Fuzzy-PID Controller for Liquid Level Control of Tank Systems

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***Abstract*— Liquid level control of tank systems is an important control engineering task in manufacturing and processing industries. It is a challenging problem due to the time varying and nonlinear characteristics, as well as the interaction resulting from the multivariable nature, of the systems, and yet a critical requirement in maintaining the desired volumes for chemical reactions, ensuring consistency, and contributing to the overall quality of the end products. In this paper, focus is on the development of a Fuzzy-PID controller for both single- and double-tank systems because of the unique capacity of the controller to operate efficiently without precise mathematical models of the systems, and to deal with nonlinearity, uncertainty, and multivariable disturbances. Simulation results of the controller showing its ability to optimize and improve the dynamic performance of the conventional PID controller are presented. The controller has an attractive merit that it can be seamlessly adopted and deployed in an industrial setting.**

Keywords*— *Fuzzy logic, Liquid level control, Proportional-integral-derivative controller, Performance metrics, Tank systems.

I. INTRODUCTION

Liquid level control systems are complex and difficult due to the pose challenges of nonlinear dynamics, inter-tank interactions, and sensitivity to disturbances. Moreover, precise liquid level control stands out as a crucial necessity among the difficulties encountered industrial sectors, such as chemical processing, petrochemical refining, water treatment, power generation, and production of construction materials [1]. The imperative to maintain optimal liquid levels has spurred a demand for sophisticated control mechanisms, positioning liquid level control systems as indispensable tools in ensuring not only operational efficiency but also paramount safety measures within industrial settings [2]. Within the chemical industry, liquid control systems are indispensable components in the orchestration of complex processes. As fluids are pumped into storage tanks, they undergo chemical reactions and possibly agitation. It is within these tanks that the true significance of liquid level control unfolds. The control of liquid levels becomes a critical factor in maintaining the desired volumes for chemical reactions, ensuring consistency, and contributing to the overall quality of the end products [3]. Similarly, in petrochemical refining, the manipulation of liquid levels is a linchpin in the refining and processing of crude oil. Liquid control systems are instrumental in managing the flow of liquids through various stages of refining, ensuring that each step in the complex refining process is orchestrated with precision [4]. Water treatment plants rely heavily on effective liquid level control to manage the flow of water through different treatment stages. The control of liquid levels in water treatment is fundamental to achieving the desired water quality standards, removing impurities, and ensuring that treated water meets regulatory requirements [5]. In the realm of power generation, liquid level control is integral to the functioning of boilers and other components. Proper management of liquid levels in boilers is critical for efficient heat transfer, preventing overheating, and maintaining safe operating conditions [6]. Even in construction material production, liquid control systems find application, particularly in processes that involve the mixing of liquids to create various construction materials. Precise control of liquid levels contributes to the consistency and quality of the final products [7]. Moreover, the control of liquid levels in industrial settings transcends being a mere technical requirement; it is a linchpin that influences the efficiency, safety, and quality of diverse technological processes. As industries continue to evolve, the demand for sophisticated liquid control systems will persist, driven by the need for precision, efficiency, and adherence to stringent quality standards across various sectors [8], [9]. The profound impact of liquid control systems extends beyond the immediate industrial applications, delving into the core design principles that govern their functionality. These systems are meticulously engineered to harmonize with diverse liquid-based processes, employing intricate control algorithms to regulate liquid levels with precision [10]. As industries continue to embrace automation and smart technologies, proportional integral derivative (PID) controller remain a cornerstone due to their adaptability role in ensuring stability, clear functionality, minimizing error, and responding dynamically to changes positions. However, the nonlinear properties of some systems—most notably, liquid level control in coupled-tank systems—provide significant difficulties for traditional PID controllers [11], [12]. Coupled-tank configurations directly affect efficiency and production costs, requiring a nuanced approach to control. They are commonly found in industries where precise control of liquid levels and inter-tank flow is paramount [13]. More recent research is investigating alternative methods of controlling coupled-tank systems due to the inefficiency of convectional PID controller in dealing with nonlinearity, uncertainty, and disturbances [14]. However, because of their unique capacity to operate without precise mathematical models, fuzzy logic controller (FLC) have grown in popularity as alluring substitutes. With their foundations in human reasoning and experience, these controllers hold great potential for managing the nonlinearities found in liquid level control systems [15], [16]. Recognizing the limitations of PID controller in handling nonlinearity, uncertainty, and disturbances, alternative approaches to control for coupled-tank systems have been studied recently. Fuzzy logic controllers are becoming more and more appealing alternatives since they don't rely on precise mathematical models. The integration of a fuzzy logic controller with a conventional PID controller, a novel approach described in this article, is made possible by the background research. By this novel combination, the control of a coupled-tank system with nonlinear liquid level is to be improved.

