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Hybrid controller design using gain scheduling approach for compressor systems

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ABSTRACT

The automatic control system plays a crucial role in industries for controlling the process operations. The automatic control system provides a safe and proper controlling mechanism to avoid environmental and quality problems. The control system controls pressure flow, mass flow, speed control, and other process metrics and solves robustness and stability issues. In this manuscript, The Hybrid controller approach like proportional integral (PI) and proportional derivative (PD) based fuzzy logic controller (FLC) using with and without gain scheduling approach is modeled for the compressor to improve the robustness and error response control mechanism. The PI/PD-based FLC system includes step input function, the PI/PD controller, FLC with a closed-loop mechanism, and gain scheduler. The error signals and control response outputs are analyzed in detail for PI/PD-based FLC's and compared with conventional PD/PID controllers. The PD-based FLC with the Gain scheduling approach consumes less overshoot time of 74% than the PD-based FLC without gain scheduling approach. The PD-based FLC with the gain scheduling approach produces less error response in terms of 7.9% in integral time absolute error (ITAE), 7.4% in integral absolute error (IAE), and 16% in integral square error (ISE) than PD based FLC without gain scheduling approach.

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1. INTRODUCTION

Compressor systems are used to enlarge the air pressure (gas) by minimizing its volume mechanically. The frequently compressed gas is air and oxygen, carbon dioxide, natural gas, and other industrial gases. These compression systems used in many applications include pipeline transportation, vehicular propulsion for military and civilian use, electrical power generation, aircraft transportation, and other thermal plant industries. The compressor has a significant drawback with surge control and rotating stall problems, which cause instabilities in mass flow and pressure conditions [1]. The proportional integral derivative (PID) controller and fuzzy logic-based PI controllers overcome the operational surge problems in the centrifugal compressor; the recycle (surge) values are controlled with PID and fuzzy-based PI controllers to overcome the instability problems in the compressor system [2]. Different controlling techniques are available as an intelligent controller in a hybrid braking system and electric motors, DC motors for controlling purposes [3], [4]. The fault detection and isolation of surge are achieved by fuzzy logic modeling for industrial centrifugal compressors and gas turbine modules [5], [6]. The different controllers, like PID, fuzzy logic controller (FLC), PID based fuzzy controllers, are used in many applications. The electronic throttle control (ETC) valve is optimized using PID type fuzzy factors with a genetic algorithm [7], and FLC achieves the air conditioning control for energy saving [8]. The ETC for autonomous vehicles using fractional-PI controllers [9], overshoot suppression for ETC using fuzzy based PI controller [10], level and pressure process control are achieved by fuzzy-PID controllers [11].

The non-linear and highly uncertain system control is a complex and challenging task for designers. These non-linear control systems are not modeled systematically, forcing unknown parameters to affect the overall system performance. The fuzzy logic methods are introduced, which are functional and adequate to solve the non-linearity system problems. The Takagi-Sugeno (T-S) fuzzy model is introduced in 1985, which elaborates the non-linear system with few linear submodules using a fuzzy rule set. The non-linear system is modeled with the help of these linear submodules, which are associated with a set of rules and are fuzzily blended. The T-S model provides better-controlling capabilities by utilizing the possible linear control methods. Advanced fuzzy dynamic systems have been developed to control the robust adaptive multiple non-linear system models [12]–[14].

Automatic control devices are essential and used in most industries for process control operations. Automatic process control is a significant part of industrial systems, which provides safe and proper control to avoid quality and environmental problems. Many processing operations in industries include thermal power plant, petroleum, and chemical industry for controlling mass flow, pressure flow, temperature, and other similar performance metrics. In general, automatic process control has a typical controller, control elements, process operation, and feedback mechanisms. The overview of the automatic control process system is represented in Figure 1. It is used to maintain the actual value by calculating the existing value with the actual value and obtaining the difference to start the action to minimize the error. The typical controller provides the controlling mechanism of the process. The control elements receive the input from the controller and perform the corresponding operation. The process is also known as a plant with an industrial compressor, gas turbines, thermal power plant, and many more. The process generates the outputs, measurable and converted to one form variable to the corresponding variable by measurement operation.

The error system (e) finds the difference between the reference valve (i) and the actual value (a). The control system performance depends on the error signal, and it is represented as e (t)=i(t)–a(t). The main aim of the controller is to reduce the error signal to exactly zero concerning time. The performance parameters of the control system have a steady-state, stability, and transient response. The transient response is calculated using rise time, delay time, peak time, settling time, overshoot, and error characteristics.

