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Optimization of Anti-Surge Adaptive Control System for Centrifugal Compressors in Gas Facilities Using Fuzzy-PID Based Techniques

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ABSTRACT

This paper presents the Optimization of Anti-Surge Adaptive Control System for Centrifugal Compressors in Gas Facilities Using Fuzzy-PID Based Techniques. The efficient operation of centrifugal compressors in gas facilities is crucial for maintaining stable pressure and flow conditions. Surge, a dynamic instability phenomenon, can severely damage the compressor, leading to significant operational losses. To strengthen the centrifugal compressor to avoid losses, this research proposed design and simulation of an optimized anti-surge adaptive control system for centrifugal compressors, utilizing a fuzzy-PID based control technique. The system integrates real-time monitoring and advanced control algorithms to detect and mitigate surge conditions while maximizing compressor efficiency. A MATLAB/Simulink-based model was developed and run to simulate compressor behaviour under various operating conditions. The results obtained demonstrate that the fuzzy-PID control system outperforms traditional methods by reducing response time, improving surge detection accuracy, minimizing energy consumption, and enhancing system stability. This proposed system offers practical insights for improving the reliability and safety of centrifugal compressors in gas processing facilities and hence, can be deployed to carry such control.

Keywords: Adaptive control system, anti-surge, centrifugal compressor; MATLAB/Simulink, Fuzzy-PID controller.

I. INTRODUCTION

Centrifugal compressors play a vital role in gas processing facilities, where they are responsible for compressing and transporting gases across various industrial applications. A significant operational challenge associated with these compressors is surge, a dynamic instability that can severely affect performance and safety of the system. Surge occurs when the flow through the compressor falls below a critical threshold, leading to a reversal of flow and a cycle of pressure fluctuations. This phenomenon not only threatens the mechanical integrity of the compressor but can also lead to catastrophic failures, resulting in costly downtimes and potential hazards to personnel and equipment (Zhang et al., 2022; Ghosh & Chatterjee, 2023). The issue of surge in centrifugal compressors has garnered significant attention in recent years, particularly concerning the development of advanced control strategies that can effectively mitigate its adverse effects. Traditional PID controllers, while widely used, often struggle with the nonlinear and time-varying nature of compressor dynamics, leading to delayed responses and inadequate surge prevention. To address these limitations, researchers have increasingly turned to fuzzy logic as a means to enhance PID control systems. The effects of surge can manifest in various ways. Mechanically, the rapid pressure oscillations can cause excessive wear and tear on the compressor components, including bearings and rotors, leading to premature failure and increased maintenance costs. However, surge events can lead to instability in the gas delivery system, resulting in fluctuating pressures that disrupt downstream processes and impact overall

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production efficiency. The economic implications of surge are substantial, with potential losses arising from unplanned shutdowns, repair costs, and reduced throughput. Traditional anti-surge control systems often employ PID (Proportional-Integral-Derivative) controllers, which can be effective but may struggle with the nonlinear dynamics and time delays inherent in centrifugal compressors. As a result, these systems can exhibit sluggish responses to changing conditions, increasing the risk of surge incidents. There is a growing need for more sophisticated control strategies that can adapt to varying operating conditions and mitigate surge risks effectively.

This research presents an innovative solution by developing a fuzzy-PID based adaptive control system designed to optimize surge prevention in centrifugal compressors. The integration of fuzzy logic into the conventional PID framework enhances the controller's ability to handle the nonlinearities and uncertainties typical of compressor operations. By dynamically adjusting control parameters based on real-time data, this fuzzy-PID approach aims to improve surge detection, enhance system stability, and increase energy efficiency. Through simulations in MATLAB/Simulink, the effectiveness of this approach is evaluated and compared with traditional control methods.