For industrial processes involving liquids to function smoothly, precise regulation of levels, flow rates, and other crucial parameters is provided by liquid control systems. Effective control can only be attained by applying a variety of techniques and plans that are specifically designed to meet the needs of each system. This review delves into the variety of traditional techniques such as: 1. float switches, 2. conductive level sensors, 3. capacitance level sensors, and ultrasonic level sensors. In addition, the traditional feedback mechanisms such as PID controller to more sophisticated technique like FLC, which used in liquid control systems [17], [18]. Every technique has a distinct function, tackling the complexities of liquid-based processes and enhancing industrial operations' safety, dependability, and optimization. Proportional Integral Derivative (PID) controller is a generic control loop feedback mechanism. The controller has the optimum control dynamics and an impressive property due to its simplicity, clear functionality, reliability and applicability to linear system, reduce steady state error, fast response, easy to implement, no oscillations, higher stability and robust performance. They are mostly used in more than 95% of the industrial process control application [19]. The three main parameters involved are Proportional (P) which is responsible for the desired set point and adjust the output controller, Integral (I) is used to remove the steady state error of control system and improve the steady state response, and Derivative (D) is used to improve the transient response of the system respectively as shown in Fig. 1. [20]. Fuzzy logic brings robustness and adaptive nature. It is successfully applied to non-linear system because of their knowledge based nonlinear structural characteristics. Fuzzy logic uses human knowledge to implement a system. It is more effective than PID controller as it reaches to its reference level in less time [21].

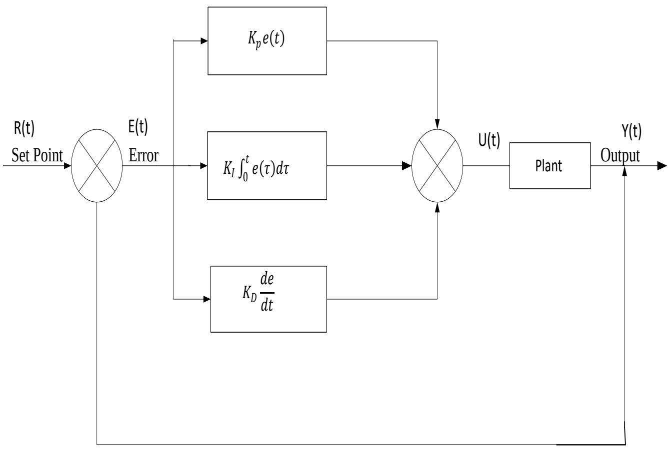

Fig. 1. Block Diagram of a Convectional PID Controller

II. SYSTEM DESCRIPTIONS

Fundamentally, tank systems are made up of liquid-holding containers having openings for fluid entrance and escape on the sides. Depending on the unique application requirements, such as storage capacity, flow rate, and level control precision, the design and configuration of tank systems might vary greatly. There are several types of tank systems such as single tank system, double tank system and quadruple tank system. Single tank system is a basic element in liquid control applications. It usually comprises of an outlet for regulated drainage and an entrance for adding liquid to the tank. A level sensor is built into the system to continuously check the liquid level. Single tank systems are widely used in many industries such as chemical processing, water treatment facilities, and industrial manufacturing, where precise liquid level control is crucial. They are essential to processes needing dependable liquid management because of their ease of use and adaptability, which guarantees effective operations and high-quality output. For a double tank system, operators can easily integrate liquid distribution, mixing, and storage into a variety of industrial processes by varying the flow rates between the tanks. A complex method of liquid control is embodied in the double-coupled tank system. The main reservoir usually takes up one tank, and the other one functions as a supplementary buffer or processing unit. Double tank systems are widely used in chemical processing plants due to its flexibility. The sophisticated design of four interconnected tanks used for various control and simulation purposes is called the quadruple tank system. As shown in Fig. 2. Several benefits come with the quad tank system such as; it provides ease flow movement of fluid from one tank to another; it makes testing sophisticated control algorithms easier and it provides a platform for practical control engineering education. It is used in a variety of contexts such as educational laboratories, chemical engineering, and process control research, where precision control and simulation of liquid systems are essential [22-25].