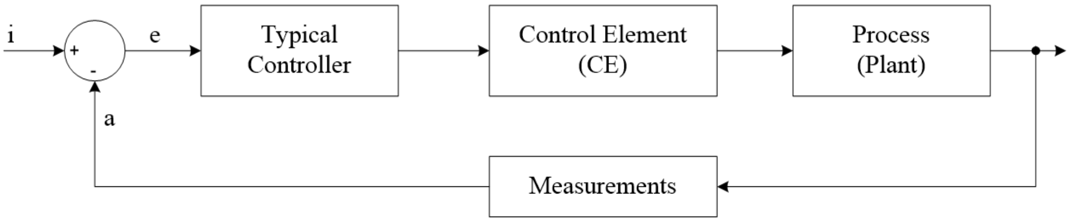


Figure 1. An overview of automatic process control system

Most controllers are designed for gas turbines, ETC applications and not particularly for the compressor system. Very few approaches are considered for the compressor system with lags of performance constraints like robustness, Stability, control response, and error responses issues. The proposed approach is used to improve the aforementioned issues, using a hybrid control mechanism and suitable to use further in a particular compressor system. In this manuscript, an efficient PI and PD-based fuzzy logic controller is modeled for compressor applications. This section explains the review of existing approaches towards different controllers for different applications with limitations. Section 2 describes the controlling strategies using PI/PD based FLC with gain scheduling. The discussion of simulation results with performance metrics realization is carried in Section 3. Finally, the overall work is concluded in Section 4 with future work.

This section elaborates on the existing approaches of the different processes using different controlling techniques with their limitations. Ahmad *et al.* [15] present the mixed fuzzy logic control method to track a flexible-joint manipulator’s trajectory and vibration control. The tip angular position control is calculated using PD-based FLC. Additionally, the non-collocated PD-based FLC module is modeled for vibration reduction of the flexible joint system with a suitable input scheme. The reduction of deflection angle for vibration and time response of angular tip position are analyzed with suitable parameters. Kozák [16] elaborates on the different controlling techniques from PID to model predictive control (MPC). The PID controller's usage in today and the future, PID tuning methods, gain scheduling methods, fuzzy-based PID methods, advanced neural network-based PID method, and hardware realization of tuning methods and their drawbacks are explained. The MPC modeling, classification, and analysis with field programmable gate array (FPGA) hardware are discussed. Liying *et al.* [17] examine the electronic throttle valve (ETC) compensation control method to improve the tracking realization. The non-linear compensation control system includes PI-controller, ETC, and the pulse width modulation (PWM) position system.

Pan *et al.* [18] present the adaptive fuzzy H^{∞} tracking control (AFHC) model for guaranteed stable tracking using PD-FLC than the sliding mode control (SMC) approach. The work analyzes the tracking performance of two controllers. The existing AFHC methods are overcome with the AFHC module incorporating the SMC. The neuro-fuzzy controller is designed for heavy-duty gas turbine plants by Iqbal *et al.* [19] to overcome load fluctuations and set-point variations. The response of different modules is analyzed using FLC and neural network controller. These controllers are acts as a speed controller in the turbine plant. Pezzetti *et al.* [20] present different controlling methods for the helium cryogenic warm compressor station to improve the transient and setup requirements. The control techniques include PID, FLC, and internal model control (IMC) techniques are used in cryogenic systems to check the high and low-pressure control variations. The ETC module is designed using the fuzzy sliding-mode controller (SMC) by Bai *et al.* [21], which includes mathematical modeling of regular and fuzzy sliding mode controller of ETC and simulation analysis of the plate angle and desired angle of the valve plate. Similarly, Yadav *et al.* [22] designed an Intelligent ETC system using different controllers like PID, SMC-based PD, and FLC. The fuzzy based PID gives better Overshoot and settling time than other approaches.

The optimal speed control for Hybrid electric vehicles is designed by Saeed *et al.* [23] using different controllers like PID, pole placement (PP), state observer-based (OB), and linear-quadratic regular (LQR) based controllers. Electric vehicles analyze the speed control process using stability factors, observability, and controllability factors. Chao *et al.* [24] describe the comparative analysis of fuzzy-PID over conventional PID controllers with constraints improvements. The optimized PID-based FLC for the higher-order control system is designed by Bharti *et al.* [25]. The work analyzes the response of the plant system using different controllers and also tabulate the performance metrics. The fractional-PID based FLC is designed by Barbosa *et al.* [26]. This hybrid controller is fine-tuned with the help of a genetic algorithm to improve the performance of the non-linear system. Somwanshi *et al.* [27] explain the speed control of DC motor in LabView and analyze the fuzzy-PID and typical PID controller results with response time.

