Engineering and Technology Journal 41 (09) (2023) 1139- 1151

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Servo and Regulatory Response of an Industrial Fluid Catalytic Cracking (FCC) Unit under Fuzzy Logic Supervisory Control

Princewill N. Josiah[a*], **Ipeghan J. Otaraku**[b], **Benson O. Evbuomwan**[b]

[a] World Bank Africa Centre of Excellence, Centre for Oilfield Chemicals Research, University of Port Harcourt, Port-Harcourt, Nigeria.
[b] Chemical Engineering Dept.,University of Port Harcourt, Port Harcourt, Nigeria.
*Corresponding author Email: princewill.josiah@uniport.edu.ng

HIGHLIGHTS

- Derive control law for classical PID.
- Develop Fuzzy Logic rule-base and Fuzzy inference scheme.
- Superiority of the fuzzy-PID scheme over the PID scheme in tracking the optimal set point of riser temperature.
- The application of fuzzy-PID scheme to temperature control offers good promise of improved FCCU operations.

ARTICLE INFO

Handling editor: Qusay F. Alsalhy

Keywords:
PID
Supervisory Control
Fuzzy Logic
Catalytic Cracking
Servo Response

ABSTRACT

A self-tuning hierarchical controller in which a Fuzzy logic controller supervises the control actions of a conventional PID has been proposed, implemented and presented in this paper. The controller has been applied to a control study of Fluid Catalytic Cracking unit (FCCU) riser temperature, and regenerator temperature respectively. Comparison between the performance of the proposed Fuzzy-PID controller and the conventional PID was made in simulation studies of regulatory and servo performances of the two controller types. Six performance measures: Percent overshoot (OS), settling time (ST), integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE) and integral time square error (ITSE) were employed as the tools for performance comparison between the conventional PID and the Fuzzy-PID controller. For the tracking of riser temperature with a set point at 524℃, the performance indicators under PID control gave the following results overshoot (14.5%); settling time (40 seconds) Integral absolute error (8.246), integral square error (3.3); integral time absolute error(1762);integral time square error (43.77) while for the same indicators under Fuzzy-PID control the following values: overshoot (3.3%); settling time (40 seconds) ;Integral absolute error (8.811); integral square error (14.5); integral time absolute error(280),;integral time square error (31.11) .The results allude to the superiority of the fuzzy-PID scheme over the PID scheme in tracking the optimal set point of riser temperature. More so, for tracking the regenerator set point temperature of 746°C, comparative study of step response under the two schemes gave the following results in six performance indicators: overshoot (PID (12.6%) / Fuzzy-PID (6%)); settling time (PID (80 seconds) / Fuzzy-PID (20seconds)); Integral absolute error (PID (14.29) / Fuzzy-PID (8.63)); integral square error (PID(6.713). Fuzzy-PID (4.506)); integral time absolute error(PID(2858)/Fuzzy-PID(305.9)), integral time square error (PID(77.55)/Fuzzy-PID(33.05)) . Moreover, the fuzzy-PID controller also showed superior performance over the conventional PID controller in terms disturbance rejection (regulatory response) of both riser and regenerator temperature. The results from this study suggest that the application of fuzzy-PID scheme to temperature control offers good promise of improved fluid catalytic cracking unit (FCCU) operations.

1. Introduction

The need for efficient material and energy integration, meeting rigid product quality specifications, operating within prescribed environmental safety, personnel and equipment safety limits and standards. Rang and Du [1] has heightened complexities in the control of chemical processes, necessitating the search for more robust control algorithms and schemes. However, most industrial processes are controlled with classical linear proportional-Integral (PI)or Proportional-Integral-Derivative (PID) techniques although such processes exhibit highly nonlinear dynamics. The main objective of a control system is to control the output variable in order to achieve a prescribed response. This objective can be met in either of two ways: to track the response to follow a set- point or its trajectory or to force the output back to the set- point value whenever there is deviation. Such control systems fall under classifications that include discrete versus continuous time control, single-input-

http://doi.org/10.30684/etj.2023.139485.1432
Received 03 April 2023; Accepted 12 May 2023; Available online 13 June 2023
2412-0758/University of Technology-Iraq, Baghdad, Iraq

single-output (SISO) control, multiple-input-multiple-output (MIMO) control which can operate under open -loop or closed-loop. The PID can function in both SISO and MIMO control and its dominance could be attributed to its advantage of having few parameters to tune according to some prescribed guidelines and the ease in implementation. However, the controller parameters, Proportional gain (Kp), Integral time (Ti) and Derivative time (Td) are highly interactive, hence the selection of optimum values of the parameters leads to solving a multi-objective optimization problem. Moreover, the application of such linear technique to control a nonlinear process is limited to the steady state conditions around which the process model is linearized. The implication is that good controller performance for other process operating regimes would not be guaranteed. To circumvent this, a trade-off between performance and robustness must be made, leading to sub-optimal designs and poor controller performance.

A plausible remedy for PID limitations is the application of supervisory control, a branch of advanced control in which a top-level controller (supervisor) oversees the actions of a lower level (regulatory) controller in a two-layer framework. In such scheme, the supervisor functions based on artificial intelligence or some other technologies and automatically updates the controller gains of the regulatory controller as operating goals change in tandem with market demand for products. Besides accommodating the incomplete process knowledge and the associated modeling errors, the fuzzy-PID scheme would provide seamless transition from one operating regime to another. In line with searching for remedies to PID drawbacks, Dey and Ayyagan [2] presented a fuzzy-PID controller design that was based on fuzzy pole placement. The essence was to eliminate or reduce parameter uncertainties in controller tuning. The controller coefficients were obtained by solving a set of fuzzy linear equations and the capacity of the controller for good tracking and disturbance rejection was demonstrated through several simulations. However, the structure of the controller is similar to that of the classical PID that does not offer self-tuning capabilities. In El-Samahy and Shamseldin [3], a supervisory control scheme in which a fuzzy logic controller directs the affairs of a classical PID controller was demonstrated. The purpose of the controller was to force the rotor of a direct current (DC) brush to follow a desired path and it was based on fuzzy logic framework as in the case of Dey and Ayyagan [2]. The authors demonstrated the superiority of the controller over conventional PID through simulation examples Results showed that the supervisory scheme has high capacity for reference tracking and disturbance rejection, although oscillatory behaviour was also observed and reported. In order to effect improvement in the control performance of a steam turbine governor, Dettori et al. [4] designed and reported a two-layer controller consisting of a classical PID and a fuzzy logic controller that supervises the PID gains. The rule –base, membership functions and fuzzy classifications were similar to those of Dey and Ayyagan [2]. The authors demonstrated the complementary role of the fuzzy supervisor in remedying the deficiencies of the classical PID controller through case studies in simulation mode. A method for obtaining optimum parameters of fuzzy-PID controllers was proposed by Kudinov [5]. The method which eliminates the ad-hoc selection of controller gains employs simplex search algorithm within the framework of fuzzy logic. However, the contribution did not address automatic tuning of PID gains under varying process dynamics and operating conditions. Similarly, a supervisory control scheme with the framework of an optimum seeking procedure was reported in Vrecko [6]. Excess oxygen ratio is a major variable in the operation of fuel cells. In order to control excess oxygen ratio, Fan et al. [7] designed a fuzzy logic controller using a coarse fuzzy classification with only three linguistic variables using triangular membership function. The consequence of coarse fuzzy classification is sluggish response of the fuzzy controller due to extended degrees of belongingness of the linguistic variables in the coarse classification. Rudriguez-Castellanos et al. [8] alludes to the assertion that PID controller response degrades in non-linear systems, especially while trying to cope with changes in operating regimes. To improve the response behaviour of PID controller, a fuzzy-PID scheme consisting of a fuzzy logic proportional derivative (FLC-PD) and a fuzzy logic proportional Integral (FLC-PI) was proposed. Significant improvement in terms of Integral average error (IAE) and Integral time average error (ITAE) were reported in the work. However, like other direct fuzzy controllers, the controller gains are static. In Kumar and Kumar [9], the suitability of fractional order fuzzy-PID controller in the control of non-linear plants was tested. A major weakness in the synthesis of the controller is the arbitrary choice of input scaling. In a related paper, Ahmad et al. [10] presented a Fuzzy-PID controller to improve the dynamic behaviour of a workstation liquid controller during varying operating conditions. It was framed on coarse fuzzy classification as with Fan et al. [7] and did not provide for controller parameter updating. However, steady state characteristics that showed superiority over classical PID were reported. In Demidova et al. [11] a control scheme in which a genetic algorithm controller was used to supervise a fuzzy logic controller was demonstrated in simulation mode. The objective of the controller was to track space objects with high accuracy. The introduction of automatic tuning of membership functions (MF) in a Mandami fuzzy framework is innovative. However, finding a suitable fitness function in the genetic code is a major challenge with the method. A hybrid controller to enhance humidity and temperature control in heating, ventilation and air conditioning systems (HVAC) was presented in Ganchev et al. [12]. The controller design was based on a combination of classical decoupling and neuro-fuzzy framework and has the incorporation of decoupling equations into Sugeno fuzzy function as its strength. Jalali et al. [13] controlled the load frequency in interconnected multi-media power system using a two-layer control scheme. The rule –base for the fuzzy logic component of the controller was formulated from zones that were obtained from open loop simulation of the process. Moreover, PID gains were updated adaptively even during transitions from one operating regime to another. Application of supervisory control in the field of medical sciences was demonstrated in Manap et al. [14] A fuzzy logic –tuned PID controller was implemented to control carbon-dioxide removal rate during extra-corporal blood purification process. The work is structurally similar to that of Domidiva et al. [11] in which genetic algorithm- based controller was employed in supervisory capacity. A major challenge with the PID controller is the static controller gains that must be tuned to accommodate changes operating policy based on operator tuition and process knowledge. In this paper, we address this challenge by presenting a three-layer control system consisting of the fluid catalytic cracking (FCC) plant, PID controllers and fuzzy logic controllers. The PID sits on the FCC plant and performs a lower level regulatory tasks while the fuzzy logic controller supervises the PID controllers by automatically tuning the gains under various scenarios and control objectives. The novelty of the Fuzzy-PID control supervisory control scheme is that the controller gains are iteratively modified based on the desired response characteristics without human operator intervention. The bounds for the membership functions and the universe of discuss for the controller gains of the fuzzy logic supervisor were selected based on process behaviour under PID control in simulation mode. Moreover, the scheme functions effectively under disturbance attenuation and tracking, a rare feature that is not offered by classical PID.

