and quadratic error is obtained between simulated and measured outputs. According to the results, the measured and simulated outputs are coincident and the quadratic error was 0.0248 [30].

In this article, the three tanks system was optimized using a genetic algorithm and Matlab/Simulink for the nonlinear PID controller. The purpose is to minimize the integral time absolute error (ITAE) for different transfer functions and comparing between them. The innovation of this work is the use of a genetic algorithm and Matlab/Simulink for the three-tank system.

3. Description of the system

According to Figure 1, the 3-tank system includes 3 tanks, 6 valves, and 2 pumps. The valves V_1 and V_2 connect tanks 1 to 2 and 2 to 3, respectively, and valve 3 is the outlet of tank 3. Valves V_4, V_5, and V_6 mean leaks from tanks and pumps 1 and 2 transfer liquid flow from the source to tanks 1 and 3, respectively. The cross-section of all tanks is the same and equal to A_T and. The density of the liquid is constant and equal to ρ.

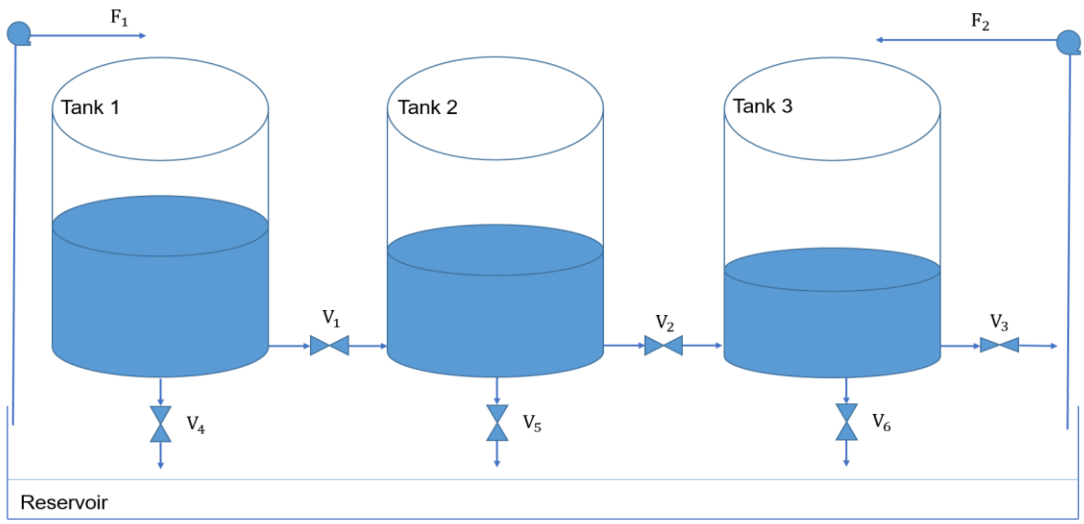

Figure 1: Schematic of three tank system

As shown in Figure 2, an optimal PID controller is proposed for minimizing ITAE error, because this controller is widely used in the industry due to its simplicity and reliability [26, 31]. The optimization of the three-tank system with the PID controller is divided into two parts: the first section simulates the system with MATLAB/Simulink. In the second section, the optimal error for the different transfer functions is obtained through the genetic algorithm link of Simulink.