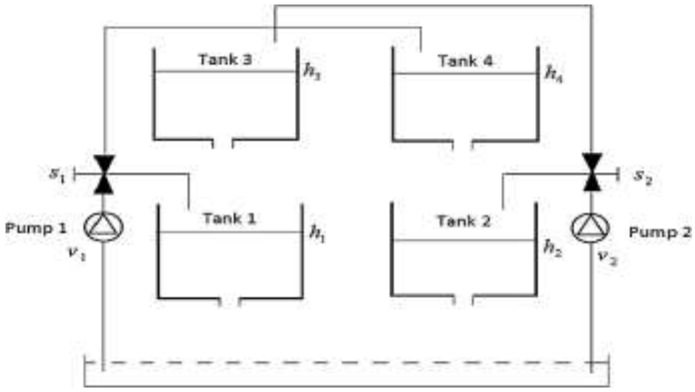

Fig. 2. Quadruple tank system [23]

III. METHODOLOGY (MATERIALS AND METHODS)

This section details the mathematical modeling of the liquid level tank system. The automatic liquid level tank control model is developed in Fig. 3, indicate that a desired input value would be set for the tank using a strain gauge, the value would be sent into the comparator, thus the comparator would compare the output value with the reference input to determine the error signal. Therefore, the Fuzzy logic would defuzzied to produce a three-output gain and auto tune the PID controller in order to have the same value as the reference input. The actuator model would be simulated using MATLAB Simulink and the performance would be evaluated based on the existing techniques in terms of rise time, settling time and percentage overshoot.

A. *Systems mathematical modeling*

As shown in Fig. 4. If the inflow rate of the water tank, Q_i, and the outflow rate of the tank outlet, Q_o, are equal and the water level of the tank, H, maintains a constant equilibrium state. Then the system can be modelled as a single-input single-output (SISO) system with the relation between the input, Q_i, and the output, H.

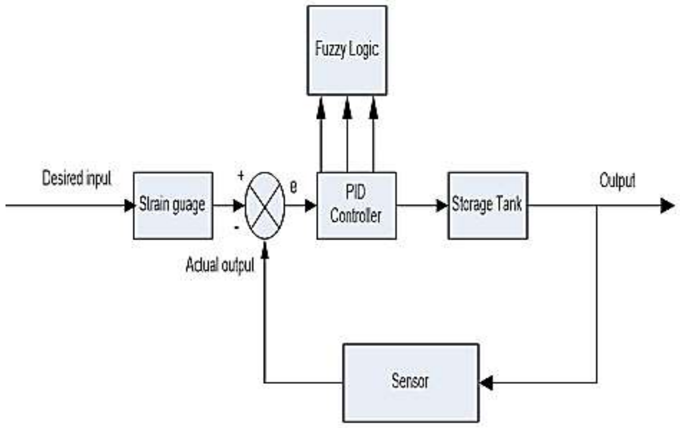

Fig. 3. Developed model of the liquid level tank

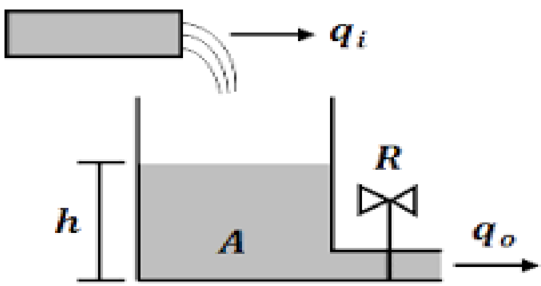

Fig. 4. Mathematical model of the liquid level tank

$$QT = Q_i - Q_o \tag{1}$$

$$A\frac{dH}{dt} = Q_i - Q_{out} \tag{2}$$

$$\frac{dH}{dt} = \frac{1}{A}(Q_i - Q_o) \quad (3)$$

Using the Bernoulli's equation, the speed at the water tank outlet would be expressed as $v = \sqrt{2gH}$, and the flow rate can be obtained when the speed is multiplied by the cross-sectional area of the water tank outlet. In other words, Q_o can be expressed using the fluid resistance at the water tank outlet.