2. Research Method

The method that was adopted in the realization of the study objective is reported here in three sub-sections. The structure of the FCCU control problem for which a hybrid method is proposed is presented in section 2.1, while the structure of classical PID vis-a-vis the challenges that are inherent in the FCCU control problem is presented in section 2.2. In section 2.3, a description of the procedure for the realization of the proposed hybrid Fuzzy-PID controller with dynamic update of controller gains is presented.

2.1 Nature of Fluid Catalytic Cracking Unit (FCCU) Control Problem

The structure of the control problem that is addressed in this paper is as follows:

Two variables namely the temperature in the riser (T_{rx}) and temperature in the dense bed of the regenerator (T_{rg}) are to be controlled by manipulating the gas oil feed rate, regenerator air flow rate or the regenerated catalyst flow rate. In an over-simplified structure, however, the interaction between variables is usually ignored, giving rise to control loops that are conceived to function independently.

2.2 Challenges with Classical FCCU PID Control

In a classical PID, the manipulated variable is adjusted by the controller according to Equation 1 below.

$$u(t) = k_{p^e} + K_I \int edt + K_D \frac{de}{dt} \tag{1}$$

where:

$$K_I = \frac{K_P}{\tau_I} \tag{2}$$

$$K_D = K_P \tau_D \tag{3}$$

In relation to the controlled and manipulated variables, writing equation 1 for each pair of variables yields Equation 4 to 6.

$$F_{gr}(t) = K_p(T_{rxs} - T_{rx}) + K_I \int (T_{rxs} - T_{rx})dt + K_D \frac{d(T_{rxs} - T_{rx})}{dt} \tag{4}$$

$$F_a(t) = K_p(O_{ds} - O_d) + K_I \int (O_{ds} - O_d)dt + K_D \frac{d(O_{ds} - O_d)}{dt} \tag{5}$$

$$F_{rc}(t) = K_p(T_{rgs} - T_{rg}) + K_I \int (T_{rgs} - T_{rg})dt + K_D \frac{d(T_{rgs} - T_{rg})}{dt} \tag{6}$$

Two major challenges with the classical multi-loop control approach is that the design procedure totally ignores the strong interaction between variables. More so, as the effects of variable interaction increasingly set in over time, the static controller gains become unreliable with consequent poor performance. While the first challenge can be overcome through the design of static or dynamic decouplers or the application of effective open-loop transfer functions during the PID design, the second one is solved in this paper. The quality of the PID controller which the fuzzy logic controller supervises, is a major factor in the successful implementation of the scheme in this paper. In this regard, the following assumptions were made:

1) Control structure for input/output variables pairing has been well selected.
2) Loop interaction has been addressed through some means such as decouplers or effective open-loop transfer function computation.
3) Selected manipulated variables do not produce inverse response
4) PID design meets minimum steady state response characteristics

2.3 Structure of Fuzzy – PID Controller

The Fuzzy –PID controller that is proposed in this paper is based on the concept of classical PID Controller. Since the classical PID controller has been designed at nominal operating conditions, it fails to provide the desired control performance over a wide range of operating conditions.

In this wise, fuzzy logic concept are combined with classical PID concepts to implement.

Controllers with self-tuning capabilities. Figure 1 shows the basic structure of the fuzzy-PID controller, the kind that is presented in this paper while Figure 2 shows the universe of discourse for the controller membership functions. In a conventional PID control loop, the controller parameters are static while in the fuzzy-PID scheme, changes (ΔKp, ΔKI, ΔKD) in each of the controller gains are calculated by the fuzzy logic controller from which new values of the gains are obtained using the update formulae given in Equation 7 ,8 and 9. This enhancement in essence ensures iterative update of controller gains in the PID structure in real time.

$$K_P(t) = k_p\, e^{*}\Delta k_p + k_p \tag{7}$$

$$K_I(t) = k_I + k_I \int edt^{*}\ \Delta k_I \tag{8}$$

$$K_D(t) = k_D + \frac{de(t)}{dt} * \Delta K_D \tag{9}$$

where: are the gains from the fuzzy logic controller component of the supervisory control scheme.

