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Liquid Level Control Using a Self-Tuning PID Controller Based on Fuzzy Logic

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Abstract

In process control systems such as liquid level regulation, proportional-integral-derivative (PID) controllers are widely used due to their simplicity, ease of implementation, and effectiveness in linear systems. The development of high-performance PI/PID controllers remains a key area of research for control engineers. However, their performance can degrade in systems characterized by nonlinearity, uncertainty, and time-varying parameters, as traditional PID controllers are primarily designed for linear, time-invariant systems. To address this limitation, self-tuning PID controllers incorporate adaptive mechanisms that adjust the controller parameters in real time based on changing system conditions. In particular, fuzzy logic-based PID controllers have been explored as a means to enhance online adaptability and improve system responsiveness to dynamic variations.

This research focuses on liquid level control, which is critically important in industries such as chemical and nuclear plants, where precise regulation of fluid levels is essential for safety and efficiency. The objective is to design an advanced fluid level control system that addresses the limitations of conventional PID control. The system is modeled and simulated using MATLAB-SIMULINK, and the performance of a traditional PID controller is compared with that of a fuzzy-PID controller. Initially, the classical PID controller is tested and its performance evaluated. Then, a Mamdani-type fuzzy inference system is implemented to adjust the PID parameters in real time. The system's performance is assessed in terms of error

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minimization and stability, both before and after applying the fuzzy-PID self-tuning method.
Keywords: PID controller, Self-tuning, Fuzzy logic system, Level control system.

التحكم في مستوى السائل باستخدام متحكم PID ذاتي الضبط المعتمد على المنطق الضبابي

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الملخص

تُستخدم وحدات المتحكم التناسبية–التكاملية–التفاضلية (PID Controller) على نطاق واسع في أنظمة التحكم بالعمليات الصناعية مثل التحكم بمستوى السوائل نظرًا لبساطتها وسهولة استخدامها وفعاليتها مع الأنظمة الخطية. وبالتالي فان تطوير المتحكمات (PI/PID) يعتبر مجالًا رئيسيًا للبحث بين مهندسي التحكم.

ومع ذلك، نتج قصور في أداء هذا النوع من المتحكمات في التعامل مع العمليات التي تتسم باللاخطية (nonlinearity) ووجود التشويش وتغير المعاملات مع الزمن (time–varying parameters)، نظرًا لأن وحدات المتحكم (PID) التقليدية صُممت أساسًا للتعامل مع الأنظمة الخطية الغير متغيرة مع الزمن. لمعالجة هذا المشكلة تم تضمين المتحكمات (PID) ذاتية الضبط آليات تكيفية تقوم بضبط معاملات المتحكم في الزمن الحقيقي بناءً على تغير ظروف اداء النظام. ان ظهور المتحكمات (PID) المعتمدة على المنطق الضبابي كوسيلة لتعزيز القدرة على التكيف في الزمن الحقيقي وتحسين استجابة النظام للتغيرات الديناميكية أسهم في حل هذه المعضلة.

تركز هذه الدراسة على التحكم في مستوى السائل، وهو أمر بالغ الأهمية في الصناعات مثل المصانع الكيميائية والوحدات النووية لإنتاج الطاقة كهربائية، حيث يُعد التنظيم الدقيق لمستويات السوائل ضروريًا للسلامة والكفاءة. ان الهدف الرئيسي من هذه الدراسة هو تصميم نظام متقدم للتحكم في مستوى السائل يعالج القصور الناتج عن التحكم التقليدي باستخدام المتحكم PID controller. تم نمذجة النظام ومحاكاته باستخدام **MATLAB–SIMULINK**، وتمت مقارنة أداء المتحكم PID التقليدي مع وحدة التحكم ذاتية التكييف باستخدام المنطق الضبابي(Fuzzy–PID Controller) . حيث

تم اختبار وحدة التحكم PID الكلاسيكية وتقييم أدائها، ثم اتجهت الدراسة الي تصميم نظام تحكم ذاتي الضبط مستخدما نظام استدلال ضبابي من نوع **Mamdani** لضبط معاملات المتحكم (PID)في الزمن الحقيقي. ان تقييم أداء النظام يكون من حيث تقليل خطأ الاستقرار(Steady State Error) وسرعة الاستجابة(Rising Time) وعدم التجاوزاللحظي للقيم المرجعية(Overshoot) قبل وبعد تطبيق طريقة الضبط الذاتي باستخدام المنطق الضبابي. بالإضافة إلى ذلك، يتم تقييم استجابة النظام تحت ظروف تغيير القيم المرجعية(set point) لإظهار قدرته العالية على التكيف في الظروف التشغيلية المختلفة في الزمن الحقيقي.

