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RESEARCH ARTICLE

Fuzzy-PID and interpolation: a novel synergetic approach to process control

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ABSTRACT

This paper presents a novel approach for tuning a fuzzy-based proportional-integral-derivative (PID) controller to enhance the control performance of a chemical process control system. The proposed approach combines the advantages of fuzzy- PID and interpolation to achieve improved control performance. Properly tuned PID controllers can help maintain process stability, minimize deviations from setpoints, and ensure efficient operation in industrial systems. Fuzzy logic allows for the incorporation of expert knowledge and linguistic rules, enabling the controller to handle uncertain and imprecise process information. Fuzzy PID controllers combine fuzzy logic and conventional PID control to enhance control performance, particularly in systems with complex or nonlinear dynamic such as chemical plant. It dynamically adjusts the PID parameters—proportional gain (Kp), integral gain (Ki), and derivative gain (Kd)—based on error $e(t)$ and change of error $\Delta e(t)$. Interpolation plays a crucial role in this context by filling in the gaps or handling situations not explicitly covered by the fuzzy rules. Comparative studies are conducted to evaluate the performance of the fuzzy PID controller against conventional PID controllers and other advanced control techniques. It is demonstrated that the synergy between fuzzy logic and interpolation not only enhances control performance but also offers a more intuitive and adaptable solution for addressing the complexities of modern chemical process control systems.

1. Introduction

Process control systems should be designed to ensure the efficient and safe operation of chemical processes in industries such as oil refining, petrochemicals, pharmaceuticals, and food processing. These systems monitor and regulate process variables such as temperature, pressure, flow rate, level and concentration with the aim of achieving optimal process performance, product quality, and resource utilization. The complexity of chemical processes, often characterized by nonlinear dynamics, time delays, and interactions between various process variables, poses significant challenges. The primary objective of a chemical process control system is to maintain these variables within desired operating ranges, despite disturbances and uncertainties in the process environment. Traditionally, control systems in chemical processes have relied on classical control techniques such as Proportional-Integral-Derivative (PID) control. PID controllers are widely used owing to their inherent simplicity, ease of implementation, and familiarity among control engineers. A

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PID controller calculates a control action based on the error between the desired setpoint and the actual process variable, taking into account the proportional, integral, and derivative components. However, traditional PID control approaches have limitations when applied to complex chemical processes. These limitations include difficulty in handling nonlinearities, interactions, and time-varying dynamics, as well as challenges in tuning the controller parameters for optimal performance. Consequently, there is a need for advanced control strategies that can address these limitations and enhance the control performance of chemical process systems.

Several classical methods pertaining to PID control have been proposed to achieve desired controller performance. Ziegler and Nichols in 1942 [1], first introduced the method of PID tuning. The tuning method described by them is a heuristic approach that provides simple and practical technique for initial tuning but had limitations in terms of control performance and robustness. To overcome the limitations of the Ziegler-Nichols (Z-N) method, researchers focused on developing more sophisticated techniques. Passivity-based control strategy [2] offers a promising alternative for controlling generalized passive systems, providing stability, robustness, and adaptability to different system dynamics. Cohen and Coon's method [3] focuses on achieving better control performance by accounting for the time delay, which can significantly impact the system's response. Despite of some limitations, Z-N is one of the most widely used PID tuning method because of its simplicity. A modified Ziegler-Nichols method is proposed in [4] by refining the calculation of ultimate gain, ultimate period and tuning rules. An Internal Mode Control (IMC) based design was proposed in [5].

This seminal work introduced the concept of Internal Model Control (IMC) and provided a comprehensive framework for designing PID controllers based on this innovative control strategy. However, the paper mainly focused on linear systems, and the robustness analysis was limited to linear uncertainties. Skogestad and Postlethwait [6] proposed the modified IMC method, which aimed to achieve the desired closed-loop response by designing an internal model that mimics the process dynamics. The IMC method showed improved disturbance rejection and robustness compared to the Ziegler-Nichols method. A comprehensive reference guide that focuses on providing practical insights and guidelines for tuning proportional-integral-derivative (PID) controllers has been presented in [7]. Detailed review of various PID controller tuning method has been discussed in [8]. In order to reduce the time and knowledge of tuning process, Åström and Hägglund [9] proposed method that focuses on the automatic tuning of simple regulators, likely referring to control systems that use basic feedback control techniques like proportional, integral, and derivative (PID) control. The main emphasis of the paper is on achieving desired phase and amplitude margins for stability and performance of control systems. Author went further to explore more of autotuning method and presented an experimental comparison of various PID autotuners. The objective of this study is likely to evaluate the performance and effectiveness of different autotuning methods in real-world scenarios [10].