Prayitno *et al.* [28] explain the fuzzy gain scheduling approach for the position of the drone system using a PID controller. The PID controller acts as the central controller of the drone system, which controls the throttle, roll, and pitch. The three PID controllers are tuned by the scheduler and calculated by the fuzzy logic module. The control response, square shape experiments, control signal waveforms (throttle, roll, and pitch) are discussed in detail for the drone system. Shah *et al.* [29] present the PID-based temperature control system are implemented for an electric kettle. The temperature control system includes PID and bang-bang controllers, followed by a driver circuit (solid-state relay), heater, and electric kettle. The temperature control system is implemented on microcontroller and connected to an electric kettle via computer. The water temperature response inside the electric kettle at different degrees celsius are analyzed using PID controller. Prabhakar *et al.* [30] present the non-linear adaptive cruise control system using fuzzy PD plus I controller to provide set-point tracking performance with adaptive features. The fuzzy-based PD controller provides better servo performance and solves the regulatory issues by integrating the integral (I) controller in the cruise control system. Khamari *et al.* [31] present the hybrid fuzzy PD-PI controller with a modified moth swarm algorithm (MMSA) is modeled for an electric vehicle system. The MMSA is used to provide the solution for distributed power generation system with frequency control features. The present work better frequency control mechanism than the existing similar approach for distributed power generation systems. Tran *et al.* [32] describe the fuzzy gain scheduling (FGS) control system for remote control hovercraft. The FCS approach is used for tuning the PID controller by scheduling the controlled gains. The PID controller outputs are used in hovercraft motion to analyze the surge, sway, and steering yaw control responses. Zhang *et al.* [33] present a reconfigurable adaptive control technique for a cabin pressure control system (CPCS). The control technique is used to compensate for the faults in sensors and actuators in CPCS. The control system works with a closed-loop structure, improving the stability and updating the online faults without using the identification process. Urrea *et al.* [34] discuss the different control strategies for robotic arm systems using a multi-level inverter. The control strategies like the gain scheduling approach with trenches and interpolation, fuzzy logic with adaptive control mechanisms are used to find a robotic arm's position with high-frequency reduction.

2. PROPOSED CONTROLLING STRATEGIES

The conventional controller's overview, fuzzy logic controller design model, and hybrid controller strategies with a gain scheduling approach are discussed in this section in detail.

2.1. Conventional controllers

The conventional PID controllers are mainly used in many industrial controlling applications because of their robust performance, smooth operation, and simplicity. The PD/PID controllers are suitable and adopted in lower and second-order control systems. For tuning the P, I, and D constant values, the Ziegler-Nichols (Z-N) method is used. The tuned values are considered for PD/PID controllers. PD and PID are considered for process control operations by tuning the KP, KI, and KD constants in the design work. The typical compressor system (process) and its transfer function are considered for different controller designs to improve the efficiency of the process. The transfer function of the compressor plant (process) is represented in (1).

$$G(s) = \frac{1}{s^3+3s^2+3s+1} \quad (1)$$

The fuzzy logic controller using the gain scheduling approach is used to improve the controller performance parameters. The hybrid approach of PI and PD-based FLC controller is designed in this next section to overcome the conventional controller's control parameters.

2.2. Fuzzy logic controller (FLC)

Fuzzy logic is a logical system and is controlled by fuzzy control. the fuzzy logic controller (FLC) is one of the best solutions for industrial control applications. The FLC achieves better performance metrics than conventional PID controllers. The FLC has many advantages over other controllers includes easy to understand; it can be tolerant of the indistinct data values. The FLC has five significant components along with the plant, namely, fuzzification, knowledgebase (Database), evaluation, ruleset, and defuzzification are represented in Figure 2. Fuzzification is a process of converting crisp (absolute) value to linguistic (fuzzy) value. The fuzzification receives the PI/PID controller's data values as crisp inputs into fuzzy systems (variables). The fuzzy variables are noticed by linguistic values, which are subsets or fuzzy sets. The fuzzy sets are addressed by membership functions, including oversized, small, low, and high. The rule evaluation makes the decision logic to control the fuzzy rule stored by the rule base. The rule base is essential for process performance improvements. The basic fuzzy set with AND, OR, and NOT are used to evaluate fuzzy rules. Defuzzification is the reverse operation of fuzzification, which is used to convert fuzzy values to crisp values. The knowledge-base has been used to stores the fuzzy set membership functions of the fuzzifier and defuzzifier.

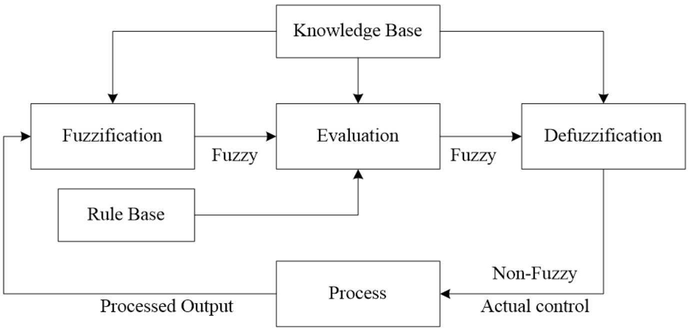


Figure 2. FLC configuration with process

2.2.1. Fuzzy variables

The fuzzy interface system (FIS) is designed for FLC using Mamdani in Simulink. The first and second input variables of the FLC is defined as (2) and (3):

$$E(i) = S_{ref} - G(s) \quad (2)$$

$$CE(i) = E(i) - E(i-1) \quad (3)$$

where i=1 to 7, S_{ref} is Step input, G(s) transfer function output, E(i-1) is previous error input with derivation (D) or integration (I) for PD-FLC and PD-FLC system. The difference between the step input and transfer function Plant output gives the error value of the controller.