$$Qo = Ao\sqrt{2gH} = \frac{1}{Ro} H \quad (4)$$

By substituting the value of Q_o into equation (2)

$$A\frac{dH}{dt} = Qi - \frac{1}{Ro} H \quad (5)$$

$$Qi = A\frac{dH}{dt} + \frac{1}{Ro} H \quad (6)$$

Applying Laplace transform function on both sides.

$$Q(s) = AsH(s) + \frac{1}{Ro} H(s) \quad (7)$$

After which we find the transfer function which is $\frac{H(s)}{Q(s)}$, so taking H(s) from the Laplace transformation.

$$H(s) = \frac{Q(s)}{As+1/R0} \quad (8)$$

Rearranging the equation, to get equation (9)

$$H(s) = \frac{Ro.Q(s)}{Ro.As+1} \quad (9)$$

Thus, for the transfer function, we arrived at equation (11)

$$\frac{H(s)}{Q(s)} = \frac{Ro.Q(s)}{Ro.As+1} / Q(s) \quad (10)$$

$$\frac{H(s)}{Q(s)} = \frac{Ro}{Ro.As+1} \quad (11)$$

Assuming the R (the flow resistance) = 1Ω, the radius of the cylinder is 2m and the height is 4m.

$$\frac{H(s)}{Q(s)} = \frac{1}{12.57s+1} \quad (12)$$

B. Optimization of PID controller using Fuzzy Logic

Since fuzzy logic is innovative technologies that modifies the design of a systems and formalize the ad-hoc approach of PID controller [27], 28]. Therefore, this work implemented fuzzy logic as the optimization to fine tune the parameters of the PID controller. The fuzzy logic applies linguistic rules on two inputs to produce three outputs derivation e and derivation rate ce are the inputs of the system. Upon the reception of the input data by the fuzzy logic, it translates it into a fuzzy form and fuzzy process according to IF THEN rules. The controller evaluates the table of fuzzy control rules to arrive at a single outcome value and before it proceeds on de-fuzzification process to get accurate values of PID gains, K_p, K_i, and K_d. The linguistic labels used to describe the fuzzy has seven sets: 'Negative Big' (NB),'Negative Medium' (NM), 'Negative Small' (NS), 'Zero' (ZE), 'Positive Small' (PS),'Positive Medium' (PM), 'Positive Big' (PB) with each set having its own membership function. The optimized PID controller improves the steady state response, minimizes the steady state error, transient response of the system and minimizes the rise time. The single, and double tank system based fuzzy PID controller Simulink diagram is illustrated in Fig. 5, and Fig. 6 respectively. The goal is to maintain the liquid levels in the tank at a setpoints by regulating the inflow. The difference between the setpoint and the actual level produces an error signal. This error is crucial as it represents the deviation of the system from its desired state and drives the subsequent control actions. The error signal is fed into both a PID controller and a fuzzy logic. The PID controller generates a control signal by calculating the proportional, integral, and derivative (P, I, and D) components of the error. The proportional term reacts to the current error, the integral term accounts for the accumulation of past errors, and the derivative term anticipates future errors based on the rate of change. These components are combined to form a comprehensive control signal that aims to reduce the error to zero.