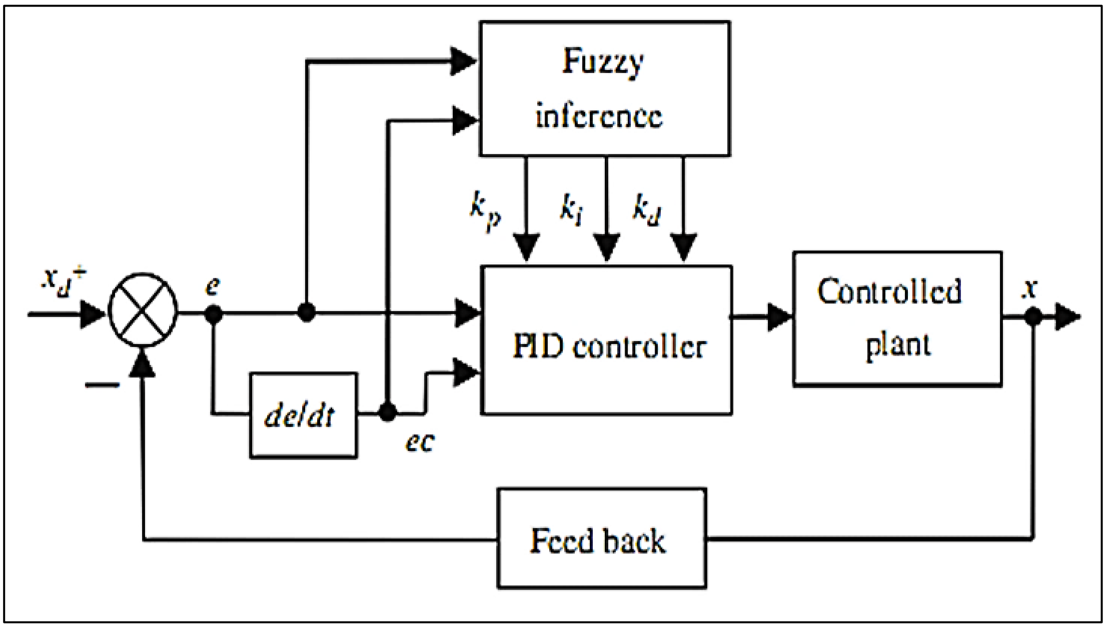

Figure 1: Fuzzy-PID controller Framework

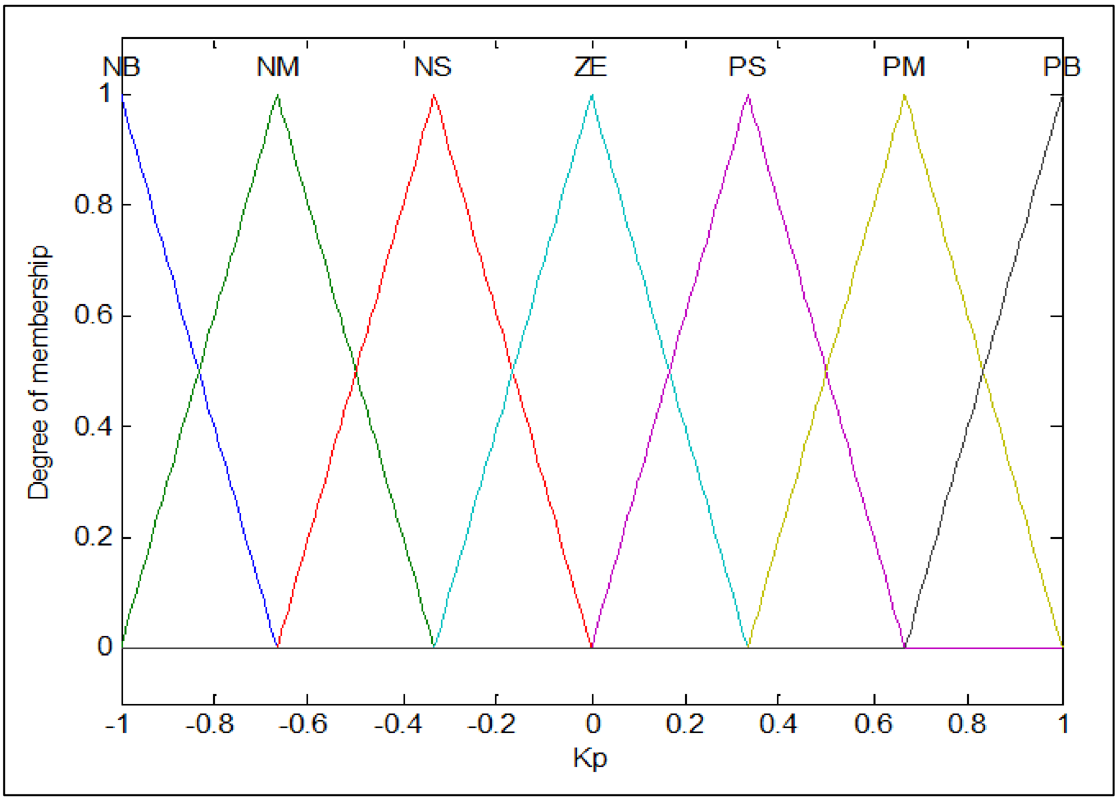

Figure 2: Membership Function for K_P, K_I and K_D

2.4 Implementation of Fuzzy-PID Controller for FCCU

This sub-section is devoted to the implementation of three fuzzy-PID controllers to control the riser temperature and regenerator temperature. In the light of the earlier assumption regarding the PID part of the fuzzy-PID scheme, the implementation of the fuzzy logic component follows a three-step procedure consisting of fuzzification, rule base and defuzzification, as outlined in Sharma [15].

2.4.1 Fuzzy Classification

Fuzzy classification or fuzzification is the conversion of crisp values to a set of fuzzy variables. Two fuzzy variables namely error and rate of change of error were used as input for the fuzzification process while the output consists of three variables namely, Δkp, ΔkI and ΔkD. In doing so, the crisp values covering the universes of discourse were grouped into clusters with the following linguistic variables: Negatively Big (NB), Negatively Small (NS), Zero (ZR), Positively Small (PS), and Positively Big (PB). The triangular membership function is used here for measuring the degree of belongingness of each fuzzy variable, as consistent with the work of Has and Rahmat [16], Vaishnav and Khan [17].

2.4.2 Rule-base and Inference Mechanism

The rule-base represents, in a structured way, the control policy of an experienced process operator and control engineer and it is obtained by first organizing the operating policy in a rule table (Table 1). The fuzzy rule-base, which was drawn from the rule-table, consists of a collection of fuzzy if–then rules such as: IF (antecedent) Then (consequent). A fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system under control.

2.4.3 Defuzzification

This last step converts the linguistic values of the output variables that were generated in the previous step, into crisp numerical values. A seven-level de-fuzzifier was used for the output fuzzy sets Δk_p, Δk_I and Δk_D. The outlined steps were followed and combined with classical PID concepts to implement supervisory controllers which were then interfaced with Simulink , (Refer to Figure 3, 4 and 5).

The rule-base represents, in a structured way, the control policy of an experienced process operator and control engineer and it is obtained by first organizing the operating policy in a rule table (Table 1). The fuzzy rule-base, which was drawn from the rule-table, consists of a collection of fuzzy if–then rules such as: IF (antecedent) Then (consequent). A fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system under control.

Table 1: Rule Table for Fuzzy Logic Component (Δk_p, Δk_I, Δk_D)

e/edot	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PS	Z	Z
	NB	NB	NM	NM	NS	Z	Z
	PS	NS	NB	NB	NB	NM	PS
NM	PB	PB	PM	PS	PS	Z	NS
	NB	PB	NM	NS	NS	Z	Z
	PS	NS	NB	NM	NM	NS	Z
NS	PM	PM	PM	PS	Z	NS	NS
	NB	NM	NS	NS	Z	PS	PS
	Z	NS	NM	NM	NS	NS	Z
Z	PM	PM	PS	Z	NS	NM	NM
	NM	NM	NS	Z	PS	PM	PM
	Z	NS	NS	NS	NS	NS	Z
PS	PS	PS	Z	NS	NS	NM	NM
	NM	NS	Z	PS	PS	PM	PB
	Z	Z	Z	Z	Z	Z	Z
PM	PS	Z	NS	NM	NM	NM	NB
	Z	Z	PS	PS	PM	PB	PB
	PB	PS	PS	PS	PS	PS	PB
PB	Z	Z	NM	NM	NM	NB	NB
	Z	Z	PS	PM	PM	PB	PB
	PB	PM	PM	PM	PS	PS	PB

2.5 Numerical Simulation

The steps that were outlined in the previous section were implemented in Simulink and combined with the basic structure of a conventional PID controller to achieve a self-tuning fuzzy-PID controller. Figure 3 shows a Simulink implementation of the proposed self-tuning controller while Figure 4 shows that of a conventional PID. For the purpose of simulation and performance comparison, a parallel combination of the two types of controllers shown in Figure 5 was also implemented in Simulink. The capacity of each of the controllers to accommodate transition from one operating point to another was then studied in simulation mode, using Figure 5 as a virtual process plant. Controller performance was evaluated at two step times: t=0 seconds and t=100 seconds respectively, using rise time overshoot and settling time as static performance measures. More so, four dynamic performance measures namely: Integral absolute error (IAE), Integral Square error (ISE), Integral time absolute error (ITAE) and integral time square error (ITSE) were used as dynamic performance indices for controller assessment. Step time t=0 represents a transition from one set point to another during start-up while the other represents a transition from one set point to another, 100 seconds from start-up. In another round of simulations, the disturbance rejection capacities of the controllers were tested by introducing unit step disturbances at the two-time frames as in the case of set point tracking.