In addition to aforementioned methods for tuning PID controllers, there are numerous other. Some of the popular tuning methods are Model-based Tuning, 'Trial and error', Optimization Techniques etc. However, in many real-world scenarios, the system's behavior may be complex, uncertain, or difficult to model accurately. In such cases, expert knowledge from experienced operators or domain experts can be valuable in improving the control performance.

Fuzzy logic has been used to incorporate the expert knowledge for the PID controller tuning. Uçak. K introduced the concept of fuzzy and proposed a novel adaptive multi-input multi-output (MIMO) fuzzy PID controller for time delay systems, building upon prior work on single-input single-output (SISO) system. The study evaluates the controller's performance in stabilization, tracking, and disturbance rejection against classical PID controllers. Results demonstrate the effectiveness of the proposed adaptation mechanism, suggesting its successful application in delay systems [11]. An another article showing the usefulness of integrated fuzzy-PI/PID control has been authored by Demirtas and Papanikolopoulos [12]. In this, AC voltage controller capable of operating at different power factors presents a power factor correction (PFC) scheme using various controllers (PI, fuzzy logic PI, and fractional order PI).

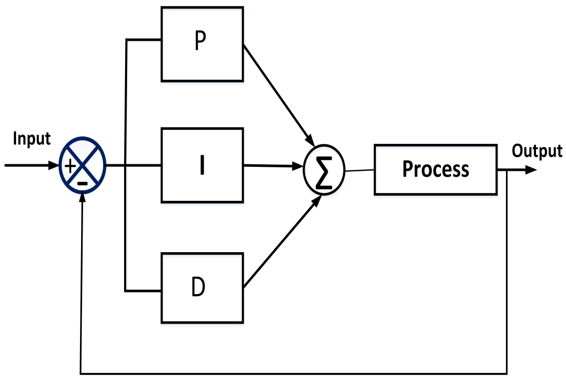


Figure 1. PID control system.

A single-phase boost converter is modeled in MATLAB/Simulink, and a filter is designed to minimize THD. The proposed model demonstrate the combination of fuzzy and PI controllers achieves the best power factor control. Tzafestas and Papanikopoulos [13] were among the first who introduced concept of Fuzzy-tuned PID controller design.

They suggested enhancing the performance of a closed-loop system by making adjustments to PID parameters. This was accomplished through a fuzzy matrix, encapsulating the operator's experiential insights within a concise rule base. In [14], [15] researchers introduced an auto-tuning algorithm for PID controller using Fuzzy logic. This algorithm aimed to dynamically adjust PID parameters in real-time, utilizing the generated error signal from the closed-loop system as input. An observer and error based adaptive proportional-integral-derivative (PID) controller has been introduced for type-2 fuzzy based system [16].

Numerous other scholars have also adopted a similar type of approach, introducing error to implement expert insights within the PID tuning process. The fuzzy tuned PID controller has some advantages over other tuning methods. Fuzzy logic-based tuning methods provide an effective means of adjusting the gains of a PID controller while minimizing overshoot, settling time, and steady-state error, particularly in nonlinear and complex systems. Contrary to other tuning methods, the fuzzy logic approach does not need an exact mathematical model of the system and can handle non-literariness and uncertainties in the process. The paper introduces a novel approach to controller tuning by combining both fuzzy logic and computational techniques to optimize the PID controller parameters. Fuzzy logic for rule-based decision-making, and interpolation techniques are combined in this work. This represents a unique approach, which has not been encountered in research arena.

A PID controller is a type of feedback control system commonly used in engineering and industrial processes (Figure 1). It continuously measures the difference between a desired set-point and the current value of a controlled variable, and adjusts an output signal to bring the two values closer together. The first term of PID provides an output proportional to the error signal, the integral term sums up the past errors to correct for any steady-state errors, and the derivative term predicts the future error based on the current rate of change. By merging all three parameters, a PID controller can achieve stable and accurate control of a wide range of systems, from simple temperature control to complex manufacturing processes.