2.2.2. Membership functions

The error (E), change in error (CE), and FLC output (O) are normalized to the display range [-1 to 1] using a set of fuzzy membership functions for the given universe of discourse. The E and CE use a combination of triangular shaped and Trapezoidal shaped membership functions. In contrast, FLC output (O) uses only triangular-shaped membership functions. The hybrid combination of the membership function improves the robustness, control response, less steady-state Error, and less overshoot time for the given system. The rule-base is activated effectively based on the FLC inputs within the universe of discourse. The seven fuzzy (linguistic) variables (FV) are used as E and CE, which includes negative big (NB), positive big (PB), negative medium (NM), positive medium (PM), negative small (NS), positive small (PS), and zero (ZO). The decision logic is evaluated with the human knowledge base into a fuzzy set by fuzzy rules. The FIS has the membership function, which includes E, CE are input variables, and output (O) variables are represented in Figures 3(a) to (c). The 3D surface viewpoint of the PI and PD-FLC controller's E and CE membership function is illustrated in Figure 3(d).

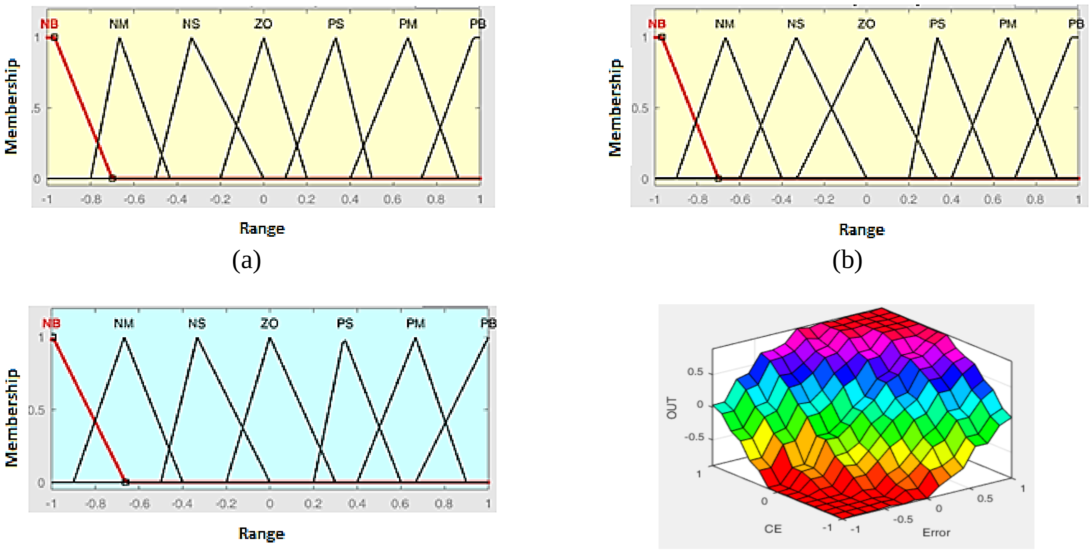
2.2.3. Fuzzy rules

To design the rule base, The fuzzy rules are categorized into seven basic fuzzy sets and are: Error input E(i): {NB, NM, NS, ZO, PS, PM, PB}, Change in error input CE(i)={NB, NM, NS, ZO, PS, PM, PB} and FLC output O(i)={NB, NM, NS, ZO, PS, PM, PB}. The fuzzy rule set for the compressor plant is tabulated in Table 1. The E, CE, The Mamdani fuzzy interface system (FIS) are used in the current FLC design. The fuzzy variables PS, PM, and PB are in the range of [0, 1], ZO is the range of [-0.2 to 0.2], and NB, NM, and NS are in the range of [-1 to 0] under the universe of discourse. Based on the display range, the big and small inputs are categorized in rule set inference.

There are 49 rules used for two inputs (E and CE) with 7 fuzzy variables. The fuzzy rules are framed by analyzing the PD/PID controller performance by tuning the controller constants. The n^{th}-order rule base (R) for the given FLC with two inputs (E and CE) is shown in (4):

$$\text{Rn: IF (error is E(i)) AND (Change in Error is CE(i)) then (FLC output is O(i)} \tag{4}$$

where n is set to 1, 2, …N_{max} for the n^{th} fuzzy rule set. E(i), CE(i), and O(i)=1,2,3,4,5,6,7 are basic fuzzy rule sets. The 49 rules are used in the rule base, which converts the two inputs to a single output. Finally, the fuzzification outputs in the ruleset are transformed into the crisp output format using the centroid method in the de-fuzzification process.