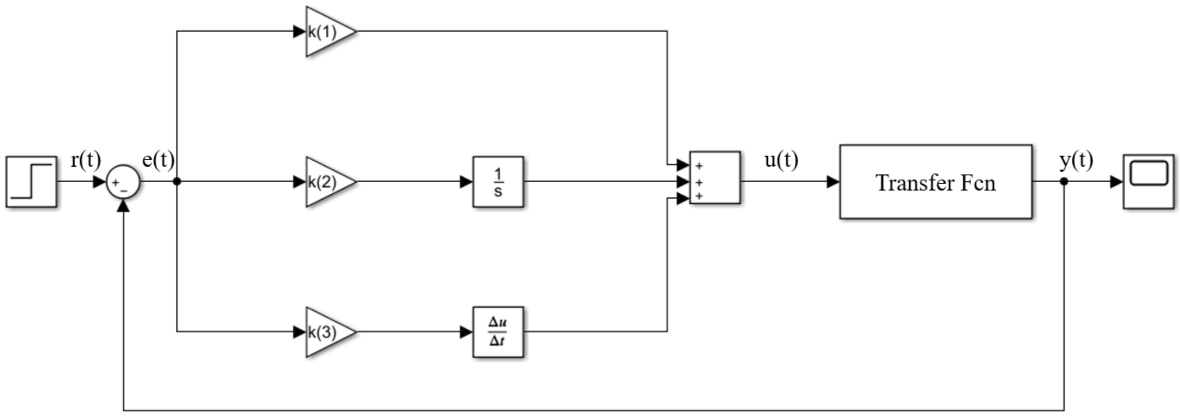

Figure 2: Block diagram of PID controller for 3TS

The PID controller is mathematically expressed as

$$u(t) = K_p \times e(t) + K_i \times \int_0^t e(t).dt + K_d \times \frac{de(t)}{dt} \qquad \text{Equation 1}$$

where u(t) is the control signal and e(t) are the control error (e(t) = r(t) – y(t)). The r(t) is the reference variable is often called the set point. The control signal is thus a sum of three terms: The controller parameters are proportional gain K_p, integral gain K_i, and derivative gain K_d. Controller parameters can be interpreted as control actions based on past, present, and future [32].

4. Methodology

According to the previous research, considering the three-tank system in a non-linear function is more consistent with reality and the goal of optimizing this system is to minimize error [7, 22, 23]. The three-tank system is nonlinear and has variable parameters. The valves, pipes, and pumps' features cause the nonlinear behavior. Additional nonlinearities result from air bubbles in the pipes and valves. Occasionally, the bubbles deflate from the pipe system [19]. For Simulink, five transfer functions from previous studies that used different algorithms such as the Gray Wolf (GWO) algorithm to optimize the three-tank system have been used (Table 1). Genetic algorithms (GA) are one of the methods used for optimization problems and are inspired by the evolution mechanism of species in nature (intersection, mutation, selection). This algorithm is an iterative method that searches for the optimal value. The genetic algorithm was used in MATLAB to obtain the optimal values for equations 1 to 5. It should be mentioned that the optimal values obtained by using the genetic algorithm were obtained under the same conditions except for the upper bound of control parameters. The lower bound for K = [K_p K_i K_d] is considered [0 0 0] and the upper bound for equations 1 to 5 is 150, 200, 10, 50, and 15, respectively. Optimization was done for population sizes of 50 and 150 generations.

Table 1: Transfer functions are used for three tank systems in SIMULINK [23, 27, 33].

No. Eq.	Transfer Equation	Parameters
1	$C(s) = \frac{0.006}{s^3 + 0.807s^2 + 0.363s + 0.002}$	$A_T = 0.06158\ m^2$, $V_1 = 0.9$, $V_2 = 0.8$, $V_3 = 1$, $V_4 = V_5 = V_6 = 0.3$, $F_1 = F_2 = 0.75 \times 10^{-4} m^3/s$
2	$C(s) = \frac{0.036s + 0.006}{s^3 + 0.807s^2 + 0.363s + 0.002}$	
3	$C(s) = \frac{0.122s^2 + 0.059s + 0.007}{s^3 + 0.807s^2 + 0.363s + 0.002}$	
4	$C(s) = \frac{1.2}{0.36s^3 + 1.86s^2 + 2.5s + 1}$	-
5	$C(s) = \frac{8}{16s^3 + 32s^2 + 16s + 2}$	$A_{T1} = A_{T2} = 1\ m^2$, $A_{T3} = 0.52\ m^2$, $V_1 = 0.54$, $V_2 = 0.54$, $V_3 = 1$, $V_4 = V_5 = V_6 = 0$, $F_2 = 0$