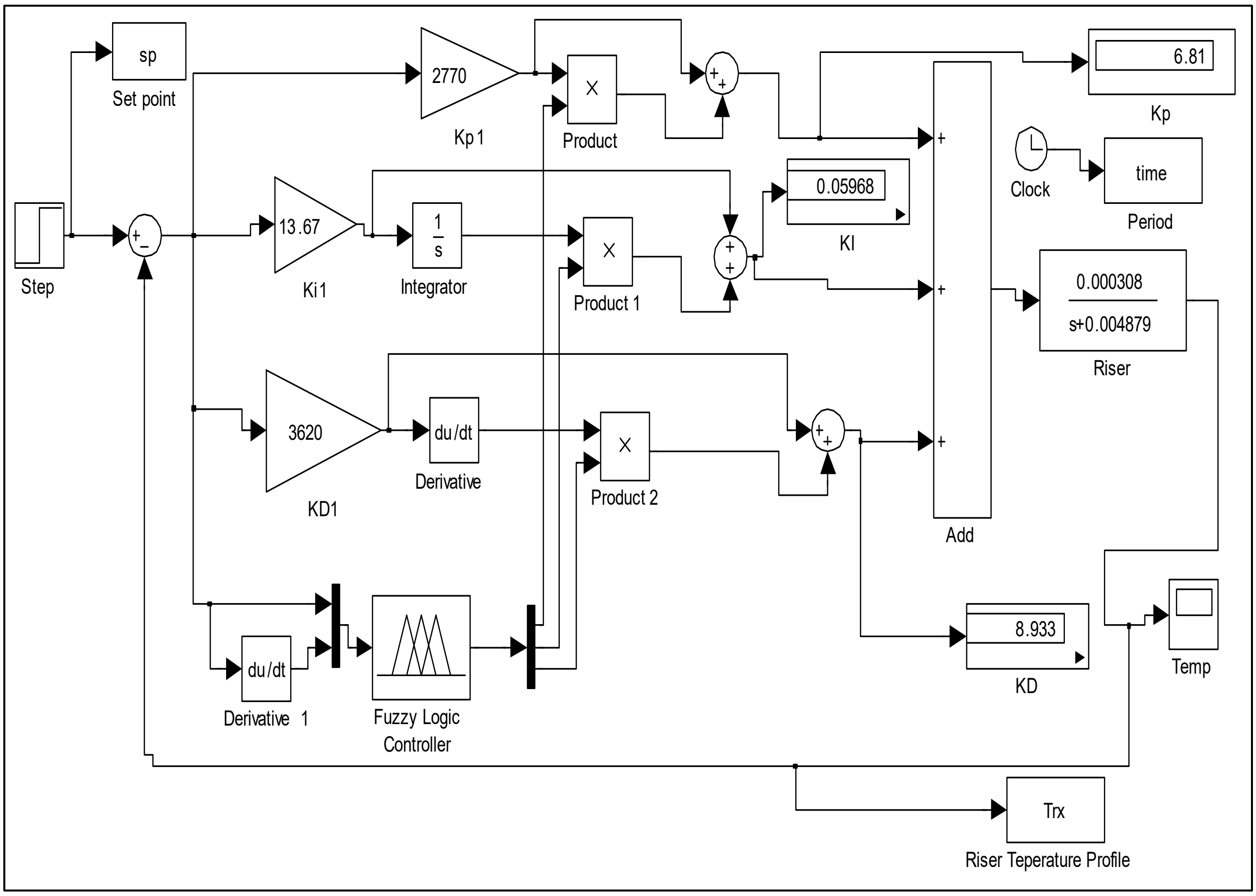

Figure 3: Simulink Implementation of Fuzzy-PID Controller

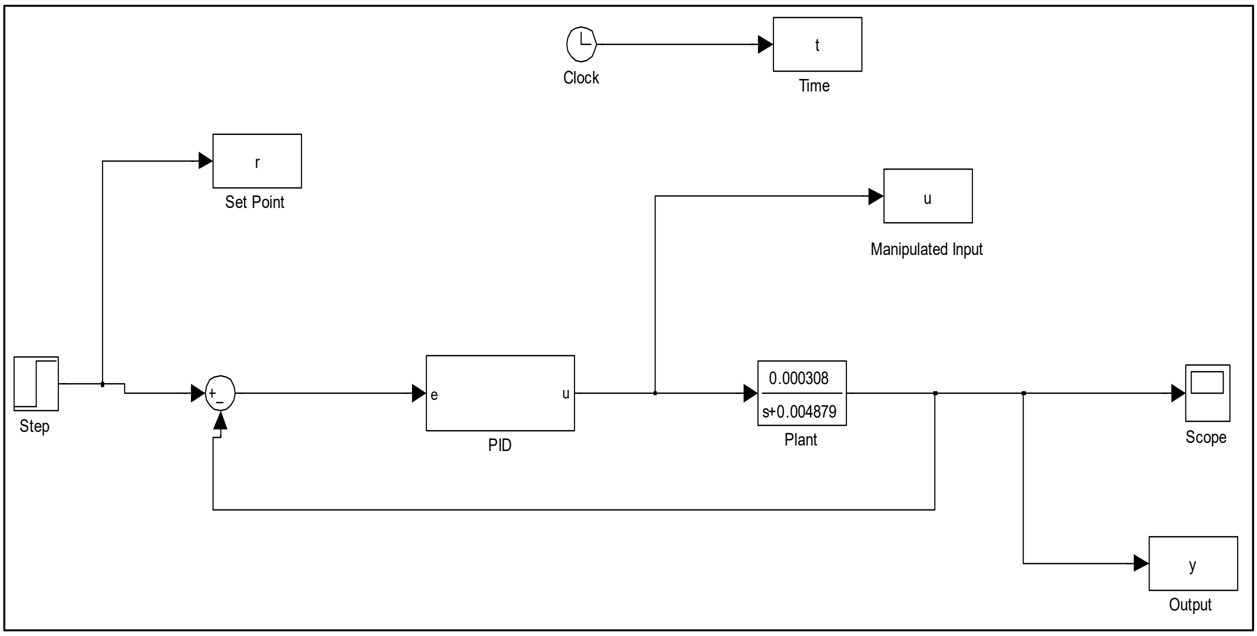

Figure 4: Simulink Implementation of PID Controller

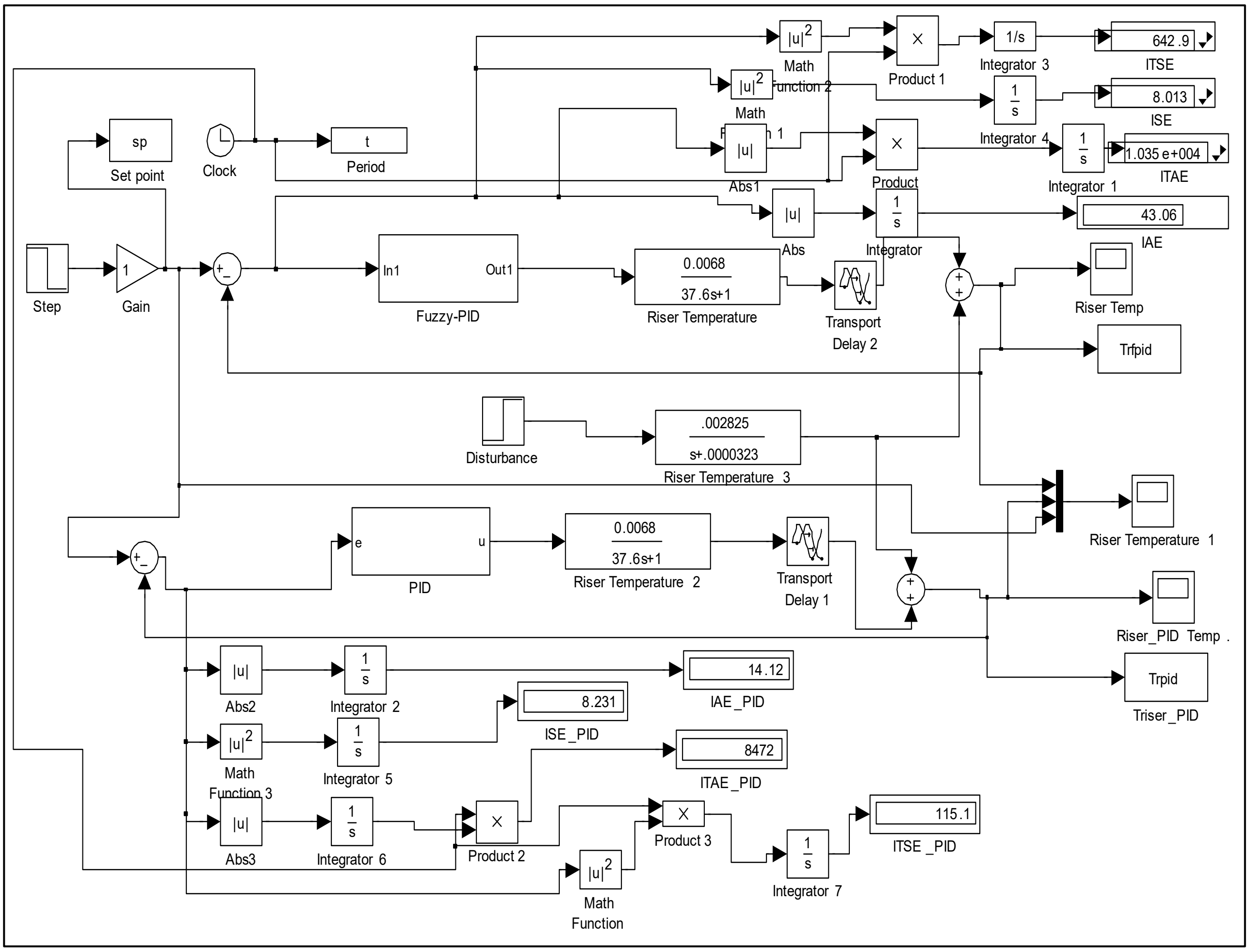

Figure 5: Implementation of ZN-PID and Fuzzy Self-Tuning PID Controllers

3. Results and Discussion

3.1 Riser Temperature Profiles

Temperature profiles for the riser under conventional PID control and the proposed Fuzzy-PID control are shown in Figures 6,7,8 and 9. Figure 6 shows riser temperature response to a unit step change in set- point from 524°C to 525°C at t=0. This represents a change in operating temperature during start-up of the unit. The profiles suggest a time- delay of about 4 seconds for temperature response with the conventional PID controller unable to attain a new steady state until after 20 seconds, exhibiting some oscillatory behaviour within the first-twenty seconds. However, the Fuzzy-PID control action on the other hand gives a desirable temperature response, seamlessly transiting from one point to another. On an insightful note, however, this study observed that riser temperature settled above 600°C, with a steady state error of more than 75°C, following the unit step change in temperature at start-up as shown in figure 6.. It is instructive to note that this situation should be avoided as a change in set point during start up would compromise the fidelity of the control schemes that were studied and perhaps any other scheme. Figure 7 and 8 show temperature responses for 20% change in set point at a step time of 100 seconds from start-up. This scenario depicts a change in operating policy after steady state has been reached after 100 seconds from start-up. Figure 7 is the outcome of simulation with 20% increase in set-point representing a change in set point temperature from 524ºC to 628.8°C while Figure 8 depicts that of a change of riser temperature set-point from 534°C to 419.2°C The figures form part of the nucleus of the narrative in this paper and lend voice to the discussion on the relationship between feed vapourization ,product yields and temperature during FCC operations as presented in Ahmed and Ateya [18], Baptatope et al. [19], Olafadehan et al. [20], Josiah et al. [21] In each case shown in the figures, the fuzzy-PID controller appears to be a better option than the conventional PID controller for FCC unit riser temperature control. A subtle but significant insight that was gained from Figures 6, 7 and 8 is that the controllers did not respond immediately to changes in temperature set point. Although set point changes were applied at t=0 and t=100 second respectively ,as shown in the figures,the control action occurred at t>0 and t>100 seconds respectively .The observed behaviour of the FCCU under the described circumstances can be explained based on the relationships between process gain, the process time constant, proportional