In recent years, various tuning methods based upon fuzzy logic have been proposed for optimizing the performance of fuzzy logic controllers. Traditional approaches, such as heuristic tuning and optimization algorithms, often rely on iterative procedures and expert knowledge to define the fuzzy ranges. These methods, while effective, can be time-consuming and may not generalize well to different problem domains. In contrast, the proposed method leverages interpolation to set the fuzzy ranges, providing a unique and efficient alternative to conventional tuning techniques. This approach simplifies the tuning process by reducing the dependency on expert intervention. Moreover, it ensures controller parameters remain within specified bounds, a crucial consideration for safety and practicality in real-world applications. A third-order reactor plant has been taken into consideration as the system. Aim of this work is to maintain the concentration of effluent in each at a certain desired level. Simulation has been done using MATLAB software to get the desired response of the system subjected to step input. The results were observed and compared with few existing relevant literature.

1.1. Tuning of PID controller

PID controller tuning refers to the process of adjusting the parameters of the controller (proportional gain, integral time constant, and derivative time constant) to achieve the desired performance of the control system. The process of tuning involves adjusting the parameters based on the response of the system to different inputs, and is done through many methods.

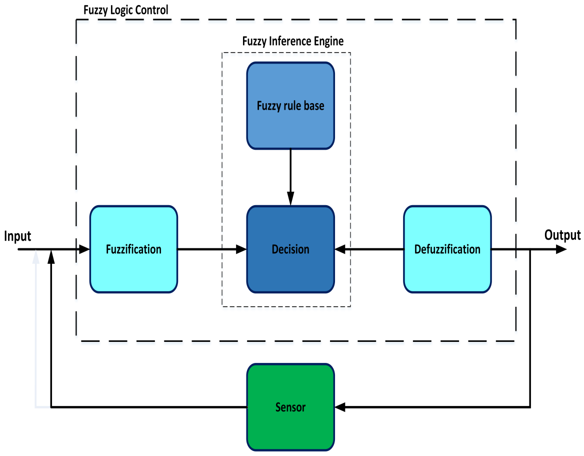


Figure 2. General Structure of Fuzzy Logic Control System

The importance of tuning a PID controller is rooted in its crucial role in ensuring the effective and efficient functioning of a control system. If the controller is not tuned correctly, the system may be unstable or oscillate, leading to inefficient operation or even damage to the system. On the other hand, a well-tuned PID controller can help maintain stable control of the process variable, reduce overshoot, improve settling time, and improve the overall performance of the system.

1.2. Fuzzy-tuned PID controller

Fuzzy logic is mathematical tool to deal with uncertainty in the system. In traditional binary logic, propositions are either true or false, but in fuzzy logic, propositions can be partially true or partially false, and the degree of truth or falsity is expressed using a range of values between 0 and 1. Primary benefit of fuzzy logic is its knowledge, that is efficient to handle imperfect and ambiguous data. Fuzzy logic is appropriate for modeling complex systems that are difficult to describe using traditional mathematical models. It allows for the use of linguistic variables, which can be more intuitive and easier to understand than traditional mathematical models. A typical Fuzzy logic control structure is depicted in Figure 2.

It takes crisp value as inputs variables. After fuzzification, processing with Fuzzy Inference Engine (FIE) and defuzzification, again desired crisp output is obtained. Fuzzy knowledge base together with decision form FIE in the control structure. A fuzzy tuned PID controller is a type of proportional-integral-derivative (PID) controller that uses fuzzy logic to tune its parameters. PID controllers are widely used in control systems to maintain a desired set-point by adjusting the output as per the difference between the set-point and the measured process variable. However, the performance of a PID controller is highly dependent on its tuning parameters, which can be difficult to determine for complex systems. Fuzzy tuned PID controllers use fuzzy logic to determine the optimal tuning parameters for the PID controller based on the current state of the system. This approach can be more effective than traditional PID tuning methods because it takes into account the complexity and uncertainty of the system being controlled. Additionally, fuzzy tuned PID controllers can adapt to changing conditions in the system, making them more robust and effective in real-world applications.

2. System description

A chemical process control system typically involves monitoring and adjusting the variables in a chemical reaction to optimize the output. In such a control industry it is required commonly to maintain the concentration of solute in a solvent. In the proposed work, the n-numbers of cascaded tanks are arranged in series, with the first tank receiving the solvent and the solute as shown in Figure 3. The output of the first tank is fed into the second tank, where further mixing occurs. The output of second tank is then fed into the third tank, where further mixing occurs. This process continues up to nth tank of the system where final mixing occurs. The concentration of solute in the solvent in final tank is measured and the signal is sent to controller, which adjusts the flow rate of the solute feed to the fist tank in order to maintain the desired concentration.