5. Results and discussion

Table 2 shows the simulation results for 5 transfer equations with and without the PID controller. As expected, the ITAE error for equations 1 to 4 without a controller is higher than with the controller. But this difference is the opposite in equation 5, according to the information in Table 1, the reason for this difference can be explained by the presence of fewer nonlinearities ($V_4 = V_5 = V_6 = F_2 = 0$). Equation 1 has the highest error and equation 4 has the lowest error in Simulink with the PID controller. Also, among equations 1, 4, and 5, which have a similar fraction, Eq. 4 has an ITAE error much less than the other two equations. The values of ITAE obtained are high and the optimal value can be found using a genetic algorithm. Therefore, the Simulink simulation was the objective function in the genetic algorithm /MATLAB. After optimization, the results show that equation 1 has the highest error of 7.332 and equation 2 has the lowest error of 0.968. The optimal ITAE error for all equations is significantly lower than the error obtained in Simulink. Anbunami et al.[23] used equations 1 to 3, and they obtained an ITAE error equal to 1.97e+7, respectively while the results obtained from MATLAB/Simulink are much lower than the values obtained from the gray wolf algorithm.

In addition to the ITAE error, the optimal control parameters [K_p K_i K_d] have also been obtained and the values of the parameters are different because of the difference between upper bounds. The important point is that in equation 3, the third variable is zero, which happens to the PI controller [3]. By paying attention to the transfer function, it can be explained that because the numerator of the fraction is a second-degree equation and the denominator of the fraction is a third-degree equation, the numerator and denominator are simplified, which becomes the transfer function for the PI controller, that is, a fraction with a first-degree equation remains in the denominator.

Table 2: Simulink/genetic algorithm applied to 3TS.

No. Eq.	Parameter	Without PID controller	With PID controller	
		Simulink	Simulink	Simulink/GA
1	Output	0.108	0.4608	1.019
	ITAE	46.68	39.8	7.332
	K = [K_p K_i K_d]	-	[1 1 1]	[56.869 2.518 122.384]
2	Output	0.186	0.936	1.005
	ITAE	42.84	23.79	0.968
	K = [K_p K_i K_d]	-	[1 1 1]	[183.562 5.53 76.435]
3	Output	0.229	0.984	1.032
	ITAE	39.85	14.23	2.013
	K = [K_p K_i K_d]	-	[1 1 1]	[10 10 0]
4	Output	0.546	0.939	0.998
	ITAE	23.37	8.954	1.099
	K = [K_p K_i K_d]	-	[1 1 1]	[42.472 1.783 21.087]
5	Output	0.815	0.29	1.001
	ITAE	9.572	35.52	3.02
	K = [K_p K_i K_d]	-	[1 1 1]	[9.669 0.293 10.714]

Figure 3 shows step response diagrams of transfer functions after optimization. As expected, in the first graph, the curve increases with a slight slope and reaches set point 1 at 5.7s, and this is in agreement with the results of Table 2, where equation 1 has the highest ITAE error. Chart 5 with a delay time of 3.1s has an error of 3.02. Diagrams 2 - 4 have delay times between 2 and 3 seconds and diagram 2 has the shortest time. Therefore, the longer the time to reach the set point, the greater the ITAE error will be [21].

Equations 1, 4, and 5 have similar graphs, fluctuating curves that gradually decrease and reach a steady state [25], this similarity of graphs can be attributed to the similarity of transfer equations. The amplitude is high at the beginning but gradually decreases. Equation 4 has the fastest response and the highest number of oscillations among the three equations, and it also has the lowest error. Therefore, the more the number of fluctuations indicates the smaller the error value for the transfer function [18]. Unfortunately, information about equation 4 is not available, but the response is oscillatory and the system model changes faster, it can be concluded that the nonlinearities of this equation are more than equations 1 and 5 [34].