(a) (b)

(c) (d)

Figure 3. Membership functions plots for error, change error (CE), output variables, and surface view of FLC (a) FLC error input, (b) FLC change in error input, (c) FLC output, and (d) surface view of FLC

Table 1. The fuzzy rule set for the compressor plant

Output		Error (E)						
		NB	NM	NS	ZO	PS	PM	PB
Change in Error (CE)	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	-ZO	PS	PM	PB	PB
	PM	NS	ZO	-PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

2.3. PI/PD based FLC with gain scheduling approach

Gain scheduling (GS) is a process of monitoring the plant's operating conditions by simply changing the controller's parameters. It is mainly used to assist changes in plant gain. The GS provides a non-linear feedback signal and has a linear controller, which monitors the operating conditions in a pre-programmed way. Thus, the GS is used to compensate for the known non-linearities and significant parameter changes of the plant. In general, The GS provides linearization for non-linear processes, measurement of auxiliary variables, and non-linear transformations. In this work, The PI/PD-based fuzzy logic controller (FLC) with gain scheduling for a compressor plant is represented in Figure 4. The design includes Step input, PI/PD-based controller followed by FLC with gain scheduling, non-linear valve, and process.

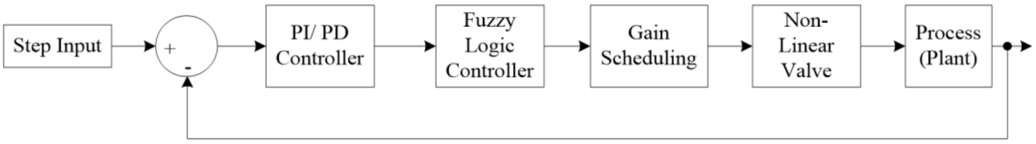


Figure 4. Modeling of PI/PD based FLC with gain scheduling (GS)

The FLC controller output is fed through the gain scheduling approach to compensate for non-linearity before being applied to the non-linear valve and process. The non-linear valve is assumed to have u^2, and it is greater than zero. The gain scheduling with 2-line segments (a, b) are used to compensate the non-linearity of the valve and Plant, and it is represented in the (5) and (6):

$$b = 0.433a \qquad ; 0 < a < 3 \tag{5}$$

$$b = 0.0538a + 1.158 \qquad ; 3 < a < 10 \tag{6}$$

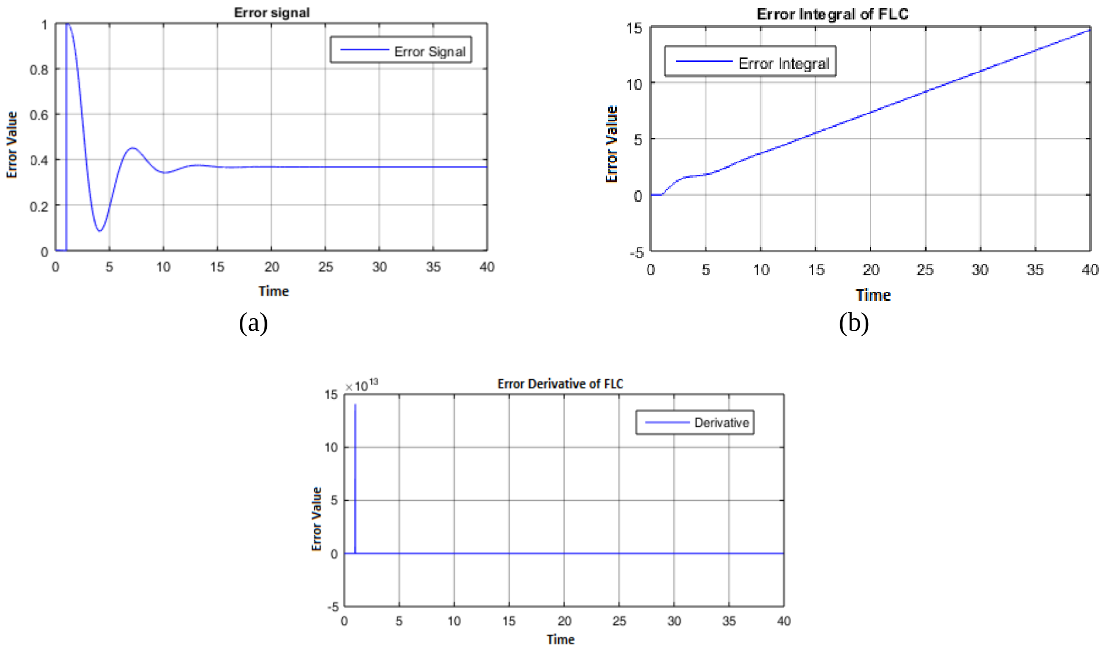
The 2-line segments (a and b) are lies in between a=0 and a=10. Therefore, to reduce the non-linearity of the Plant, increase the line segments in gain scheduling.