2.1. Modeling of the system

In order to obtain simple mathematical model of the aforementioned system, volume-flow rate and corresponding volumes are assumed to be constant. Writing mass-balance equation for first two tank.

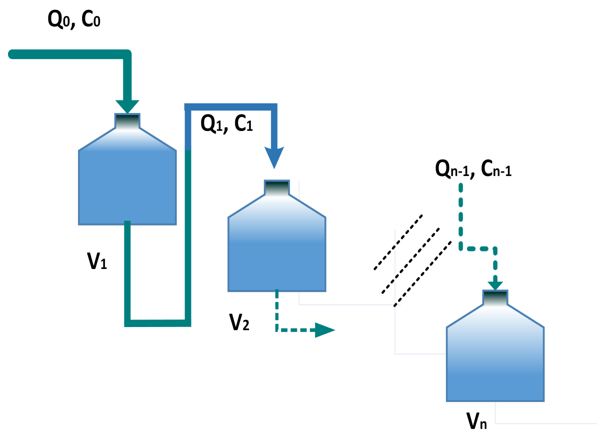


Figure 3. Cascaded 'n' number of tanks.

$$T_1 \frac{dC_1}{dt} = C_0 - C_1, \quad (1)$$

$$T_2 \frac{dC_2}{dt} = C_1 - C_2, \quad (2)$$

where, $T_1 = V_1/q0$ and $T_2 = V_2/q0$. In the above equation V, C and $q0$ represents volume, concentration and inlet flow rate of the both the tanks in proper unit with subscript number denoting the tank number. Transforming the above equations in Laplace domain yields.

$$\frac{C_1}{C_0} = \frac{1}{T_1 s + 1}, \quad (3)$$

$$\frac{C_2}{C_1} = \frac{1}{T_2 s + 1}. \quad (4)$$

The effect of C_0 on C_2 can be computed as:

$$\frac{C_2}{C_0} = \frac{1}{T_1 s + 1} \times \frac{1}{T_2 s + 1}. \quad (5)$$

For 'n' number of tanks in series, the generalized equation can be expressed as;

$$\frac{C_n}{C_0} = \frac{1}{(T_1 s + 1)(T_2 s + 1)........(T_n s + 1)}. \quad (6)$$

Order of the system described by the equation (6) will vary with the value of 'n' or number of tanks. for the proposed work a 3-tank process control system has been considered, where, values of T1, T2 and T3 is assumed to be 1,3 and 5 respectively. Transfer function of the aforementioned system can be written as:

$$G(s) = \frac{1}{(S+1)} \times \frac{1}{(S+3)} \times \frac{1}{(S+5)}. \quad (7)$$

Subsequently, rewritten as:

$$G(s) = \frac{1}{(S+1)(0.33S+1)(0.2S+1)}. \quad (8)$$

2.2. Design of fuzzy tuned PID controller

The solute concentration in the solvent is measured continuously and the signal is sent back through feedback to a fuzzy PID (Proportional-Integral-Derivative) controller. The fuzzy PID controller uses a set of rules and linguistic variables to adjust the flow rate of the solute feed to the first tank, in order to maintain the desired solute concentration in the solvent. The controller takes into account factors the current concentration error the rate of change of the error. The proposed structure of Fuzzy-PID control has been shown in Figure 4.