gain of the controller and the error. Recall that, the proportional action of a controller is a product of proportional gain and the error. In the case of the classical PID, a constant proportional gain operates on a dynamically changing error. However, in the supervisory scheme, the proportional gain is updated in a rule-based fashion at the instance of the magnitude of the dynamically changing error. Similar oscillatory behaviour in the light of FCC riser temperature classical control was reported in Yendamuyi and Rao [22], Rang and Du [1], An interesting feature regarding the profiles stems from the point of application of step change in set point. As shown in the Figures, a step change at start-up (t=0) translates to more than proportionate overshoot, compared to when such step change is introduced at steady state. This simulated process behaviour suggests that the FCC unit is more difficult to control during start up than any other time afterwards. It could also be deduced from the observed profiles that; controller performance is more susceptible to deterioration when operating policy changes at start-up. The disturbance rejection capacity riser temperature profiles are shown in Figure 9, with the fuzzy-PID out-performing the conventional PID controller. Recall from theory that disturbance attenuation action forces the process variable to the desired set-point in the presence of factors that are external. As shown in Figure 9, the simulated FCC unit under PID control displayed riser temperature overshot and under shoot for at least 20 seconds before attaining steady state in the face of load disturbance. On attaining steady state, the PID control action was unable to drive temperature to the set point (the zero mark on the y-axis), leaving a constant steady state error from t>40 seconds to t=200 seconds. However, the fuzzy-PID controller seamlessly attenuated disturbance and maintained riser temperature at the set point. The fluid catalytic cracking unit operates under heat balance between the riser and regenerator to ensure process safety, personel safety and consistent product quality. Hence,insights gained from Figures 6,7,8 and 9 are important contributions to knowledge in achieving the goal of enhanced operations of the FCCU. Although the fields of applications a, the insights and the scenarios differ from this study, similar sentiments and results in favour of the fuzzy logic controller and its variants are alluded to in Dey and Ayyagan [2], El-Samahy ans Shamseldin [3],Vrecko [6], Ahmad et al. [10], Demidova et al.[11], Jalali et al.[13], Veleyudhaan [23] and Lotfi et al [24].

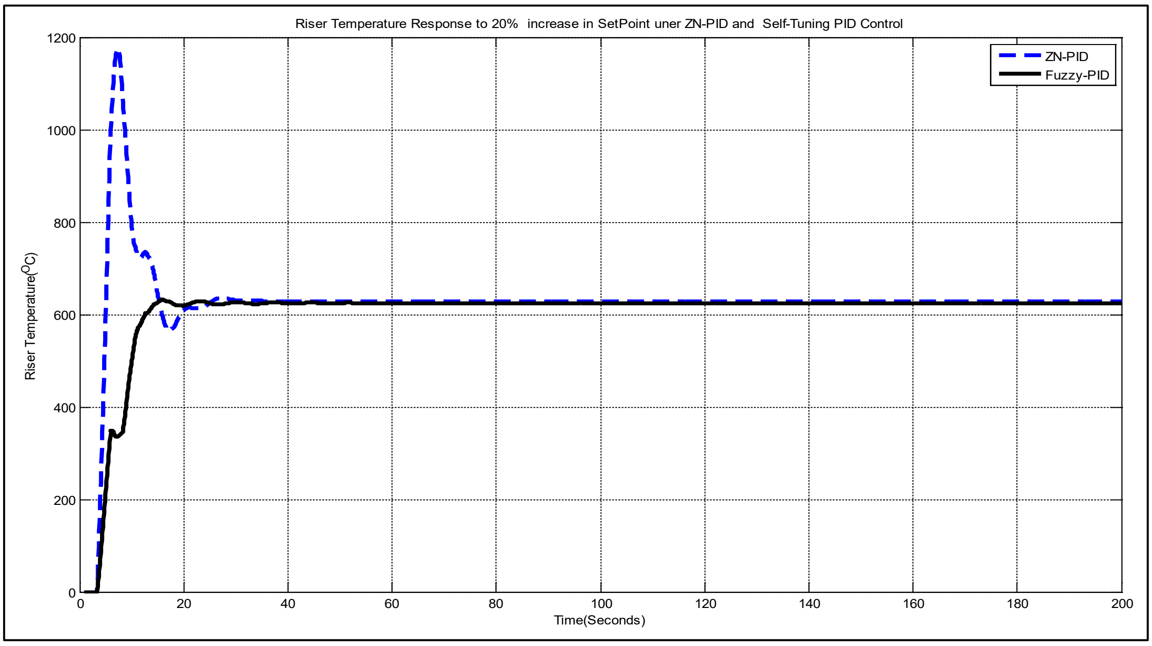

Figure 6: Riser Temperature Profiles under ZN-PID and Fuzzy-PID Control (Step change at t=100 s)

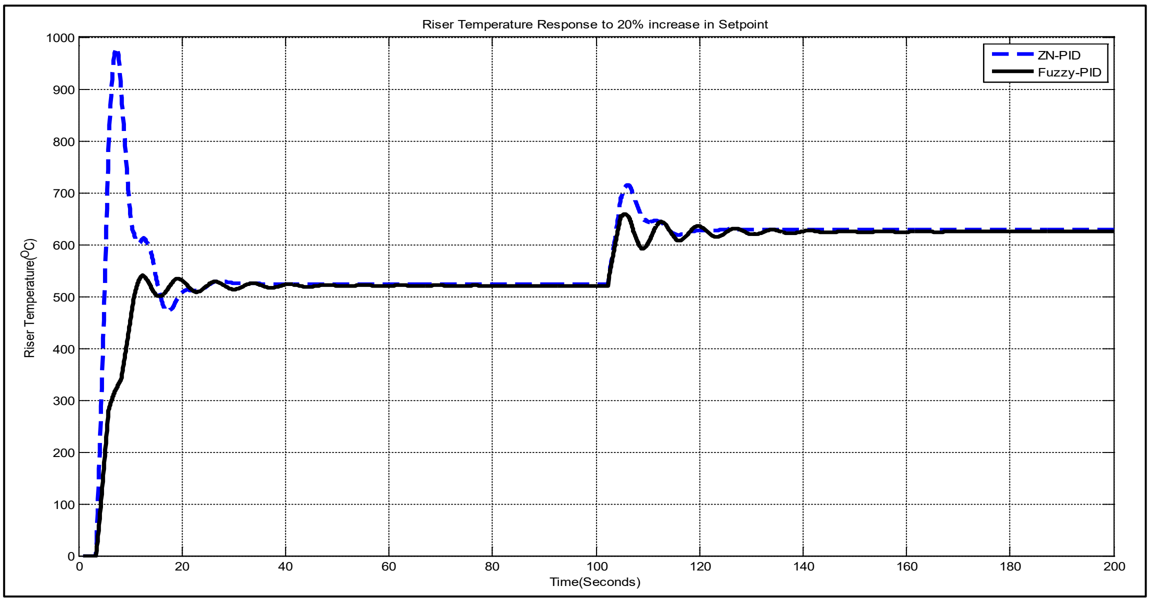

Figure 7: Riser Temperature Profiles under ZN-PID and Fuzzy-PID Control (Base case, Steptime=100 s,+20% step change in setpoint)