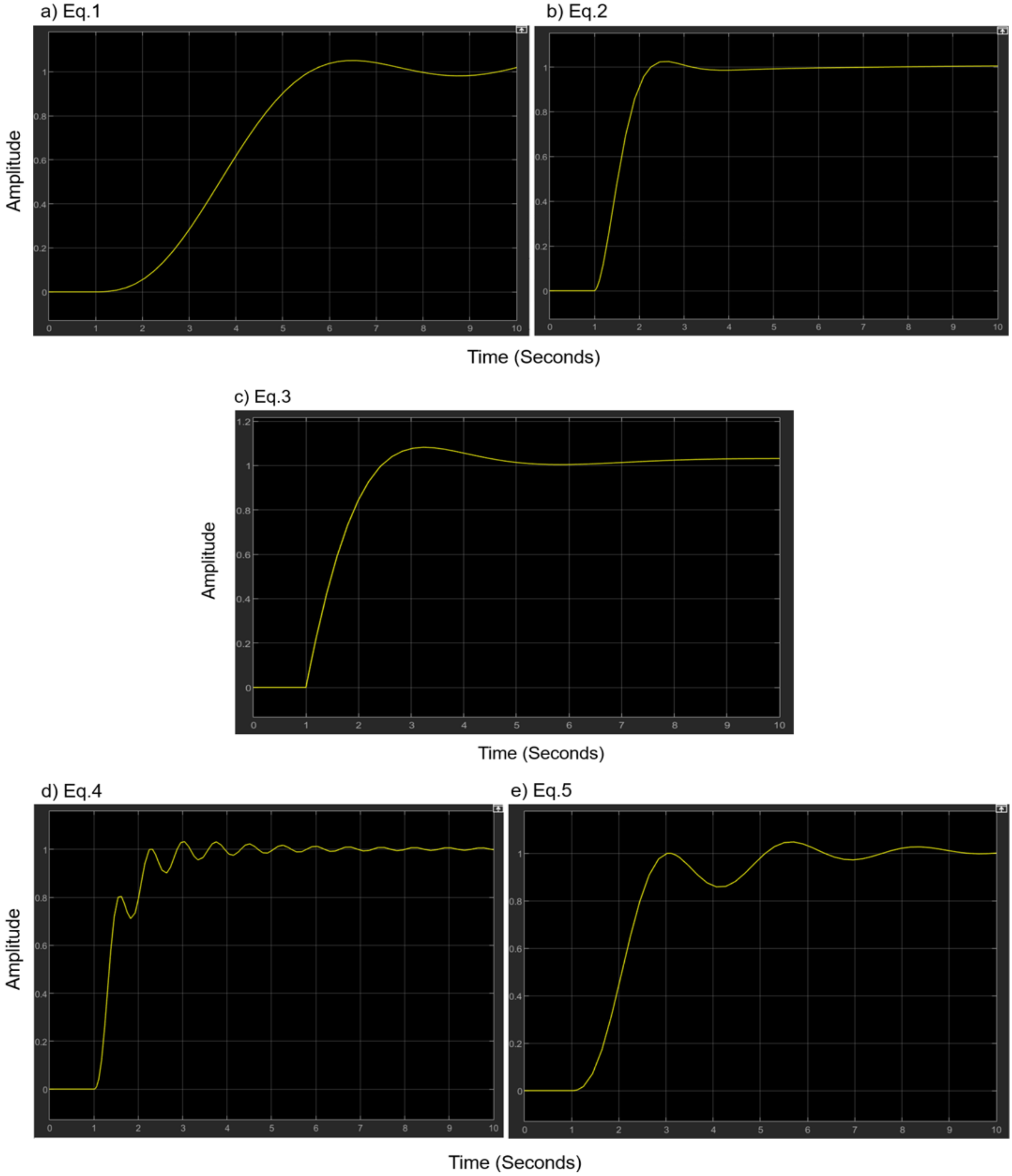

Figure 3: PID controller-based step response of three tanks for equations from 1 to 5.

6. Conclusion

This paper used different transfer functions in the PID controller for a three-tank system. The simulation results using Simulink MATLAB have a big ITAE error, but the use of the genetic algorithm works very well in obtaining the optimal values of the controlling parameters and error. Also, the optimal values are less compared to other optimization algorithms. The IATE error obtained from the Genetic algorithm is much smaller than the ITAE error from the Gray Wolf algorithm for the same transfer function.

7. Authors' Contribution

Khadijeh Mirza: Conceptualization, Conducted the research, assessed the results, and wrote the original draft.

Ali Farzi: Review editing, and visualization of the manuscript.

8. Conflict of Interest

The authors declare there are no competing interests.

9. Acknowledgment

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