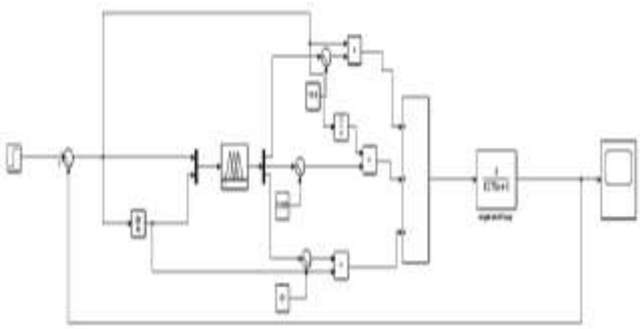

Fig. 5. Single tank system with Fuzzy-PID controller

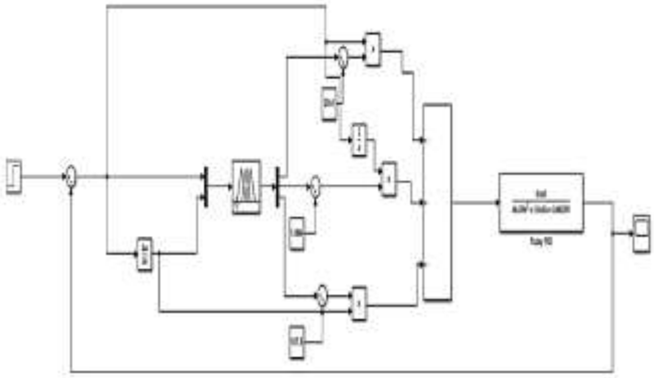

Fig. 6. Double tank system with Fuzzy-PID controller

The surface view of the output K_p, K_i, and K_d parameters are shown in Fig. 8, Fig. 9 and Fig. 10. Respectively. The proportional gain is determined by the difference between the set-point and the process value. The integral gain account for the accumulation of the past errors and caused the output to decrease when the process variable increase rapidly. The derivative gain improved the transient response of the system. The result showed that a small error term caused the derivative part to increase slowly. Moreover, K_p is smaller when the error and change in error are close to zero or at extreme values. K_i is decreased when both the error and the error's change are positive or extremely high or low. K_d is smaller when the error is very high or very low and the error change is positive.

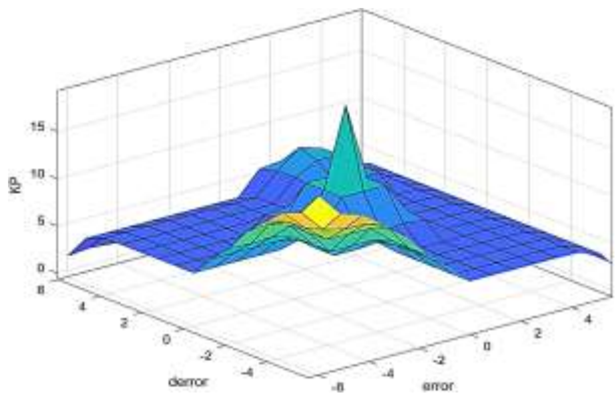

Fig. 8. Output surface view of K_p

TABLE II
MODIFIED CONTROLLERS FOR SINGLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
P	0.852	25.90	-
PI	0.853	23.45	-
PID	0.857	21.81	0.94

TABLE III
FUZZY PID CONTROLLER FOR SINGLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
Fuzzy PID	0.750	20.00	0.02

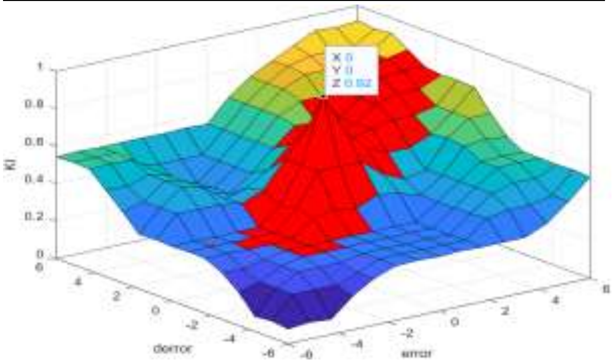

Fig. 9. Output surface view of K_i

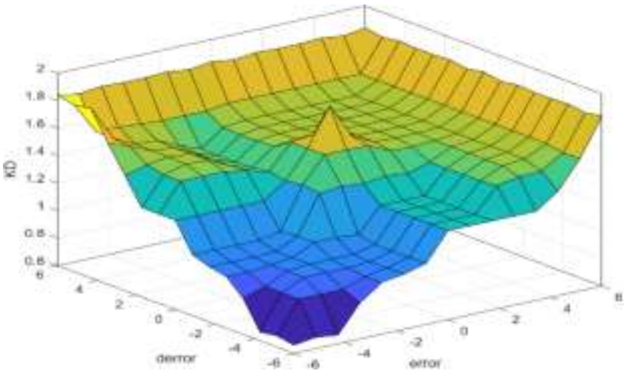

Fig. 10. Output surface view of K_d

IV. RESULT AND DISCUSSION

This section detailed the control signal responses from the use of fuzzy PID controller. These signals are analyzed to see how each of the methods improve the liquid storage tank system in any way. The performance evaluations of the system are characterized in terms of rise time, settling time and overshoot percentage. The rise time indicates how quickly the liquid level reaches the desired setpoint after a change is made. The settling time indicates how long it takes for the liquid level to stabilize around the setpoint after a disturbance or change in setpoint. The overshoot represents the extent to which the liquid level temporarily exceeds the desired level after a change. Therefore, Table I-III and Table IV-VI deduced the performance characteristics of the subjected controllers, proportional (P), proportional integral (PI), proportional integral derivative (PID) and fuzzy-PID for single tank system based on performance metrics of rise time, settling time and overshoot percentage.