3. RESULTS AND DISCUSSION

The PI and PD-based FLC models are designed using a gain scheduling approach for the compressor system. The work is carried out using the MATLAB Simulink environment. The simulation results of both PI and PD-based FLC without and with gain scheduling approach are represented. The Performance parameters for the same are discussed in detail. The PI-FLC model generates the error signal, and the error integral is represented in Figures 5(a) and 6(b) and Figures 6(a) and 6(b), respectively, for without and with gain scheduling. Similarly, the error derivative is generated by PD-FLC is represented in Figures 5(c) and 6(c), respectively, for without and with gain scheduling.

The conventional PD and PID controllers and PI-FLC and PD-FLC's control output response are compared without and with gain scheduling represented in Figures 7(a) and 7(b). The step time is set to 1 as an input to the controller and followed by a process. The output response is controlled by feedback PI-FLC and PD-FLC controllers and is working based on the operation of the compressor system. The system output rises at 1.48 sec and 4.26 sec for PI-FLC and PD-FLC without GS, respectively. The PI-FLC output response settles at 12.24 sec, and similarly, PD-FLC takes a 9.4 sec settling time. Thus, the PD-FLC output response without GS has less overshoot than the conventional PD and PID controller. The system output rises at

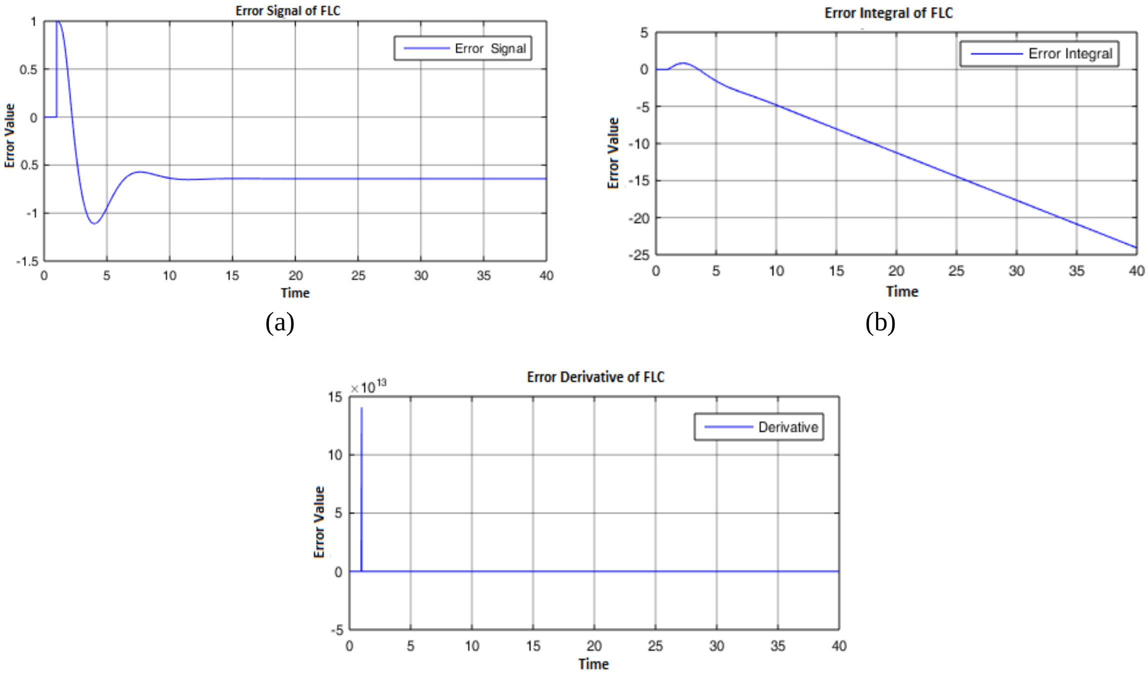
1.475 sec and 4.19 sec for PI-FLC and PD-FLC with GS, respectively. The PI-FLC output response settles at 10.07 sec, and similarly, for PD-FLC takes a 9.27 sec settling time. The PD-FLC with-GS output response has less overshoot than the PI-FLC and conventional PD, PID controller with-GS. The PD-FLC with GS gives better control response output than other controllers.