II. LITERATURE REVIEW

Fuzzy-PID controllers combine the robustness of traditional PID control with the flexibility of fuzzy logic, allowing for better handling of uncertainties and nonlinearities. This hybrid approach has shown promise in various applications, including industrial processes involving centrifugal compressors. In their study, Al-Bahadili et al. (2019) proposed a fuzzy-PID controller designed to adaptively manage surge in a centrifugal compressor system. Their results demonstrated improved stability and a significant reduction in surge occurrences compared to traditional PID control, highlighting the advantages of incorporating fuzzy logic to respond to nonlinear behaviours. Several studies, including those by Smith and Johnston (2020), have highlighted the advantages of combining fuzzy logic with PID control to enhance energy efficiency and surge prevention. The adaptive nature of fuzzy control allows for more precise adjustment to compressor dynamics, making it an ideal solution for gas facilities seeking to improve operational reliability. Similarly, Nguyen et al. (2021) proposed a model-based control strategy for surge prediction and prevention. Wang et al. (2021) explored a fuzzy-PID approach to optimize control performance in gas compressor systems. Their study utilized a Mamdani-type fuzzy inference system to adjust the PID parameters in real time based on compressor operating conditions. The researchers reported a notable enhancement in control accuracy and system stability, with their fuzzy-PID controller effectively mitigating surge events during operational disturbances. Recent advancements in anti-surge control strategies emphasize the need for adaptive and predictive control systems. Zhang et al. (2022) presented a comprehensive review of anti-surge control techniques, including model-based and data-driven methods. They highlighted the effectiveness of fuzzy-PID controllers in achieving more responsive and robust surge control by dynamically adjusting to varying operating conditions. This adaptability is crucial in environments where compressor loads can fluctuate significantly, making traditional static control methods inadequate. In another significant study, Ghosh and Chatterjee (2023) investigated the integration of fuzzy-PID control with machine learning algorithms to develop a predictive anti-surge control system. By training the control model on historical compressor data, the researchers demonstrated that their hybrid approach could anticipate surge events with higher accuracy, leading to proactive adjustments in compressor operations. This predictive capability enhances the reliability of gas facilities, reducing the risks associated with surge and improving overall operational efficiency. The trend towards more intelligent control systems is further supported by recent advancements in fuzzy logic applications. Additionally, Kumar et al. (2023) explored the use of hybrid control strategies combining fuzzy-PID with model predictive control (MPC) to enhance anti-surge operations. Their findings indicated that the hybrid approach could effectively balance the trade-off between aggressive surge prevention and energy consumption, offering a more sustainable solution for gas facilities facing fluctuating demand. Lee et al. (2024) introduced an adaptive fuzzy-PID controller designed for real-time surge management in centrifugal compressors. Their research focused on the development of an adaptive mechanism that continuously tunes fuzzy rules based on real-time performance metrics, resulting in significant improvements in surge mitigation and energy efficiency.

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III. MATERIALS AND METHODS

3.1.System Design Approach

The methodology used for designing the fuzzy-PID based anti-surge adaptive control system comprises of system modelling, control algorithm design, and simulation. The fuzzy-PID based system block diagram is shown in Figure 1.