الكلمات المفتاحية: المتحكمPID ، ذاتي الضبط، نظام المنطق الضبابي، نظام التحكم في المستوى

1• Background

A PID controller consists of three components: the proportional (P), integral (I), and derivative (D) terms. These controllers are widely used in industrial control applications and serve as fundamental building blocks in many control systems, including complex networks. Originally developed as analog devices, PID controllers have evolved into modern digital implementations, proving highly effective in managing high-volume industrial processes [1].
PID controllers play a vital role in industrial automation due to their robustness, simplicity, and ease of implementation, making them a preferred choice for engineers and operators [2]. However, manually tuning the PID parameters-proportional (k_p), integral (k_i), and derivative (k_d) can be difficult, especially in multi-variable or dynamic systems where delayed responses require extensive testing and iterative adjustments [3].
Manual tuning of PID controllers often leads to suboptimal performance, as parameter adjustments typically require multiple iterations to achieve the desired system response. In systems with frequently changing setpoints, auto-tuning becomes essential for efficient automation. In such scenarios, methods like fuzzy logic-based PID control provide an effective solution [4,5].
Fuzzy Logic Control (FLC) is a widely adopted technique that mimics human reasoning through IF-THEN rules, making it suitable

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for modeling systems that are too complex or uncertain to be described by traditional mathematical approaches. FLC effectively handles imprecision and uncertainty in control systems [6]. Its flexibility makes it particularly well-suited for designing self-tuning PID controllers, enabling real-time adjustment of PID gains in response to process variations and nonlinear behaviour.
The fuzzy PID controller utilizes a fuzzy inference system (FIS) to adjust the PID parameters dynamically. The control structure can be represented as:

$$k_p = f_1(e(t), y(t), k_i = f_2(e(t), y(t), k_d = f_3(e(t), y(t), \qquad (1)$$

The fuzzy inference system computes these values through a set of rules, adjusting the gains to optimize control performance [6].

2. Literature Survey

A helpful review of classical PID design and application in the process industry can be found in [3,4].
The concept of fuzzy logic was first introduced by Lotfi Zadeh in 1965. Building on his work, Ebrahim Mamdani developed one of the earliest fuzzy logic controllers in the mid-1970s, which spurred significant research and industrial applications in control systems. This foundational work inspired further contributions from researchers such as Sugeno, Pedrycz, Lee, Berenji, Yamakawa, and others in [6].
The applications of fuzzy logic system in industrial have been introduced in the literature. such as nuclear plants, water treatment processes, petro-chemical unit and many other applications conducted on pilot plants. The application of the fuzzy logic control concept in tuning PID controllers can be found in [1, 2, 7]. These studies presented a case study in which PID controller gains are adaptively changed via fuzzy logic. In this scheme, different values of the PID parameters are tabulated, and the fuzzy logic scheme selects the most suitable set of values based on the information collected about the process.
García-Martínez et al. [8] proposed a PID-type fuzzy logic controller (FLC) designed to adapt PID gains dynamically based on fuzzy rules. Their study demonstrated that integrating fuzzy logic

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with classical PID controllers can significantly enhance control performance in industrial applications. By adjusting the PID parameters in real time, the system was able to handle nonlinearities and disturbances more effectively, achieving improved transient response and steady-state performance. This work highlights the potential of fuzzy logic in tuning PID controllers, providing a flexible and robust approach suitable for a wide range of industrial processes.

It is assumed in [9-11] that k_p, k_i and k_d are in prescribed ranges $[k_{pmin}\ ,\ k_{pmax}]$, $[k_{imin}\ ,\ k_{imax}]$and $[k_{dmin}\ ,\ k_{dmax}]$, respectively.The adaption scheme, hence, starts from the minimum values of the parameters and using fuzzy logic adaptation the parameters are varied in the prescribed range.