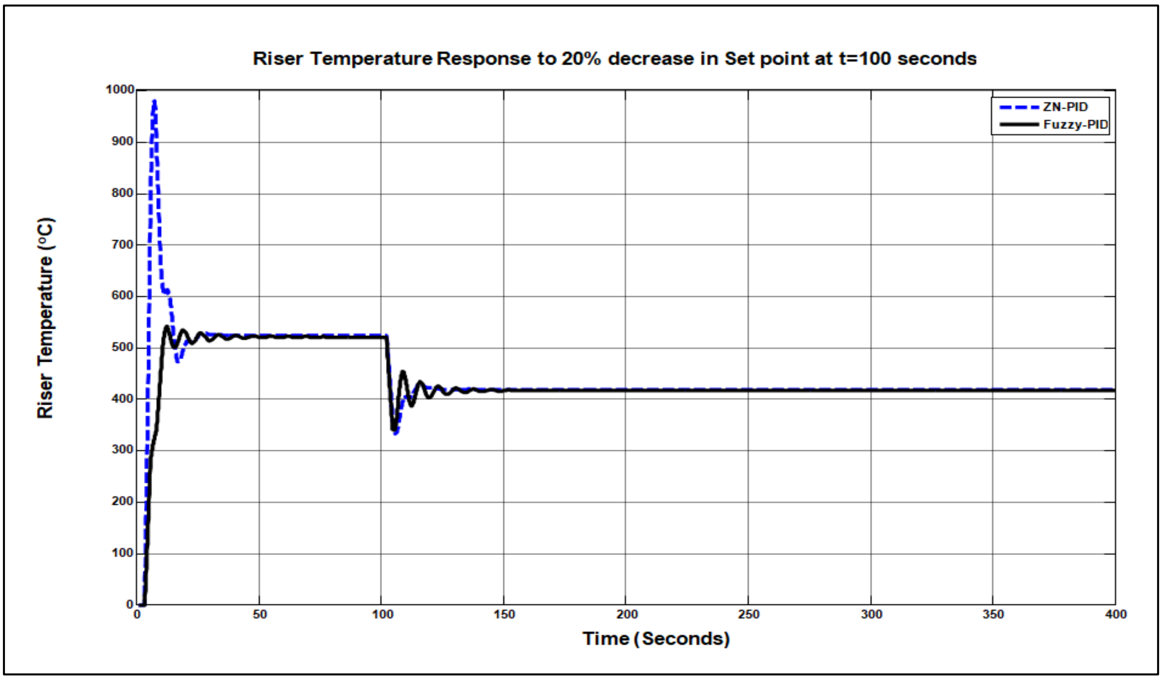

Figure 8: Riser Temperature Profiles under ZN-PID and Fuzzy-PID Control (Step time=100 s,-20% step change in setpoint)

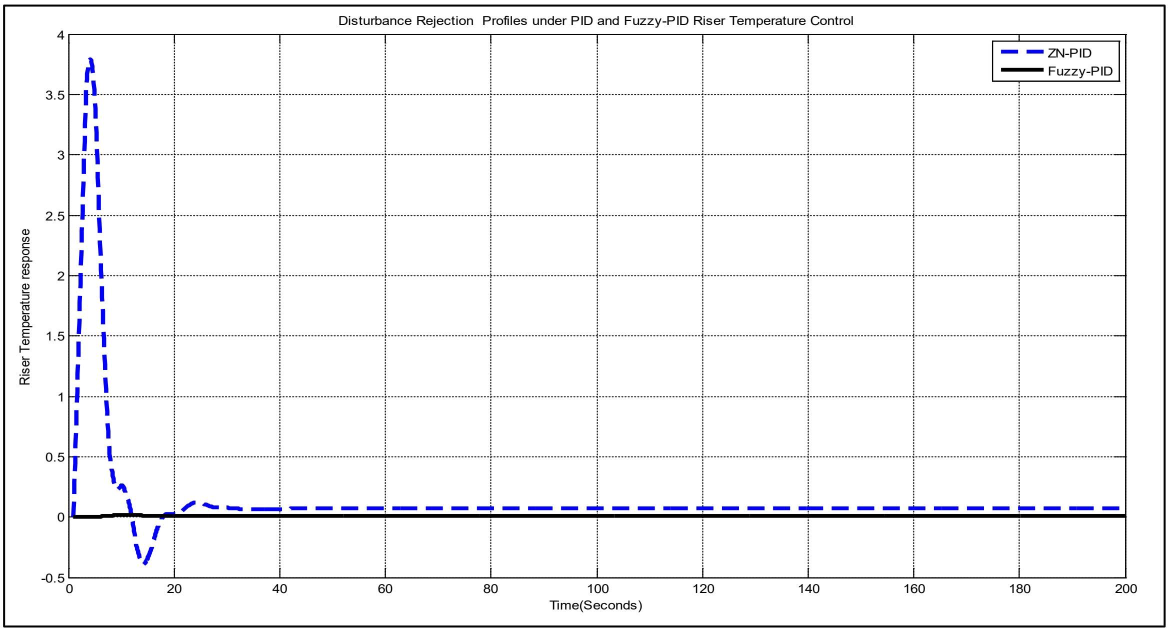

Figure 9: Riser Temperature Profiles under ZN-PID and Fuzzy-PID Control (Step disturbance at t=0 s)

3.2 Rggenerator Temperature Profiles

Figure 10 and 11 show the temperature profilee in thr FCCU regenerator under PID and fuzzy-PID control for sttep changes of +20% in set point and -20% in set point, at t=100 seconds respectively. One of the plaussible deductions from Figure 10 is that a steady nominal temperature of 742℃ is achieved within 20seconds from start-up for the plant under fuzzy-PID control. Whreas, the elarpsed time for steady operations under conventional PID is 100 seconds. For a setpoint change from 742℃ to 890℃ at t=100 seconds, the response time to track and maintain the new set point is 20 seconds under fuzzy-PID control as against 60 seconds for conventional PID regenerator temperature control, as captured in Figure 10. A similar trend showing the superiority of the fuzzy-PID controller over the conventional PID control controller in the context of regenerator temperature control, is shown in Figure 11. While it is a seamless transition in the case of the fuzzy-PID controller, the conventional PID controller exhibits an oscillatory feature, making undershoots and overshoots before finally attaining a steady state with offset, after 60 seconds. Controller tolerance for unmeasured disturbance during steady operations is depicted by Figure 12. Here, the first part of the temperature profile for the period $0 \leq t \leq 100$ seconds repersent steady operation regime while the second part accounts for when the FCC plant experiences unmeasured disturbance. In both set point tracking and disturbance rejection, the fuzzy-PID controller offers good promise of improving unit performance as deduced from Figure 10 through 12.Although the fields of application are different, the results from this study are in tandem with the contexts and arguments presented in Valayudhaan[23], Lofti et al [24] ,Van et al [25] and Rani et al [26]

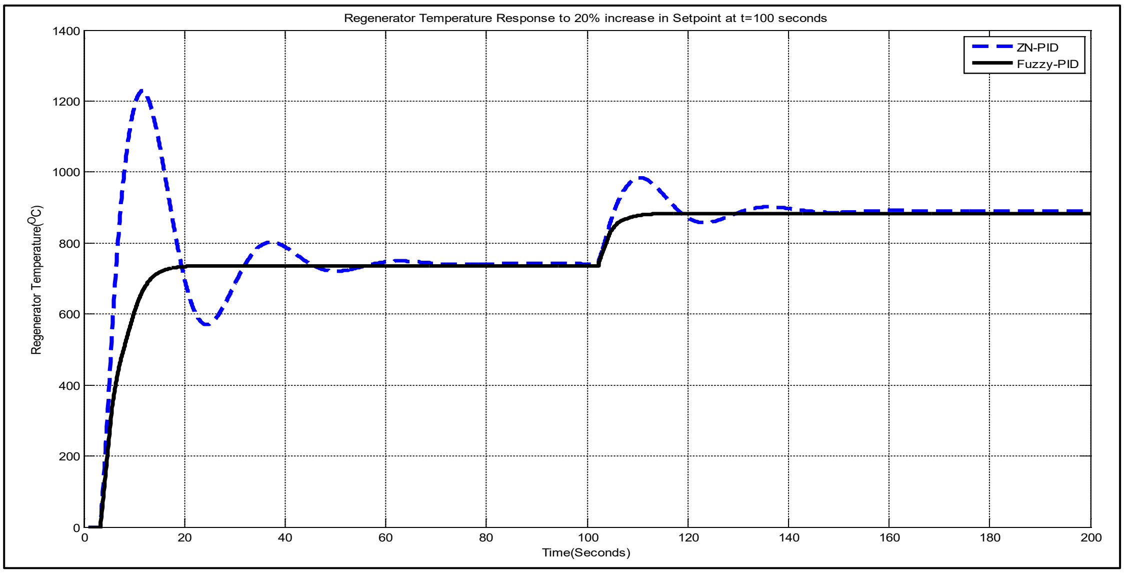

Figure 10: Regenerator Temperature Profiles under ZN-PID and Fuzzy-PID Control (Step change at t=100 s)