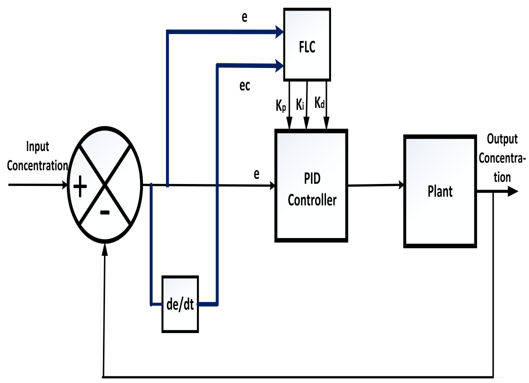


Figure 4. Fuzzy-PID controller for a chemical mixing plant

The design process involves tuning of PID controller parameters with the help of Fuzzy logic controller, which takes 'error(e)' and 'rate of change of error(ec)' as inputs and provide Kp, Ki and Kd as output. Hence, there are total of five linguistic variables. For each of these variables total of seven fuzzy values (NL,NA,NT,ZE,PT,PA,PL) have been chosen. The range of the 'e' and 'ec' are between -3 and 3, whereas, by formulating a kind of interpolation, fuzzy values for Kp,Ki and Kd are kept between 0 and 1. Aim of performing interpolation is to keep the values of the variable within some range. In the following equations, interpolation has been applied to keep the value of parameters (Kp, Ki and Kd) between 0 to 1. As the result, parameters are scaled to a common range, enabling a consistent, normalized and controlled analysis.

The determination of these ranges involves the following two steps:

- **Identification of Extreme Values:** The maximum and minimum values of all the three parameters of controller are identified.
- **Normalization Process** Once the minimum and maximum values are identified, the values of controller parameter are normalized to the range [0, 1] using the following equations:

$$K_p = \frac{K_{p,0} - K_{p,\min}}{K_{p,\max} - K_{p,\min}} \tag{9}$$

$$K_i = \frac{K_{i,0} - K_{i,\min}}{K_{i,\max} - K_{i,\min}} \tag{10}$$

$$K_d = \frac{K_{d,0} - K_{d,\min}}{K_{d,\max} - K_{d,\min}} \tag{11}$$

$K_{p,0}$, $K_{i,0}$ and $K_{d,0}$ are initially estimated values of K_p, K_i and K_d respectively. Fuzzy rule base for the three PID parameters are shown in Table 1, 2 and 3.

Table 1. Rule base for proportional gain, K_p

e/ec	NL	NA	NT	ZE	PT	PA	PL
NL	PL	PL	PA	PA	PT	ZE	ZE
NA	PL	PL	PA	PT	PT	NT	NT
NT	PA	PA	PA	PT	ZE	NT	NT
ZE	PA	PA	PT	ZE	NT	NA	NA
PT	PT	PT	ZE	NT	NT	NA	NA
PA	PT	ZE	NT	NA	NA	NL	NL
PL	PT	ZE	NA	NA	NA	NL	NL

Table 2. Rule base for proportional gain, K_i

e/ec	NL	NA	NT	ZE	PT	PA	PL
NL	NL	NL	NA	NA	NT	ZE	ZE
NA	NL	NL	NA	NT	NT	ZE	ZE
NT	NL	NA	NT	NT	ZE	PT	PT
ZE	NA	NA	NT	ZE	PT	PA	PA
PT	NA	NT	ZE	PT	PT	PA	PL
PA	ZE	ZE	PT	PT	PA	PL	PL
PL	ZE	ZE	PT	PA	PA	PL	PL

Table 3. Rule base for proportional gain, K_d

e/ec	NL	NA	NT	ZE	PT	PA	PL
NL	PT	NT	NL	NL	NL	NA	PT
NA	PT	NT	NL	NA	NA	NT	ZE
NT	ZE	NT	NA	NA	NT	NT	ZE
ZE	ZE	NT	NT	NT	NT	NT	ZE
PT	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PA	PL	NT	PT	PT	PT	PT	PL
PL	PL	PA	PA	PA	PT	PT	PL