Study [12] indicates that fuzzy logic controllers effectively stabilize liquid levels in tank systems by reducing steady-state error and overshoot compared with conventional PID controllers. Using centroid defuzzification, the fuzzy controller achieves faster response and higher accuracy, with settling time reduced to around 50 seconds versus 80 seconds for PID and overshoot below 1%, demonstrating superior performance for nonlinear industrial processes.

This paper [13] addresses precise liquid level control in single-tank systems with continuous actuation and modulated setpoints. A feedback linearization–based PI controller, using parameters from a simple fill-and-drain test, is proposed. Simulation and experimental results on a large-scale laboratory system demonstrate effective level tracking and disturbance rejection, highlighting its potential for both stand-alone industrial applications and integration within supervisory control schemes in a DCS.

3. Methodology

To address the limitations of conventional PID control, fuzzy logic is incorporated to adaptively tune the PID parameters. In this fuzzy PID control system, figure 1, the parameters k_p, k_i, and k_D are adjusted dynamically based on real-time feedback from the system. The error e(t) and the output changing rate $\Delta y(t)$are fuzzified, and a fuzzy inference system (FIS) is used to generate the appropriate adjustments for the PID parameters[13,14].

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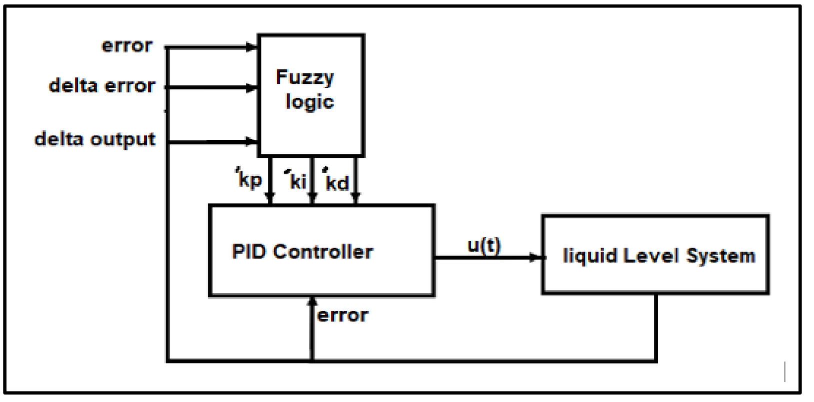

Fig 1: Block diagram of self-tuning PID fuzzy control system.

3.1. Modelling of Level Control System

The model of an open tank system, figure 2, is derived using the mass balance principle, which is relating the tank level $H(t)$ and inflowQ$_{in(t)}$[15].

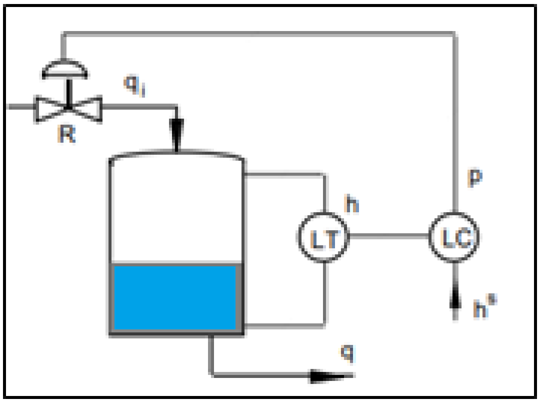

Fig 2: single tank water level system.

$$A\frac{dh}{dt} = q_{in} - q_{out} \tag{2}$$

According to Bernoulli's equation:

$$q_{out} = a\sqrt{2gh} \tag{3}$$

$$A\frac{dh}{dt} = q_{in} - a\sqrt{2gh} \tag{4}$$

Where:

$a = 0.015\ m^2$;Tank output, $A = 2.5\ m^2$;Cross-sectional area of the tank, $g = 9.81\ \frac{m}{s^2}$; gravitational constant.

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Figure 3 shows the system model represented in block diagram form, while figure 4 illustrates the subsystem valve model.

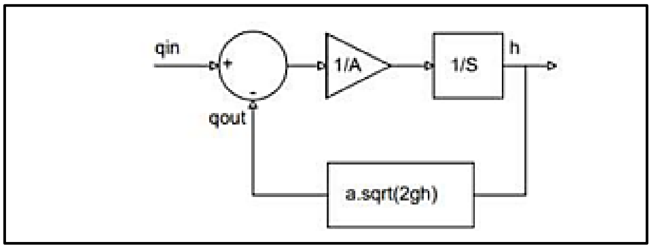

Fig 3: modeling of single tank level with an input and output flow.