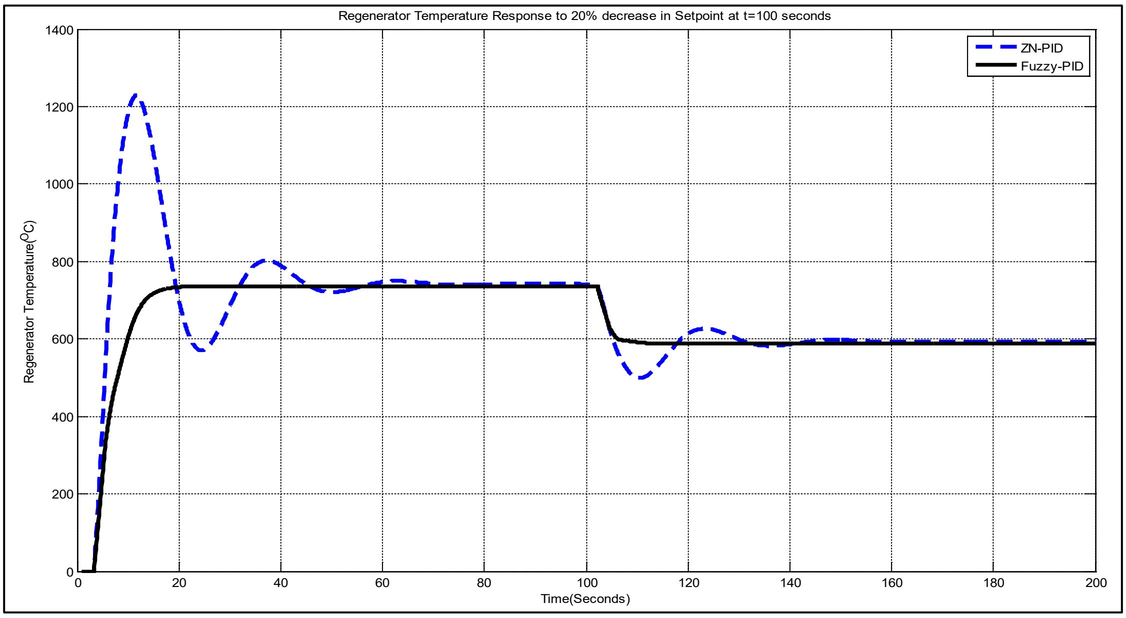

Figure 11: Regenerator Temperature Profiles under ZN-PID and Fuzzy-PID Control (Step disturbance at t=100 s)

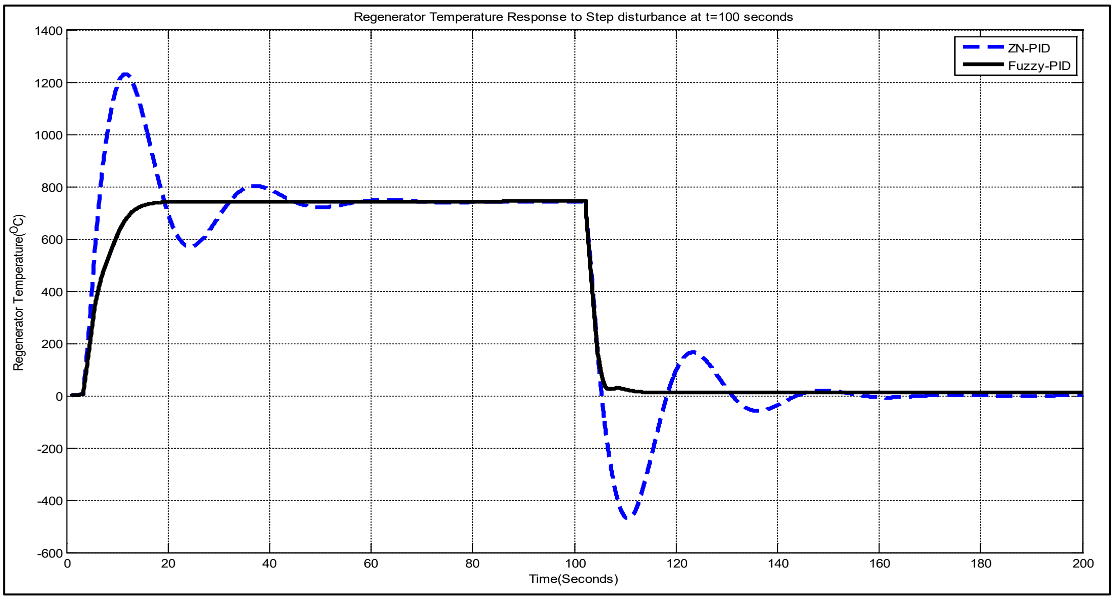

Figure 12: Regenerator Temperature Profiles under ZN-PID and Fuzzy-PID Control (Disturbance at t=100 s)

3.3 Controller Performance Measures

In addition to evaluating controller performance using the plots to estimate static measures such as overshoot, rise time and settling time, other qualitative measures: Integral Absolute error (IAE), Integral Square error (ISE), Integral Time Absolute error (ITAE) and Integral Time Square error (ITSE) were evaluated. These measures are given in Table 2 and 3, to further support the discussed results. In Table 2 some steady state and dynamic characteristics of riser temperature following step changes in set-point are shown. For a +20% step change in riser temperature set-point , representing a change in set-point from 524℃ to 628.8℃,the PID control scheme produced a temperature overshoot of 14.3% while the fuzzy-PID scheme recorded mere 3.3% which translates to 76.92% improvement in overshoot.. In the case of -20% change in riser temperature set point,representing a change from 524℃ to 419.2℃,results show 86.8% improvement of overshoot over that of PID. The improvement is as a result of the capacity of fuzzy-PID controller to iteratively update the proportional gain of the PID controller in real time, following a change in set-point.The results did not show improvement in settling time but other characterisctics support the capacity of the fuzzy-PID to improve process performance. Results in Table 3 further show the superior performnance of the Fuzzy-PID control scheme in the light of regenerator temperature tracking over the classical PID controller and they are inportant to process safety and operation.For instance, a regenerator temperature oversoot of 12.6% that is unattended to for 80 seconds is capable of causing undesirable temperature fields in the vessel,with unintended consequences such has damage to regenemerator wall refractory, unit shut down and production loss.

Table 2: Controller Performance Characteristics for Riser Temperature Set Point Tracking

Performance Measure	PID (+20 %Step)	Fuzzy-PID (+20% Step)	PID (-20 %Step)	Fuzzy-PID (-20% Step)
Overshoot (%)	14.5	3.3	1.9	2.5
Settling Time(s)	40	40	50	50
IAE	8.811	8.246	8.811	8.238
ISE	5.29	4.469	5.29	4.484
ITAE	1762	280.1	1762	270.2
ITSE	43.77	31.19	43.77	31.17

Table 3: Controller Performance Characteristics for Regenerator Temperature Set Point Tracking

Performance Measure	PID (+20% Step)	Fuzzy-PID (+20% Step)	PID (-20 %Step)	Fuzzy-PID (-20% Step)
Overshoot (%)	12.6	6	4	0.7
Settling Time(s)	80	20	40	20
IAE	14.29	8.63	14.28	8.086
ISE	6.713	4.506	6.701	4.46
ITAE	2858	305.9	2857	234.5
ITSE	77.55	33.05	77.7	28.63

4. Conclusion

Two major challenges with the PID controller stem from the static nature of the tuning parameters and the difficulty in operating efficiently in both set point tracking and disturbance attenuation. To proffer solutions to the challenges, supervisory controllers with dynamic PID-gains update features have been implemented and presented in this paper. The controllers have been tested in simulation mode for servo and regulatory response behaviour of riser temperature and regenerator temperature of industrial fluid catalytic cracking unit. In the light of the results that were obtained from a performance comparison, it is safe to infer that the two-layer control scheme offers improved set point tracking and disturbance rejection behaviour for both riser temperature and regenerator temperature. That translates to a good promise of seamless switch from one operating policy to another, in response to market demand for products. The implementation of the supervisory scheme would require a minor modification of the conventional scheme with a benefit of smooth running of the FCCU, reduced downtime, availability of products and consequent cut in the importation of premium motor spirit (PMS), in the face of an economically unfriendly subsidy regime. Haven expressed general views and sentiments regarding the subject matter, a few take -aways would be expedient at this point.

- Both controllers exhibited time lag between when process perturbation such as step change in set point was introduced and when controller response was manifested in the process variable.
- A new steady state was always attained after control action on such perturbations.
- In addressing perturbations and getting the process variable back to the set point through both servo and regulatory action, the fuzzy-PID scheme is the way and choice to go with.