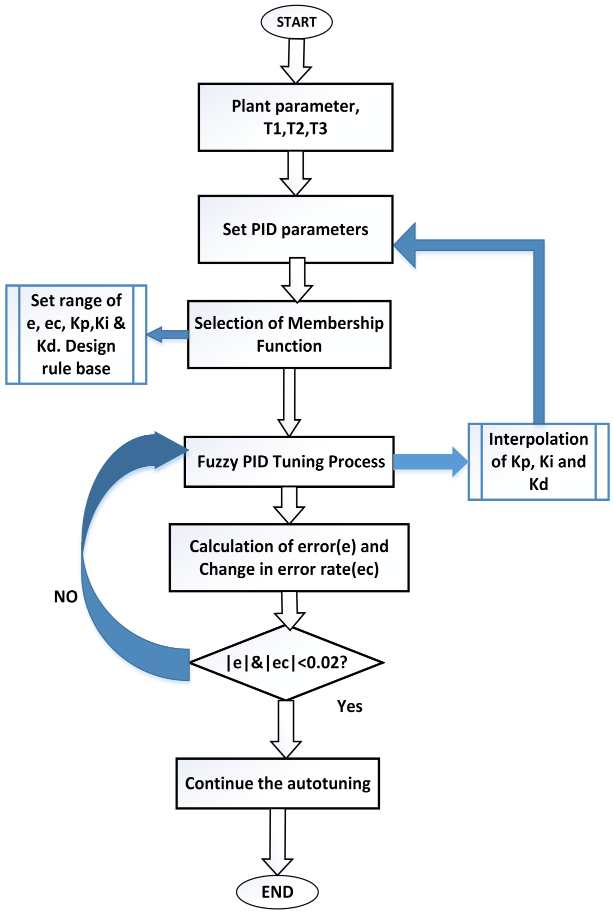
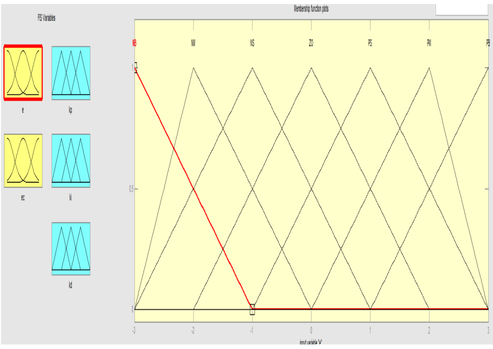


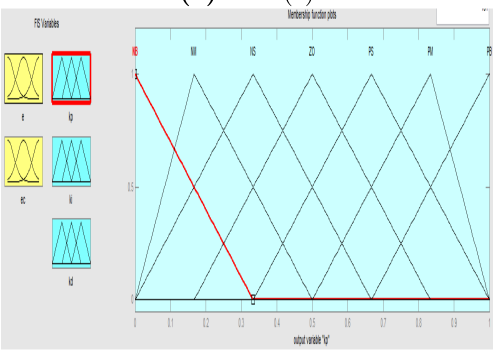
Figure 5. Flow chart of the control action.

2.3. FIS computational model and control action

Entire scheme of control action has been shown in the form of flow chart in the Figure 5. A fuzzy inference engine (FIE) employs fuzzy logic to approximate human reasoning/experience. Two input "error(e)" and "rate of change of error(ec))" have been taken as input variables as well as K_p, K_i and K_d as output. Triangular membership function has been chosen for both input and output variables. For the illustration purpose range of the membership function for 'e' and 'K_p' have been shown in the Figure 6.



(a) error(e)

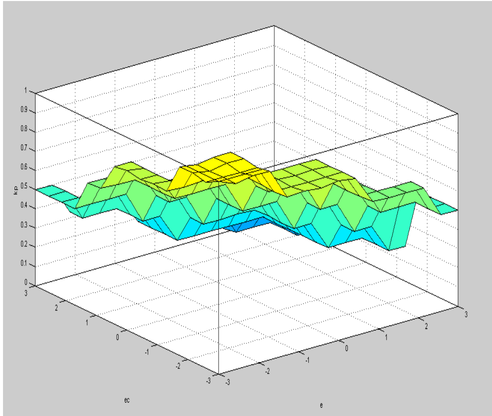


(b) K_p

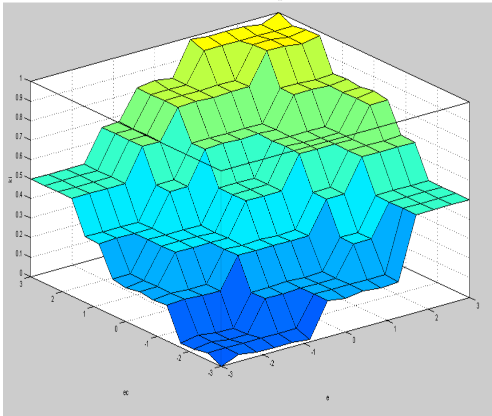
Figure 6. Membership function plots with its range for (a)error(e) and (b) proportionality constant (K_p)

Fuzzy logic uses linguistic variables, which are variable that take on values in a fuzzy set. On the basis of these variables linguistic rules (rule base) are made that plays a crucial role in the interpretation of fuzzy logic systems by defining the meaning of linguistic variables and interpreting the output in a way that is understandable to humans.