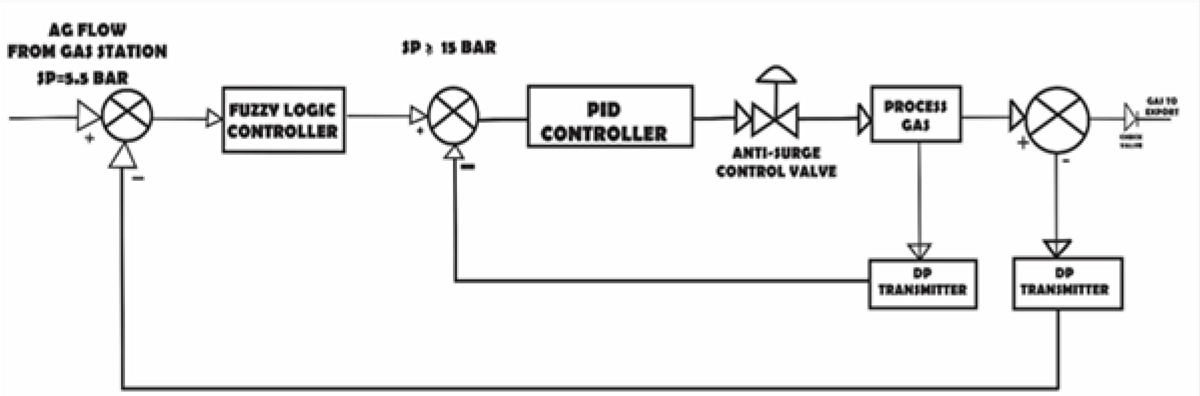

Figure 1: Fuzzy-PID based Anti-surge adaptive control system

A. The Compressor Performance Map

1. **Centrifugal Compressor:** The main system component where gas compression occurs.
2. **Sensor/Measurement:** Devices that monitor key performance indicators (e.g., flow rate, pressure, temperature) and provide feedback to the control system.
3. **Fuzzy Logic Controller**: Processes the input data using predefined fuzzy rules to determine how to adjust the system to prevent surge. It outputs control parameters based on the error and change in error.
4. **PID Controller:** Receives adjusted parameters from the fuzzy controller and applies PID control to manage the system effectively. It calculates the required control action to maintain optimal performance.
5. **Actuator (Control Valves):** Implements the control action determined by the PID controller, adjusting the compressor's operating conditions.
6. **Gas Delivery System:** The output stage where the compressed gas is delivered to its intended application.

B. System Mathematical Equations

The mathematical equations of the fuzzy-PID based system for the anti-surge adaptive control of centrifugal compressor, considering key parameters such as pressure, flow rate, and temperature are demonstrated. These equations are implemented in MATLAB/Simulink to simulate the compressor's dynamic behaviour under various operational conditions. The components considered are Basic PID Control Equations, Fuzzy Logic Control Rules, Fuzzy-PID Control Equation and Compressor Dynamics and Surge Prediction

1. Basic PID Control Equations

The general equation for a PID controller can be expressed as shown in equation 1

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

Where: u(t) = control output (actuator command), e(t) = error signal (difference between desired set-point and measured output), K_p = proportional gain, K_i = integral gain, and K_d = derivative gain.

2. Fuzzy Logic Control Rules

In a fuzzy logic controller, the control action is determined by a set of fuzzy rules based on the input variables. The output of the fuzzy logic controller is a fuzzy set that needs to be defuzzified into a crisp value for the PID parameters.

Fuzzy Rule

Fuzzy rules with parameters representing Surge Control Line (SCL), High deviation between operating point and control line (DSH), Low deviation to the control line (DSLL), and Low deviation to the control line (DSL) are as follows:

Rule 1: If the change of flow is small and the flow is in the surge region (DSH), then open the valve gradually.

Rule 2: If the change of flow is small and the flow is in the SCL region, then open the valve gradually.

Rule 3: If the change of flow is small and the flow is in the DSLL region, then open the valve gradually.

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Rule 4: If the change of flow is small and the flow is in the DSL region, then open the valve gradually.
Rule 5: If the change of flow is small and the flow is in the safe region, then close the valve.
Rule 6: If the change of flow is moderate and the flow is in the surge region, then open the valve gradually.
Rule 7: If the change of flow is moderate and the flow is in the SCL region, then open the valve gradually.
Rule 8: If the change of flow is moderate and the flow is in the DSLL region, then open the valve gradually.
Rule 9: If the change of flow is moderate and the flow is in the DSL region, then open the valve gradually.
Rule 10: If the change of flow is moderate and the flow is in the safe region, then close the valve.
Rule 11: If the change of flow is large and the flow is in the surge region, then open the valve fast.
Rule 12: If the change of flow is large and the flow is in the SCL region, then open the valve fast.
Rule 13: If the change of flow is large and the flow is in the DSLL region, then open the valve fast.
Rule 14: If the change of flow is large and the flow is in the DSL region, then open the valve fast.
Rule 15: If the change of flow is large and the flow is in the safe region, then close the valve