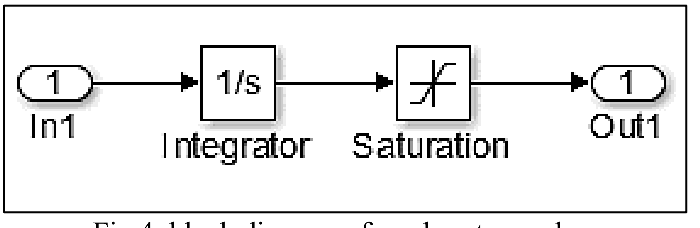

Fig 4: block diagram of a subsystem valve.

3.2. PID Controller Design via Root Locus

The response of the open-loop control system exhibits an overshoot of approximately 80% and a settling time of 30 sec. To improve the transient response, the root locus method was employed to design a proportional–integral–derivative (PID) controller. The design specifications were based on a desired rise time of 3 sec., a settling time of 30 sec., and a maximum overshoot of 10% [16].

As shown in figure 5, to reduce the overshoot to less than 10%, the dominant poles are located at approximately –3.04 ± 4.05j. The corresponding PID controller parameters obtained from the root locus design method are summarized in Table 1.

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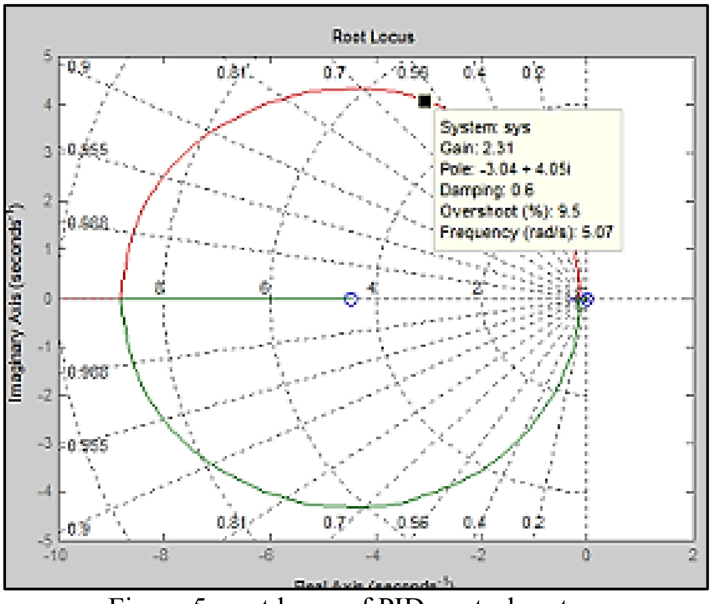

Figure 5: root locus of PID control system

Table 1. PID gains via root locus designing method.

Controller Type	k_p	k_i	k_d
P-Controller	0.7	-	-
PI-controller	0.63	3.33	-
PID controller	0.8	2	3.31

3.3. Designing of Self –Tuning PID System

Designing a self-tuning fuzzy PID controller requires an understanding of both conventional PID dynamics and fuzzy logic principles. When the PID controller tunes, and by observation the output characteristics with PID variations around the setting gains (K_P, K_i, K_D), so we can get an understanding about the input/output relationship. For that, the designing of fuzzy- PID controller will divided to three stage, self-tuning P controller, self-tuning PD controller and finally, self-tuning PID controller as in figure 6.