TABLE I
CONVECTIONAL CONTROLLERS FOR SINGLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
P	1.001	26.4	-
PI	1.001	24.3	-
PID	1.002	23.3	2.57

The graphical representations of the convectional P, PI and PID controllers for single storage tank control at desired set point of 4m is shown in Fig. 11. The P, PI, and PID controllers is used to control the liquid level tank in order to have a pre-set value as its output. Based on the performance metrics, the controllers respond to changes based on setpoint. The values for the respective P, PI, and PID controllers metrics are 1.001 sec, 1.001 sec, and 1.002 sec for rise time; 26.4 sec, 24.3 sec, and 23.3 sec for settling time; 0.00 %, 0.00 %, and 2.57 % for percentage overshoot. It is deduced from the result that; the time takes for the liquid level to stabilize around the setpoint after a disturbance or change in setpoint (settling time) for PID controller decreases compare to the P, and PI controllers. While, the decreases of overshoot in P, and PI controller justify that, there is no presence of steady state error and distortion along the settling path. This feature is helpful in liquid-level control situations when overfilling or overflow are possible. Consequently, the graphical representation of the modified P, PI and PID controllers for single storage tank control at desired set point of 4m is shown in Fig. 12. The P, PI, and PID controllers is used to control the liquid level tank in order to have a pre-set value as its output. Based on the performance metrics, the controllers respond to changes based on setpoint. The values for the respective modified P, PI, and PID controllers metrics are 0.852 sec, 0.853 sec, and 0.857 sec for rise time; 25.90 sec, 23.45 sec, and 21.81 sec for settling time; 0.00 %, 0.00 %, and 0.94 % for percentage overshoot. It is deduced from the result that; the time takes for the liquid level to stabilize around the setpoint after a disturbance or change in setpoint (settling time) for PID controller decreases compare to the P, and PI controllers. While, the decreases of overshoot in P, and PI controller justify that, there is no presence of steady state error and distortion along the settling path. This feature is helpful in liquid-level control situations when overfilling or overflow are possible. The optimized performance for single storage tank control using fuzzy PID controller at desired set point of 4m is shown in Fig. 13. From the result, it is deduced that, the values of the performance metrics in terms of rise time, settling time and overshoot are 0.750 sec, 20.00 sec, and 0.02 % respectively decreases when compare to the convectional PID and modified PID controllers as presented in Table I and Table II. It is observed that the time taken for Fuzzy-PID controller to reach the steady state value is lesser and the percentage overshoot is minimized compared with PID controller presently in use.