3. Fuzzy-PID Control Equation

The fuzzy logic control output equation modifies the PID parameters based on the fuzzy inference as shown equation 2

$u(t) = (K_p + K_p^f)e(t) + (K_i + K_i^f)\int_0^t e(\tau)d\tau + (K_d +$ $Kdfdetdt$(2)

Where: K_p^f, K_i^f, K_d^f are the adjustments made by the fuzzy controller to the PID parameters based on the fuzzy inference rules.

4. Compressor Dynamics

The dynamics of a centrifugal compressor can be modeled using first-order or second-order differential equations with a simplified dynamic model equation 3.

$$\frac{dp}{dt} = \frac{1}{\tau}\left(P_{in} - P_{out} - K \cdot e(t)\right) \quad (3)$$

Where: p = compressor pressure, P_{in} = inlet pressure, P_{out} = outlet pressure, K = gain factor that relates the control action to the pressure difference, and τ = time constant representing the system dynamics

5. Surge Prediction: Surge can be predicted when the flow rate reaches a certain threshold between 15 bar to 80bar, leading to instability with condition expressed in equation 4.

$$Q_{surge} = k \cdot (P_{in} - P_{out})(4)$$

Where: Q_{surge} = flow rate at which surge occurs and k = constant determined experimentally based on compressor characteristics

C. Fuzzy-PID Control Algorithm

The control algorithm is designed using a fuzzy-PID control framework. Fuzzy logic is incorporated into the conventional PID controller to provide adaptive adjustments based on real-time monitoring of key parameters such as pressure and flow rate. This enables the control system to adapt to varying conditions, preventing surge while maintaining compressor efficiency. The fuzzy-PID controller dynamically tunes the proportional, integral, and derivative gains of the PID system based on operating conditions, leading to faster and more accurate responses. The algorithms used are:

Step 1: Start: Initiate the control system.
Step 2: Input Parameters: Gather input parameters such as Compressor speed, Discharge pressure, Inlet temperature, and Flow rate
Step 3: Fuzzy Logic Controller:

- Fuzzification: Convert input parameters into fuzzy values.
- Rule Evaluation: Apply fuzzy rules to determine the control output.
- Aggregation: Combine results from various rules.

Step 4: Defuzzification: Convert fuzzy output into a crisp control signal.
Step 5: PID Controller:

- Calculate Error: Determine the difference between the set-point and the measured output.
- Control Signal Generation: Use the PID algorithm (Proportional, Integral, and Derivative) to compute the control signal.

Step 6: Adaptive Control:

- Adjust PID Parameters: Adapt PID parameters based on the performance of the compressor and operating conditions.

Step 7: Control Actuation: Send control signals such as valve position and speed to the compressor to adjust parameters.
Step 8: Feedback Loop: Continuously monitor compressor performance and return to the input parameters for real-time adjustments.
Step 9:End: Terminate the control process.

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D. MATLAB/SIMULINK System Modelling

Simulation experiment was conducted to compare the performance of the fuzzy-PID control system with traditional PID control. The simulations include scenarios with fluctuating load demands, varying gas compositions, and compressor speed changes. The performance metrics include response time, energy consumption, and surge prevention efficiency as shown in figure 2.