(a) (b)

(c)

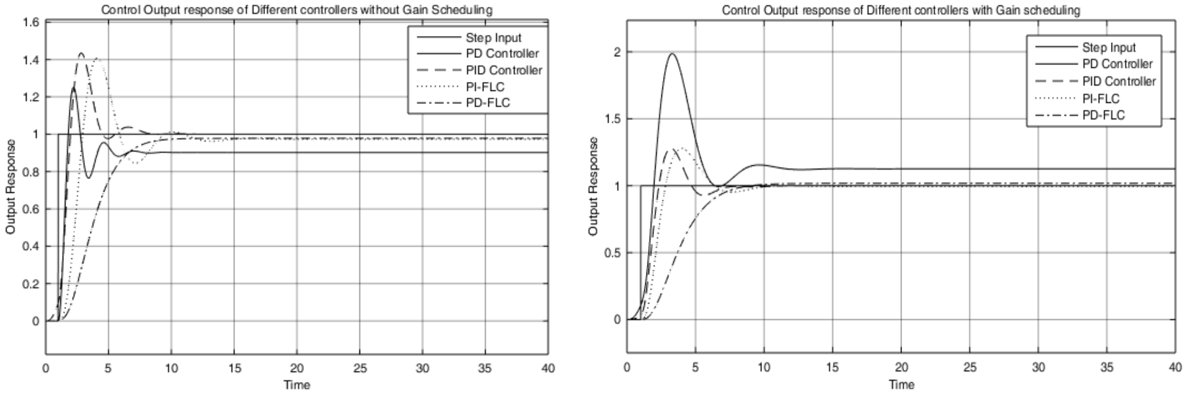
Figure 5. Error signal generation using of FLC controller-without gain scheduling (a) error signal, (b) error integral, and (c) error derivative



(a) (b)

(c)

Figure 6. Error signal generation using of FLC controller-with gain scheduling, (a) error signal, (b) error integral, and (c) error derivative



(a) (b)

Figure 7. Comparison of control output response of different controllers (a) without gain scheduling and (b) with gain scheduling

The different performance parameters, like rising time (RT), settling time (ST), maximum overshoot (OS), peak value, and peak time, is calculated based on the control response output of different controllers without and with GS are tabulated in Table 2. The fuzzy logic Based controllers with GS has less overshoot than conventional PID controllers with and without GS. On the other hand, the Peak time is relatively high in the FLC controller than the PID controller because of the process (plant) transfer function. The PI-based FLC and PD-based FLC with Gain scheduling approach consume less overshoot time of 35.6% and 74%, respectively, than the PI-based FLC and PD-based FLC without gain scheduling approach.

Table 2. Performance analysis of output response using different controllers

Parameters	Controllers without Gain Scheduling				Controllers with Gain Scheduling			
	PD	PID	PI-FLC	PD-FLC	PD	PID	PI-FLC	PD-FLC
Rise Time (RT)	0.6	0.85	1.48	4.26	1.12	1.2	1.475	4.19
Settling Time (ST)	7.01	8.47	12.24	9.4	9.64	7.97	10.07	9.27
% Overshoot (OS)	31.61	42.1	44.36	0.014	61.74	26.6	28.53	0.0036
Peak Time (PT)	3	4	5	19	5	4	5	15
Peak Value	1.18	1.42	1.4	0.97	1.84	1.2	1.27	1

The error analysis regarding simulation time for the control response output using different controllers with and without gain scheduling is tabulated in Table 3. The error analysis includes integral time absolute error (ITAE), integral absolute error (IAE), and integral square error (ISE) parameters. The different controllers with a gain scheduling approach utilize fewer error responses than the different controllers without a gain scheduling approach. The error response of PD-based FLC with the gain scheduling approach improves 7.9% in ITAE, 7.4% in IAE, and 16% in ISE than PD-based FLC without gain scheduling approach.

Table 3. Error analysis of the output response using different controllers

Parameters	Controllers without Gain Scheduling				Controllers with Gain Scheduling			
	PD	PID	PI-FLC	PD-FLC	PD	PID	PI-FLC	PD-FLC
ITAE	79.21	3.12	2.935	17.54	10.65	0.338	5.157	16.15
IAE	4.335	1.23	0.147	0.85	0.6972	0.129	0.257	0.787
ISE	0.7671	0.544	6.06E-03	0.018	0.0026	0.0063	0.0018	0.015

4. CONCLUSION AND FUTURE WORK

In this manuscript, The PI/PD-based fuzzy logic controller using the gain scheduling approach is designed to improve performance constraints for the compressor plant. The PI/PD based fuzzy logic controller has a compressor plant with a closed-loop system, The PI-based FLC receives P and I constant as inputs, and similarly, PD-FLC receives P and D constants as an input to the fuzzy system and based on the Fuzzy rule set, the system output is obtained. The conventional PD/PID controller is also designed for comparison purposes. A control output response, controller output, and error signal output are also represented for all the controllers without gain scheduling. The PI/PD-FLC with GS has less overshoot, better rise time, settling time, and better error response than the conventional PID controllers with and with GS. In the future, Performance constraints are still improved by using artificial neural networks (ANN) for compressor systems.