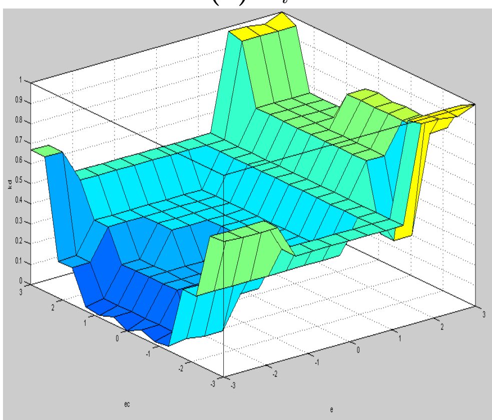
A number of such rules are made to provide the direction to controller for appropriate action. With seven assigned membership values to each variable, a total of 49 rules base have been proposed to completely describes the control action. These rules for PID coefficients (K_p, K_i and K_d) are summarized in the form



(a) K_p



(b) K_i



(c) K_d

Figure 7. Surface view of (a) K_p (b)K_i and (c) K_d

of three tables. The variations of these with respect to inputs (e and ec) are shown as the form of surface view in Figure 7.

Table 4. Comparison in terms of few performance indicators of different methods.

Method	T_r	T_s	$\%M_p$	$ITAE$
Salem	9	10	0.2	0.9405
Z-N	0.5	5	60	7.905
CA	0.8	1.6	2	50
Proposed	1.7	2	0.8	0.63

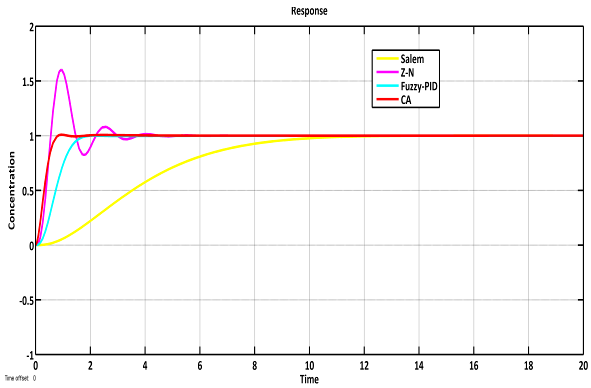


Figure 8. Response of system without any disturbance.

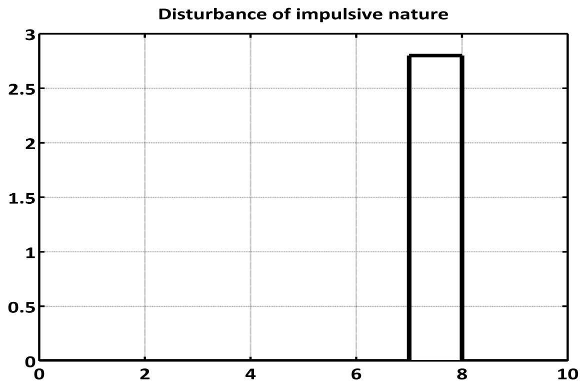


Figure 9. Disturbance to the system

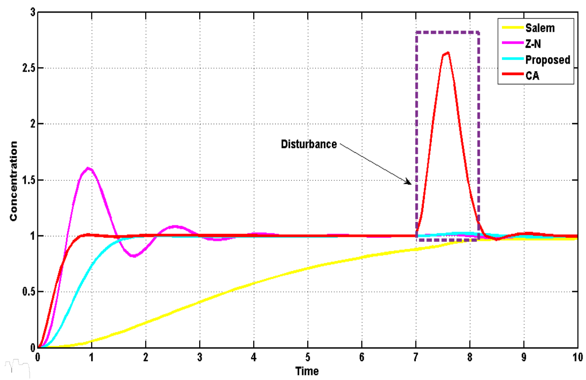


Figure 10. Response of system with some disturbance.

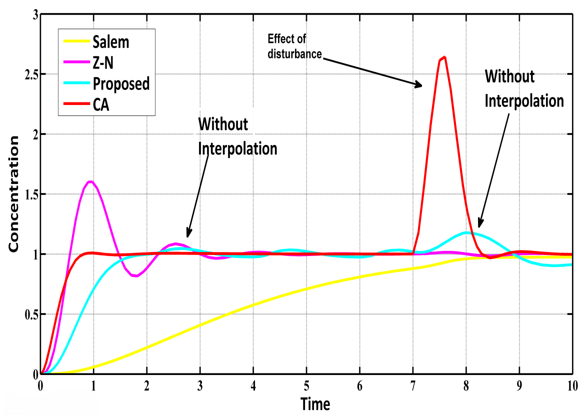


Figure 11. Response of system without using interpolation.