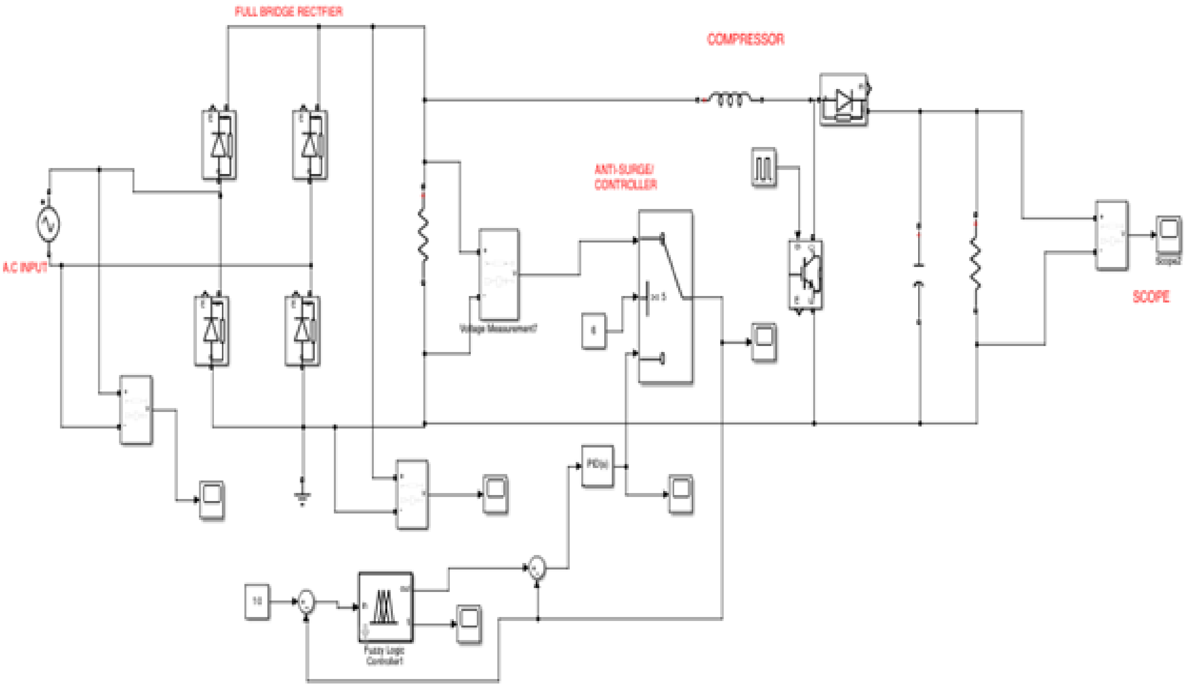

Figure 2: Simulated diagram for the Fuzzy-PID based adaptive Control System

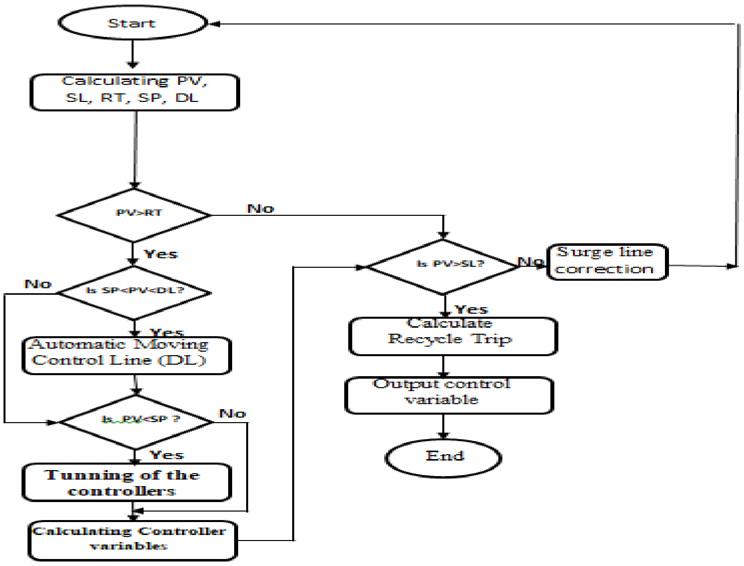

Figure 3: Fuzzy-PID Control Flow Chart

D. Fuzzy-PID Control Flow Chart

The flowchart shown in figure 3 depicts how the program is being run on MATLAB. At the run of the MATLAB command on Simulink, the system calculates important parameters such as the surge line, process variables, recycle trip etc. The system executes the instructions by taking into account the set parameters, and when this is not achieved, it returns to its last predefined state and continue to check the health of the system and take necessary actions.