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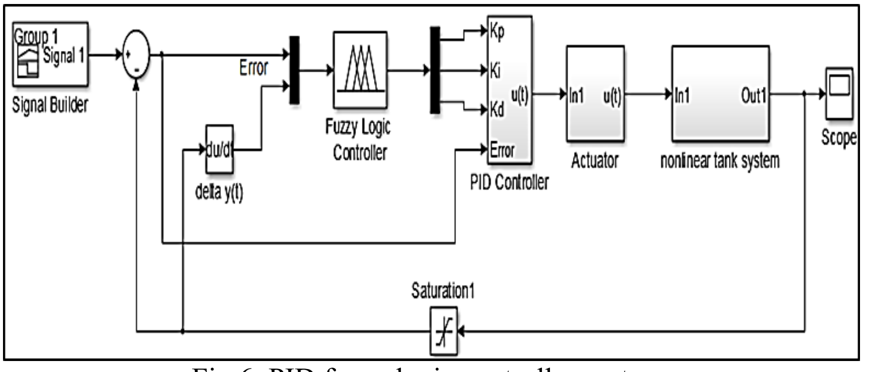
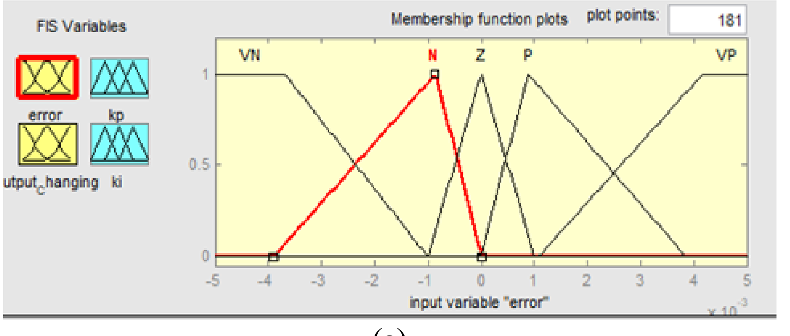
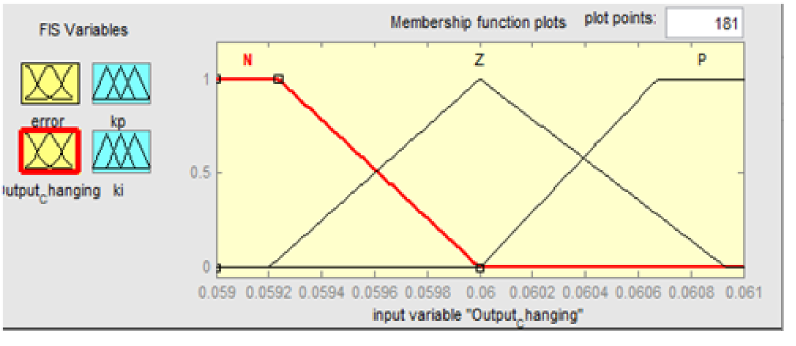


Fig 6: PID fuzzy logic controller system.

Firstly, the membership functions of the input variables, error (e) and rating of output changing $\Delta Y(t)$ respectively, which have range {-0.005 , 0.005}and {0.059, 0.061}.The corresponding membership functions are shown in Figures 7.a and 7.b.



(a)



(b)

Fig 7.a: Fuzzification of Input Variable "e". Fig 7.b: Fuzzification of Input Variable "Δy(t)".

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The fuzzy outputs ΔK_P , ΔK_i and ΔK_D represent online adjustments to the PID gains, figure 8.a, 8.b and 8.c, A rule base consisting of fifteen fuzzy rules, figure 9, defines the relationship between input and output variables.

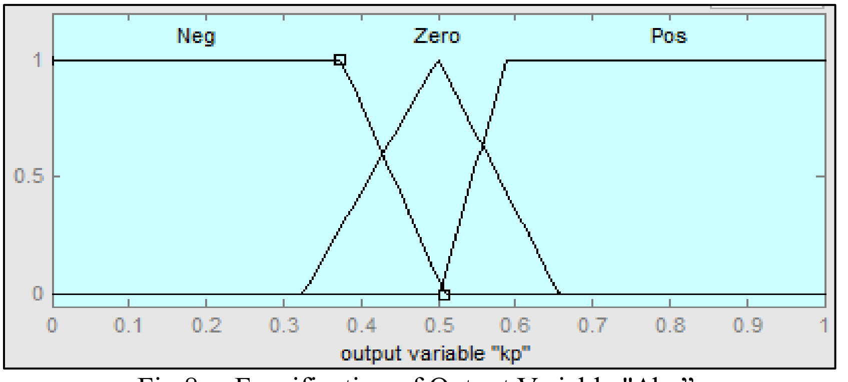

Fig 8.a: Fuzzification of Output Variable "Δkp".