3. Results and discussions

The proposed Fuzzy-PID process control system is designed to maintain the concentration of solute in the tanks. With the step input(concentration of solute), proposed system is analyzed considering two cases, first assuming no disturbance on the system, secondly taking disturbances into the account at seventh second in given test time. The function of the system is to track this step input. Again, in chemical process control systems, disturbances can occur due to fluctuations in feed composition, temperature variations, or unexpected reactions. These disturbance are usually of impulsive nature . In the proposed work, disturbance that is taken for account, is of periodic impulsive nature, whose amplitude and time period have been considered of 2.8 unit and 10 seconds respectively, while pulse width is 10 percent of time period as shown in Fig. 9 . The fuzzy logic system continuously monitors the system's performance under such disturbances and adjusts the PID parameters accordingly. The interpolation mechanism allows for smooth adjustments, preventing abrupt changes that could destabilize the system. A total of four performance specification parameters have been considered analyzing the working of the system. A step input is applied to the proposed system and compared with Ziegler-Nicolas(Z-N) method [1], model-based design in [7] and computational approach (CA). response of the proposed system is shown in Figure 8. It can be observed that PID-tuning by Z-N method has highest overshoot and settle to steady state in approximately 5 second, when system is subjected to step input. Model based approach proposed by *Salem* [14] is quite sluggish as rise time of the response is 9 seconds. Computational approach(CA) [9] has somewhat satisfactory results in terms of rise time, settling time and maximum overshoot. However, CA has poor "disturbance rejection" capacity having *Integral time absolute error(ITAE)* nearly equal to 50, that result in spike(shown by the arrow) when subjected to disturbance of impulsive nature at 7th second as shown in Figure 10. Proposed system qualify in all the four performance specification parameter and shows satisfactory performance even at the onset of sudden disturbance. It has fast response, low settling time, low overshoot and good disturbance rejection capacity. Values of performance parameters of different methods are tabulated in Table 4. It is also worth mentioning the importance of interpolation technique in settling the system response specially under the effect of disturbance which is occurring at the 7th second of operation. Without interpolation, disturbance try to hinder the tracking of desired value in the proposed method as shown in Fig. 11. Effect can also be seen at the 2.5 sec, when there is slight overshoot causing unsettling of system-response. Thus interpolation mechanism used in the self-tuning Fuzzy PID controller is achieving smooth the PID parameters. By interpolating between predefined range, the controller can fine-tune its responses to varying process conditions more effectively. Therefore, synergetic approach introduced in this work enhances the self-tuning Fuzzy PID controller by combining the strengths of fuzzy logic and traditional PID control. This combination provides a dual benefit: fuzzy logic handles the nonlinearity and uncertainty in the process, while the PID control ensures precise regulation. The Synergetic approach's particularly useful scenarios with high process variability, where it maintains control performance and robustness.

4. Conclusions

In this study, a interpolation-enhanced Fuzzy-PID controller has been designed to control the concentration of a solute in a process control system. The proposed synergistic approach has been applied to a chemical process control system consisting of three tanks, aimed at maintaining a constant effluent concentration, has proven to be successful. This method has demonstrated the ability to attain the desired performance in the closed-loop system by dynamically adjusting the controller parameters, K_p, K_i and K_d. Performance of Fuzzy-PID controller has been assessed for third order chemical process system. Aim of the controller function is to regulate the level of concentration of solute in the solution in three tanks. A comprehensive set of simulation and case studies have been conducted to illustrate the versatility and robustness of the fuzzy PID controller across a range of chemical processes. It has been observed that proposed system seems is working satisfactorily even in the case of sudden disturbance and it tries to maintain the level of solute at pre-defined values in all the tanks. The simulation results indicate that the suggested approach outperforms the conventional PID controller when it comes to handling disturbances and accurately following set-points. The fuzzy PID controller display improved performance in the presence of uncertainties and disturbances. The result was compared with few existing literature, proposed system seems to be working better among all. The Synergetic methods developed in this work have potential applications in various industrial domains where precise and adaptable process control is critical.

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