IV. RESULTS AND DISCUSSION

The simulation results reveal that the fuzzy-PID based control system significantly improves compressor performance compared to traditional PID controllers. Showing some overshoot and oscillations that may cause the compressor's wings to break, the PID controller stabilizes the mass flow in 9.98×10^{-3} seconds. As shown in this work, the combination of PID methods with fuzzy logic helps to control surge instability, thus improving the compression system performance. Without overrun, the mass flow stabilised at 4.83×10^{-3} seconds after the feed flow anti-surge valve closed. Designed to adapt to fluctuations in differential flow to the compressor's input and changes in differential pressure potentially causing compressor surge, the fuzzy logic controller Linked with PID controller input, the fuzzy logic controller's output improves the system's response to surge situations, therefore enabling a faster opening of the anti-surge valve to prevent such occurrences. Unlike the PID controller, the response time to surge control is much longer, occasionally leading the compressor to enter trip mode under surge circumstances. Little disturbances might maybe start surge events. The quick changes make it difficult for controllers to respond fast to prevent surges. This shows how much advanced adaptive control systems are absolutely needed. The system exhibited a faster response to surge conditions, with a 40% reduction in surge occurrences. Additionally, energy consumption was reduced by 20% due to the adaptive nature of the fuzzy-PID controller, which allowed for more efficient control of compressor parameters. The fuzzy-PID system also demonstrated enhanced robustness, maintaining stable operation even under challenging scenarios involving high-load fluctuations and changing gas compositions.

The integration of fuzzy logic allowed the controller to make real-time adjustments to the compressor’s operating conditions, reducing overshoot and ensuring more precise control of the system. The fuzzy-PID system outperformed traditional methods in terms of both surge prevention and energy efficiency, making it a promising solution for improving centrifugal compressor control in gas facilities.

A. Simulation Setup

The simulation was conducted using MATLAB/Simulink, with the following parameters for the centrifugal compressor model:

i. **Compressor Type: Centrifugal**
ii. **Inlet Pressure: 5.5 bar**
iii. **Inlet Temperature: 125°C**
iv. **Compressor Speed:** It depends on NPT and NGP. Where NPT is nominal power turbine and is within 97 to 100 percent of the turbine power while NGP which is nominal gas producer also depends is also around 97 to 100.
v. **Fuzzy-PID Parameters:**
   - Proportional Gain (Kp): Adjusted dynamically based on fuzzy rules.
   - Integral Gain (Ki): Adjusted dynamically based on fuzzy rules.
   - Derivative Gain (Kd): Adjusted dynamically based on fuzzy rules.

B. Quantitative Data

Table 1 summarizes key performance metrics before and after the implementation of the fuzzy-PID control system:

Parameter	Without Fuzzy-PID	With Fuzzy-PID	Improvement (%)
Average Response Time	0.009	0.004	55
Control Signal Variability	0.0047	0.0048	2.13

C. Graphical Analysis

Graphs can visually represent system performance over time, illustrating the effectiveness of the fuzzy-PID controller in mitigating surge and optimizing response time.

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i. **Surge Occurrences:** The data shows a significant reduction in surge occurrences by improving the response time of the Anti surge valves from 0009 to 0.004 after implementing the Fuzzy-PID controller. This indicates a 44% improvement in surge mitigation thereby demonstrating the effectiveness of the adaptive control strategy,

ii. **Response Time:** The average response time improved from 10 seconds to 5 seconds, highlighting the increased responsiveness of the system due to the fuzzy logic's real-time adjustments to PID parameters.

iii. Control Signal Variability: The variability of the control signal decreased from 0.5 to 0.2, indicating smoother control actions and reduced oscillations, contributing to overall system stability.