The intervention of fuzzy logic controller on the PID gains provided the merit of seamlessly operating the FCC unit from one objective to another without compromising process efficiency. However, a major challenge with the success of the scheme is that selecting the membership universe of discourse for the controller gains and formulating the rule base is tedious and time-consuming as it requires FCC unit simulation under PID control However, a method to quantify the gains that are accruable in the application of two-layer in the light of process economics is needful. Such subjects as economic optimization and real time optimization can be interfaced in further research as enhancement to attract attention and consequent patronage from industry.

Acknowledgements

P.N. Josiah would like to thank Prof Ayo O. Kuye of the Department of Chemical Engineering, University of Port Harcourt, Nigeria for the useful insights and suggestions during the conceptual phase of the research. The candid and constructive review of the first draft of the manuscript by Dr. John Nwalor, Dr. Tolu Ajayi and Dr Williams Almouroff, all of the Department of Chemical Engineering, university of Lagos, Nigeria is hereby acknowledged. For providing the platform and conducive environment for this research, my thanks are due to, Prof Ogbonna F Joel. the center leader at the World bank Africa center for oilfield chemicals research, university of Port Harcourt, Nigeria.

Author contribution

Conceptualization, P. N. Josiah, I. J. Otaraku and B.O. Evbuomwan; methodology, P. N. Josiah; software, P. N. Josiah; writing—original draft preparation, P. N. Josiah; writing—review and editing, I. J. Otaraku and B.O. Evbuomwan; supervision, I. J. Otaraku; All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] Y. Rang and V. Du, An Integrated methodology for the modelling of Fluid Catalytic Cracking (FCC) riser reactor, Appl. Petrochem. Res., 4 (2014) 423-433. https://doi.org/10.1007/s13203-014-0084-8

[2] A, Dey and R. Ayyagan, Robust PID Controller design using Fuzzy Pole Placement Techniques, IFAC-PapersonLine, 49 (2016) 789–794. https://doi.org/10.1016/j.ifacol.2016.03.153

[3] A.A. El-Samahy and M.A. Shamseldin, Brushless DC motor tracking control using self-tuning fuzzy PID control and model reference adaptive control, Ain Shams Eng. J., 9 (2018) 341-352. https://doi.org/10.1016/j.asej.2016.02.004

[4] S. Dettori, V. Iannino , V. Colla and A. Signorini , A Fuzzy Logic-based Tuning Approach of PID Control for Steam Turbines for Solar Applications, Energy Procedia, 105 (2017) 480–485. https://doi.org/10.1016/j.egypro.2017.03.344

[5] Y. I. Kudinov, V.A. Kolesnikov , F.F. Pashchenko , A.F. Pashchenko and L. Papic ,Optimization of Fuzzy PID Controller's Parameters, Procedia Comput. Sci., 103 (2017) 618–622. https://doi.org/10.1016/j.procs.2017.01.086

[6] D. Vrecko, M. Nerat , B. Dolenc , D. Vrančić , F. Meyer and Đ. Juričić , Optimizing the operation of solid oxide fuel cell power system with a supervisory controller based on extremum-seeking approach, Energy Conserv. Manag., 187 (2019) 53-62. https://doi.org/10.1016/j.enconman.2019.03.012

[7] Z. Fan, X. Yu, M.Yan and C. Hong, Oxygen Excess Ratio Control of PEM Fuel Cell Based on Self-adaptive Fuzzy PID, IFAC-PapersOnLine, 51 (2018) 15–20. https://doi.org/10.1016/j.ifacol.2018.10.004

[8] J.E. Rodríguez-Castellanos , V. H. Grisales-Palacio and J. E. Cote-Ballesteros , A tuning proposal for direct fuzzy PID controllers oriented to industrial continuous processes, IFAC-PapersOnLine, 51 (2018) 657–662. https://doi.org/10.1016/j.ifacol.2018.06.172

[9] A. Kumar and V. Kumar, A novel interval type-2 fractional order fuzzy PID controller: Design, performance evaluation, and its optimal time domain tuning, ISA Trans., 68 (2017) 251–275. https://doi.org/10.1016/j.isatra.2017.03.022

[10] S. Ahmad, S. Ali and R. Tabasha, The design and implementation of a fuzzy gain-scheduled PID controller for the Festo MPS PA compact workstation liquid level control, Eng. Sci. Technol. Int. J., 23 (2020) 307-315. https://doi.org/10.1016/J.JESTCH.2019.05.014

[11] G.L. Demidova , D.V. Lukichev, A.Yu. Kuzin and A. Genetic , Approach for Auto-Tuning of Adaptive Fuzzy PID Control of a Telescope's Tracking SystemProcedia Comput. Sci., 150 (2019) 495–502. https://doi.org/10.1016/j.procs.2019.02.084

[12] I. Ganchev, A. Taneva, K. Kutryanski and M. Petrov, Decoupling Fuzzy-Neural Temperature and Humidity Control in HVAC Systems, IFAC-PapersOnLine, 52 (2019) 299–304. https://doi.org/10.1016/j.ifacol.2019.12.539

[13] N. Jalali, H. Razmi and H. Doagou-Mojarrad, Optimized fuzzy self-tuning PID controller design based on Tribe-DE optimization algorithm and rule weight adjustment method for load frequency control of interconnected multi-area power systems, Appl. Soft Comput., 93 (2020) 106424. https://doi.org/10.1016/j.asoc.2020.106424

[14] H. H. Manap, A. K. Abdul Wahab and F. M. Zuki,Control for Carbon Dioxide Exchange Process in a Membrane Oxygenator Using Online Self-Tuning Fuzzy-PID Controller, Biomed. Signal Process. Control, 64 (2021) 102300. https://doi.org/10.1016/j.bspc.2020.102300

[15] D. Sharma, Designing and Modeling of Fuzzy Control Systems, Int. J. Comput. Appl., 16 (2011) 46-53. https://doi.org/10.5120/1973-2644

[16] Z. Has and M.F. Rahmat, Application of Self-Tuning Fuzzy-PID Controller on Industrial Hydraulic Actuator using System Identification Approach, Int. J. Smart Sens. Intell. Syst., 2 (2009) 246-267. https://doi.org/10.21307/ijssis-2017-349

[17] S.R. Vaishnav and Z.J. Khan, Design and Performance of PID and Fuzzy Logic Controller with Smaller Rule Set for Higher Order System, Proc. World Congr. Eng. Comp. Sci., (2007) 1-4.

[18] D. F. Ahmed and S. K. Ateya , Modelling and Simulation of Fluid Catalytic Cracking Unit, J. Chem. Eng. Process Technol., 7 (2016) 2-13 . https://doi.org/10.4172/2157-7048.1000308

[19] B. Olufemi and K. Latinwo, A. Olukayode, Riser Reactor Simulation in a Fluid Catalytic Cracking Unit, Chem. Process Eng. Res., 7 (2013) 12 – 24.

[20] O. A. Olafadehan, O. M. Daramola, O. P. Sunmola and G. O. Abatan, Modelling and Simulation of Riser Reactor for a commercial Fluid Catalytic cracking unit using 6-lump kinetics of Vacuum Gas Oil, Pet. Petroch. Eng. J., 3 (2019) 194. https://doi.org/10.23880/ppej-16000194

[21] P. N, Josiah, J.U. Nwalor and T.O. Ajayi, Basic Modelling of the Riser-Stripper- Regenerator Unit of a Fluid Catalytic Cracker, J. Niger. Soc. Eng., 29 (2019) 31-48. https://doi.org/10.1007/s13203-018-0212-y

[22] P. T. Yendamuri and C. S. Rao, Design of Robust PI controller with Decoupler for a Fluid Catalytic Cracking Unit, Ind. Eng. Chem. Res.,58 (2019) 20722-20733. https://doi.org/10.1021/acs.iecr.9b04770

[23] A.K.D. Velayudhaan, Design of a supervisory fuzzy logic controller for monitoring the inflow and purging of gas through lift bags for safe and viable salvaging operations, Ocean Eng., 171 (2019) 193-201. https://doi.org/10.1016/j.oceaneng.2018.10.049

[24] M. Lofti ,M. B. Menhaj, S. A. Hosseini and A. S. Shirani, Design of switching Supervisory Control based on Fuzzy-PID Controllers for VVER-100 Pressurizer System with RELAP5 and MATLAB Coupling, Ann. Nucl. Energy,147 (2020) 107-118. https://doi.org/10.1016/j.anucene.2020.107625

[25] M. Van and X. P. Do , M. Mavrovouniotis , Self-tuning fuzzy PID-nonsingular fast terminal sliding mode control for robust fault tolerant control of robot manipulators, ISA Trans., 96 (2020) 60-68. https://doi.org/10.1016/j.isatra.2019.06.017

[26] H. Rani, S. Navasree, S. George and S. Ashok , Fuzzy logic supervisory controllers for Multi-input non-isolated DC to DC converters connected to DC grid, Electr. Power Power Syst., 12 (2019) 49-60. https://doi.org/10.1016/j.ijepes.2019.04.018