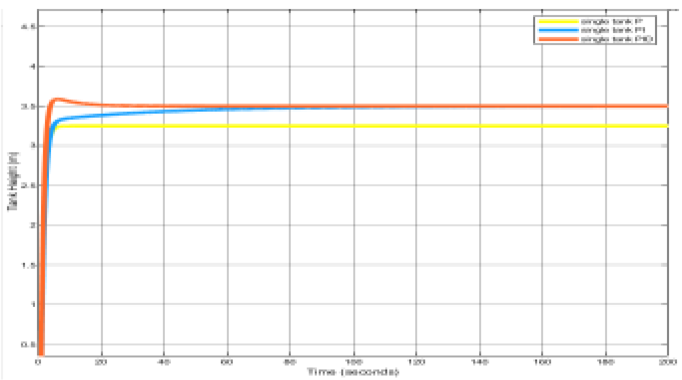

Fig. 11. Convectional controllers for single tank system

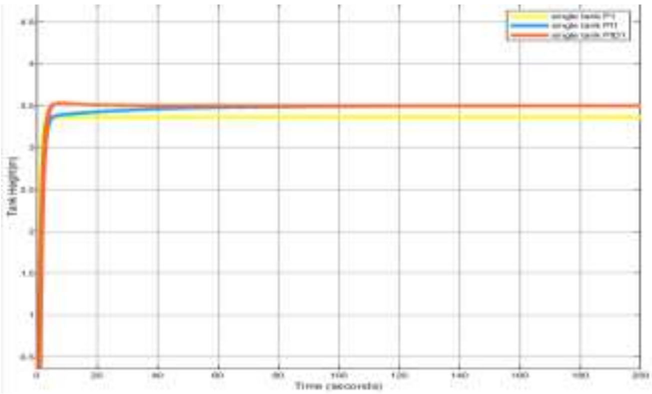

Fig. 12. Modified controllers for single tank system

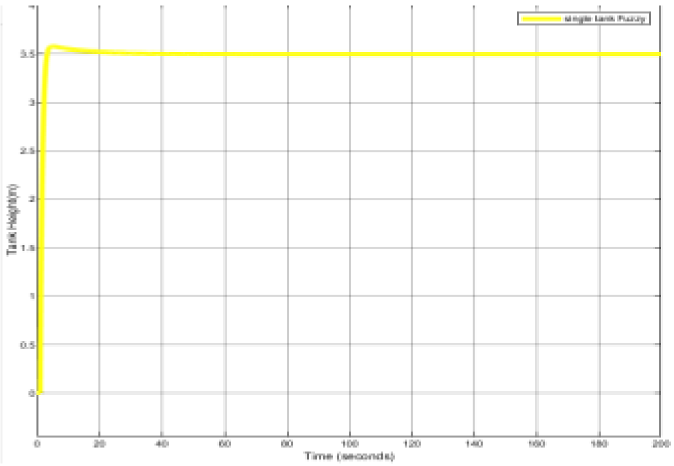

Fig. 13. Fuzzy-PID controller for single tank

TABLE IV
CONVECTIONAL CONTROLLERS FOR DOUBLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
P	1.100	150	42.0
PI	1.983	250	69.6
PID	1.039	132	53.9

TABLE V
MODIFIED CONTROLLERS FOR DOUBLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
P	1.230	141	55.5
PI	0.850	130	57.4
PID	0.800	125	63.1

TABLE VI
FUZZY PID CONTROLLER FOR DOUBLE TANK SYSTEM

Controller Type	Rise time (Sec)	Settling time (Sec)	Overshoot percentage (%)
Fuzzy PID	0.75	100	34.3

The graphical representations of the convectional P, PI and PID controllers for single storage tank control at desired set point of 4m is shown in Fig. 14. The P, PI, and PID controllers is used to control the liquid level tank in order to have a pre-set value as its output. Based on the performance metrics, the controllers respond to changes based on setpoint. The values for the respective P, PI, and PID controllers metrics are 1.100 sec, 1.983 sec, and 1.039 sec for rise time; 150 sec, 250 sec, and 132 sec for settling time; 42.0 %, 69.6 %, and 53.9 % for percentage overshoot. It is deduced from the result that; the time takes for the liquid level to stabilize around the setpoint after a disturbance or change in setpoint (settling time) for PID controller decreases compare to the P, and PI controllers. While, the decreases of overshoot in P, and PID controller justify that, there is no presence of steady state error and distortion along the settling path. This feature is helpful in liquid-level control situations when overfilling or overflow are possible. Consequently, the graphical representation of the modified P, PI and PID controllers for single storage tank control at desired set point of 4m is shown in Fig. 15. The P, PI, and PID controllers is used to control the liquid level tank in order to have a pre-set value as its output. Based on the performance metrics, the controllers respond to changes based on setpoint. The values for the respective modified P, PI, and PID controllers metrics are 1.230 sec, 0.850 sec, and 0.800 sec for rise time; 141 sec, 130 sec, and 125 sec for settling time; 55.5 %, 57.4 %, and 63.1 % for percentage overshoot. It is deduced from the result that; the time takes for the liquid level to stabilize around the setpoint after a disturbance or change in setpoint (settling time) for PID controller decreases compare to the P, and PI controllers. While, the decreases of overshoot in P, and PI controller justify that, there is no presence of steady state error and distortion along the settling path. This feature is helpful in liquid-level control situations when overfilling or overflow are possible. The optimized performance for single storage tank control using fuzzy PID controller at desired set point of 4m is shown in Fig. 16. From the result, it is deduced that, the values of the performance metrics in terms of rise time, settling time and overshoot are 0.750 sec, 100 sec, and 34.3 % respectively decreases when compare to the convectional PID and modified PID controllers as presented in Table IV and Table V. It is observed that the time taken for Fuzzy-PID controller to reach the steady state value is lesser and the percentage overshoot is minimized compared with PID controller presently in use.