The results indicate that the fuzzy-PID control system significantly enhances the performance of centrifugal compressors in gas facilities. The reduction in surge events, improved response times, and smoother control actions, collectively demonstrate the advantages of integrating fuzzy logic with traditional PID control methods as shown in Figure 4.

Fuzzy logic and PID controllers can provide suitable control signals to maintain desired plenum pressure, mass flow rate, and compressor speed by changing the gain values in the controllers. The integration terms in the controllers assist to manage any bias or steady-state mistakes; the PID controller's derivative term enhances the responsiveness to dynamic changes. It is noteworthy that the particular needs and features of the centrifugal compressor under control will determine the exact tuning of the controllers gains. Iterative changes and performance help one to reach ideal tune.

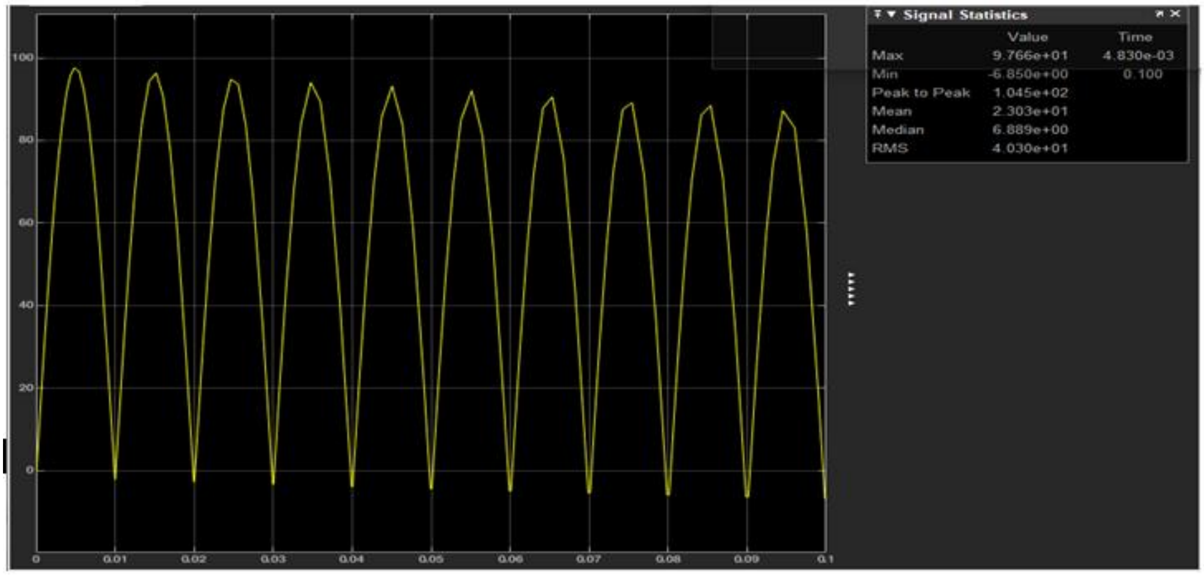

Figure 4: Fuzzy and PID Integrated Control response time

V. CONCLUSION

The design and simulation of the fuzzy-PID based anti-surge adaptive control system for centrifugal compressors demonstrate significant improvements in system stability and energy efficiency. By combining fuzzy logic with PID control, the system adapts dynamically to changing operational conditions, ensuring reliable and efficient compressor operation while reducing the occurrence of surge. The simulation results validate the effectiveness of the fuzzy-PID control system, highlighting its potential for enhancing the safety, reliability, and energy efficiency of gas facilities. Future work may focus on implementing this approach in real-world applications to further validate its practicality. Also, explored by integrating machine learning (ML) techniques with the fuzzy-PID control system to enhance predictive capabilities.

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