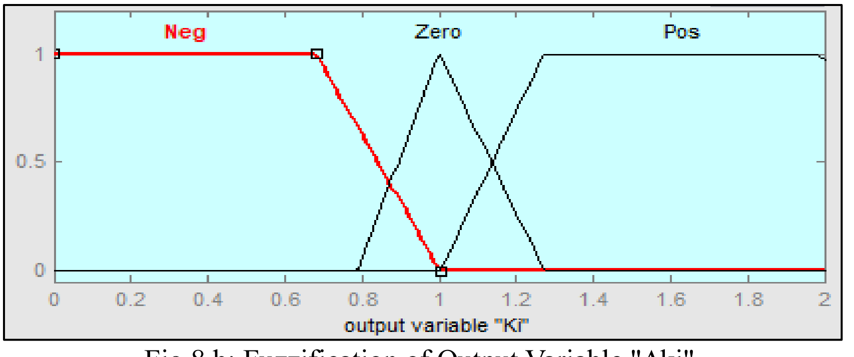

Fig 8.b: Fuzzification of Output Variable "Δki".

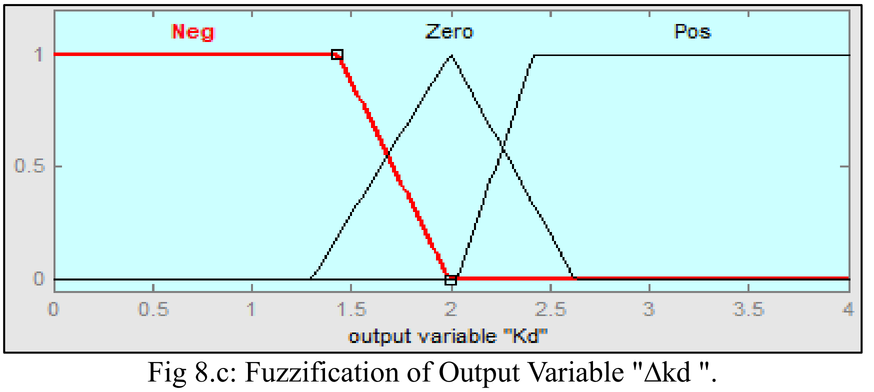

Fig 8.c: Fuzzification of Output Variable "Δkd ".

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1. If (error is N) and (Output_Changing is N) then (kp is Neg)(Ki is Neg)(Kd is Neg) (1)
2. If (error is N) and (Output_Changing is Z) then (kp is Zero)(Ki is Zero)(Kd is Zero) (1)
3. If (error is N) and (Output_Changing is P) then (kp is Pos)(Ki is Pos)(Kd is Pos) (1)
4. If (error is Z) and (Output_Changing is N) then (kp is Neg)(Ki is Neg)(Kd is Neg) (1)
5. If (error is Z) and (Output_Changing is Z) then (kp is Zero)(Ki is Zero)(Kd is Zero) (1)
6. If (error is Z) and (Output_Changing is P) then (kp is Pos)(Ki is Pos)(Kd is Pos) (1)
7. If (error is P) and (Output_Changing is N) then (kp is Neg)(Ki is Neg)(Kd is Neg) (1)
8. If (error is P) and (Output_Changing is Z) then (kp is Zero)(Ki is Zero)(Kd is Zero) (1)
9. If (error is P) and (Output_Changing is P) then (kp is Pos)(Ki is Pos)(Kd is Pos) (1)
10. If (error is VN) and (Output_Changing is N) then (kp is Neg)(Ki is Neg)(Kd is Neg) (1)

Fig 9: Rule base considered.

3.4. Evaluation of Results

Simulation results are used to compare the performance of conventional PID and self-tuning fuzzy PID controllers. Figure 10 shows the fuzzy-P controller response with a rise time of 9 sec, settling time of 20 sec, and 8% overshoot.

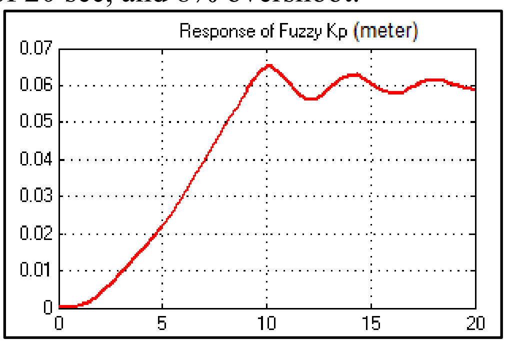

Fig 10: response of fuzzy-P controller.