Hence, the summary results of the controllers under investigation based on the control of liquid level tank in single and double system response indicate that Fuzzy PID controller has the least in rise time, settling time and overshoot percentages. This reflects the superior performance of the Fuzzy-PID over other investigated controllers.

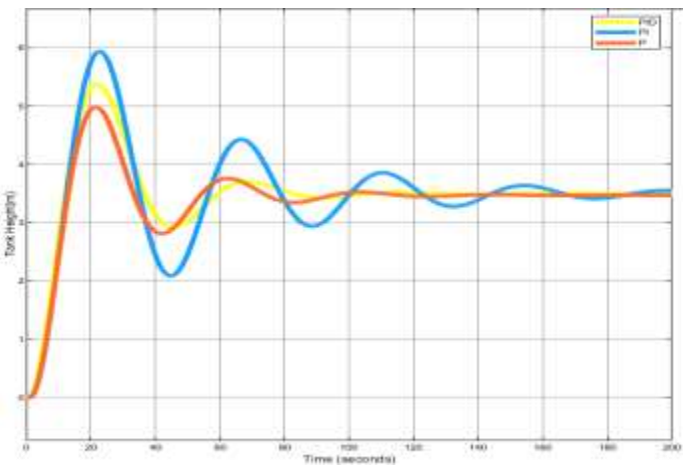

Fig. 14. Convectional controllers for double tank system

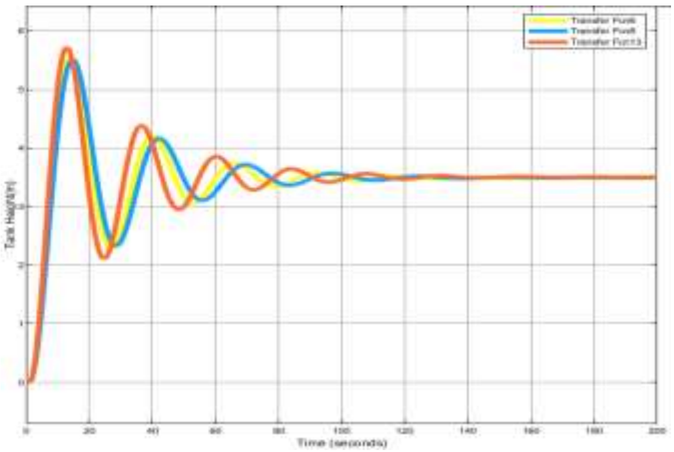

Fig. 15. Modified controllers for double tank system

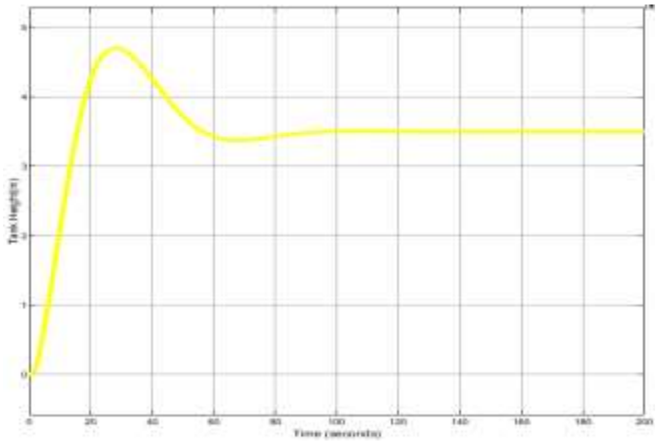

Fig. 16. Fuzzy-PID controller for double tank

V. CONCLUSION

A fuzzy-PID controller for both single- and double-tank systems has been developed and presented in this paper. The strategy explores a simple, efficient, and feasible optimization method to control the coupled liquid level tank system, reducing the steady-state error and achieving satisfactory dynamic performance at minimal time under different operating conditions. The results of the simulation show that the controller gives a superior performance over other conventional controllers presently in use based on the performance metrics such as the rise time, settling time and percentage overshoot. In addition, this performance reflects that a fuzzy-PID controller is effective in dampening oscillations and stabilizing the system quickly, making it ideal for applications requiring precise and dynamic control. This technique can be further extended to more complicated liquid level tank system arrangements, and seamlessly deployed to enhance industrial process operations' safety, optimization and sustainability.

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