Figure 11 illustrates how the fuzzy logic controller adaptively varies the proportional gain (k_p) according to changes in process error. This adjustment helps maintain the desired output level while improving stability and reducing overshoot compared to the conventional PID controller.

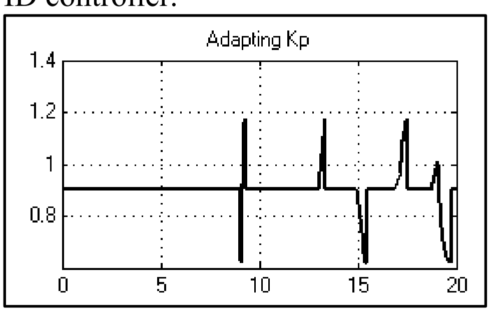

Fig 11: variation of P-controller.

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To decreasing rising time, the integral term add, and the self-tuning PI controller used, the output response improved as shown in figure 12.so the rising time equal to 5 sec. and the settling time equal to 20 sec. but the overshoot increasing to 16%.

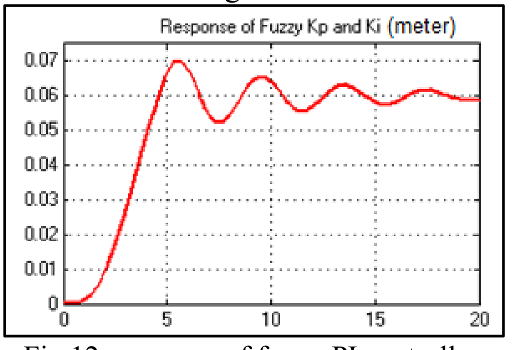

Fig 12: response of fuzzy-PI controller.

Figure 13) shows how the fuzzy controller tuned the gains k_p and k_i for improvement the liquid level response.

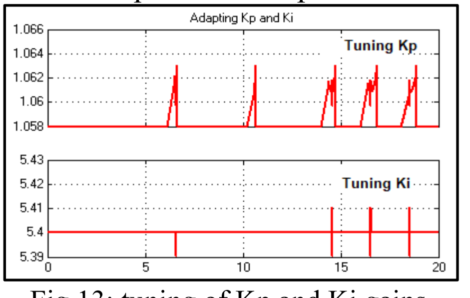

Fig 13: tuning of Kp and Ki gains.

The derivative term further refines performance, the response of self-tuning PID controller appears satisfactory performance as in figure 14, the rising time less than 8 sec, the settling time equal to 20 sec, and overshoot of 5%.

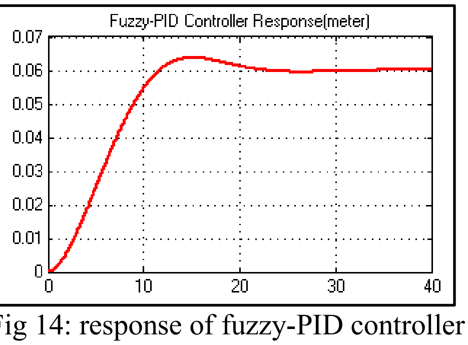

Fig 14: response of fuzzy-PID controller

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The tuned of PID controller gains to improvement the level control response illustrated in figure 15, and shows how the gains updates with response dynamic . Figure 16 illustrates the dynamic fluctuations observed in the actuator valve response under the influence of the adaptive PID controller signal.

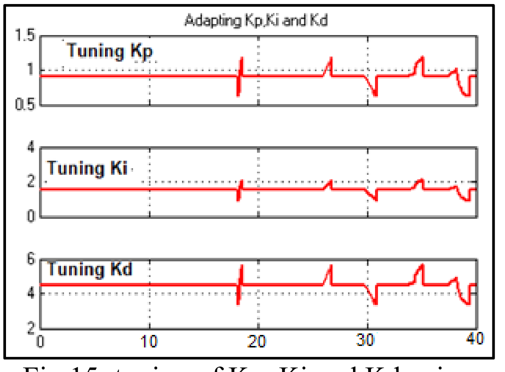

Fig 15: tuning of Kp, Ki and Kd gains.

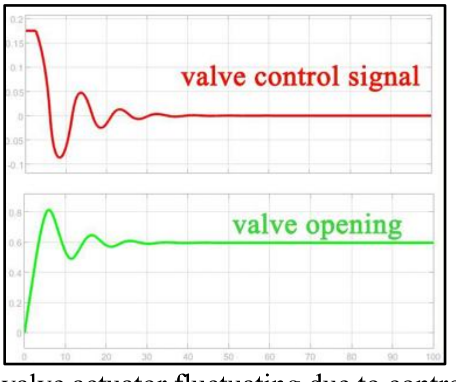

Figure 16: valve actuator fluctuating due to controller signal

Throughout the study, when comparing the performance of PID and self-tuning PID controller in figure (17), the self-tuning PID appears improvement in output response and overcome the limitations of level control system as nonlinearities and uncertainties.

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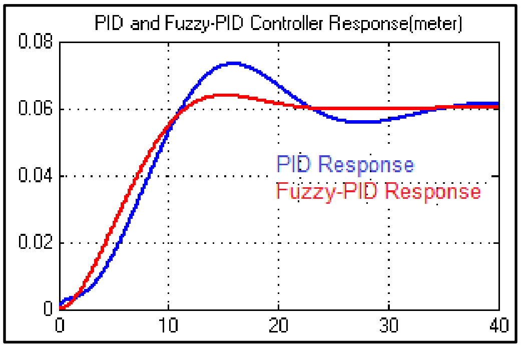

Fig 17: PID and Self-tuning PID response of level control system.

Table 2 illustrates the performance optimization achieved by the proposed self-tuning fuzzy PID controller relative to the conventional PID controller, with comparative metrics including rise time, settling time, and maximum overshoot.

Table 2. Characterized performance of the PID versus the Self – tuning fuzzy PID controller.

Controller Type	PID Controller	Tuning P-controller	Tuning PI-controller	Tuning PID-controller	Optimization Self-Tuning versa PID
Rising Time	10 sec.	9 sec.	5 sec.	8 sec.	20%
Settling Time	40 sec.	20 sec.	20 sec.	20 sec.	50%
%O.S	15%	8%	16%	5%	66%

Figure 18 presents the surface viewer output of the fuzzy inference system (FIS), which provides a 3-D graphical representation of the controller behavior. The surface illustrates how the fuzzy logic system maps the input variables — error (*e(t)*) and change in output (*Δy(t)*) — to the corresponding control output. The smoothness of the surface indicates the continuous and nonlinear nature of the fuzzy control action, ensuring a gradual adjustment of the control signal. This feature enables the self-tuning PID controller to achieve improved transient performance and reduced overshoot compared to the conventional PID controller.

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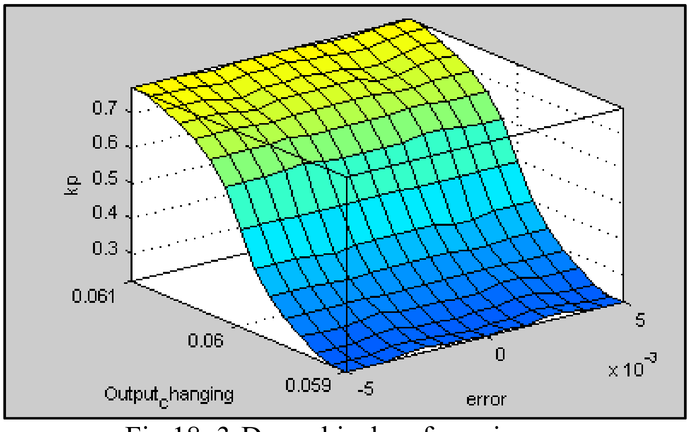

Fig 18: 3-D graphical surface viewer.

4. Conclusions

This research focuses on flow control as a representative case. Fluid level management is particularly critical in process industries, such as chemical and nuclear plants, where achieving and maintaining the desired fluid level setpoint poses a significant control challenge. The adaptive gains of the PID controller enable real-time adjustment of the system's response by tuning the controller according to the dynamic behavior of the process.

The simulations conducted in this study demonstrate that the self-tuning PID-Fuzzy controller achieves a commendable transient response, reducing the settling time by approximately 50% compared to the conventional PID controller, while maintaining nearly 0% overshoot. The fuzzy logic-based self-tuning PID controller provides a robust method to enhance performance in real-time, especially for systems subject to dynamic setpoint changes, parameter variations, nonlinearities, and uncertainties common in level control applications. By enabling continuous adaptation, the fuzzy-PID controller offers significant improvements over traditional PID controllers.

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