REFERENCES

[1] S. Budinis and N. F. Thornhill, "Supercritical fluid recycle for surge control of CO2 centrifugal compressors," *Computers and Chemical Engineering*, vol. 91, pp. 329–342, Aug. 2016, doi: 10.1016/j.compchemeng.2016.03.012.

[2] B. Chetate, R. Zamoum, A. Fegriche, and M. Boumdin, "PID and novel approach of PI fuzzy logic controllers for active surge in centrifugal compressor," *Arabian Journal for Science and Engineering*, vol. 38, no. 6, pp. 1405–1414, Jun. 2013, doi: 10.1007/s13369-013-0601-6.

[3] G. A. Chandak and A. A. Bhole, "A review on regenerative braking in electric vehicle," in *2017 Innovations in Power and Advanced Computing Technologies (i-PACT)*, Apr. 2017, pp. 1–5, doi: 10.1109/IPACT.2017.8245098.

[4] L. dos Santos Coelho and A. A. R. Coelho, "An experimental and comparative study of fuzzy PID controller structures," in *Advances in Soft Computing*, London: Springer London, 1999, pp. 147–159.

[5] A. Hafaifa, F. Laaouad, and K. Laroussi, "Fuzzy modeling and control for detection and isolation of surge in industrial centrifugal compressors," *Journal of Automatic Control*, vol. 19, no. 1, pp. 19–26, 2009, doi: 10.2298/JAC0901019H.

[6] R. Ganguli, "Fuzzy logic intelligent system for gas turbine module and system fault isolation," *Journal of Propulsion and Power*, vol. 18, no. 2, pp. 440–447, Mar. 2002, doi: 10.2514/2.5953.

[7] W. Gritli, H. Gharsallaoui, and M. Benrejeb, "PID-type fuzzy scaling factors tuning using genetic algorithm and simulink design optimization for electronic throttle valve," in *2016 International Conference on Control, Decision and Information Technologies (CoDIT)*, Apr. 2016, pp. 216–221, doi: 10.1109/CoDIT.2016.7593563.

[8] H. Nasution, K. Sumeru, A. A. Aziz, and M. Y. Senawi, "Experimental study of air conditioning control system for building energy saving," *Energy Procedia*, vol. 61, pp. 63–66, 2014, doi: 10.1016/j.egypro.2014.11.907.

[9] I. Dimeas, C. Psychalinos, A. Elwakil, and A. Tepljakov, "OTA-C realization of PI λ brake and throttle controllers for autonomous vehicles," in *2017 European Conference on Circuit Theory and Design (ECCTD)*, Sep. 2017, pp. 1–4, doi: 10.1109/ECCTD.2017.8093229.

[10] A. Jansri, M. Chatpoj, T. Phatrapornnant, and P. Sooraksa, "Fuzzy strategy with overshoot suppressor for electronic throttle control," in *2016 7th International Conference of Information and Communication Technology for Embedded Systems (IC-ICTES)*, Mar. 2016, pp. 36–40, doi: 10.1109/ICTEmSys.2016.7467118.

[11] R. Tipsuwanpom, T. Runghimmawan, S. Intajag, and V. Krongratana, "Fuzzy logic PID controller based on FPGA for process control," in *2004 IEEE International Symposium on Industrial Electronics*, 2004, pp. 1495–1500 vol. 2, doi: 10.1109/ISIE.2004.1572035.

[12] N. A. Sofianos and Y. S. Boutalis, "Stable indirect adaptive switching control for fuzzy dynamical systems based on T–S multiple models," *International Journal of Systems Science*, vol. 44, no. 8, pp. 1546–1565, Aug. 2013, doi: 10.1080/00207721.2012.659697.

[13] Q. Zhou, H. Li, C. Wu, L. Wang, and C. K. Ahn, "Adaptive fuzzy control of nonlinear systems with unmodeled dynamics and input saturation using small-gain approach," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 8, pp. 1979–1989, Aug. 2017, doi: 10.1109/TSMC.2016.2586108.

[14] N. A. Sofianos and Y. S. Boutalis, "Robust adaptive multiple models based fuzzy control of nonlinear systems," *Neurocomputing*, vol. 173, pp. 1733–1742, Jan. 2016, doi: 10.1016/j.neucom.2015.09.047.

[15] M. A. Ahmad, M. Z. M. Tumari, and A. N. K. Nasir, "Composite fuzzy logic control approach to a flexible joint manipulator," *International Journal of Advanced Robotic Systems*, vol. 10, no. 1, Jan. 2013, Art. no. 58, doi: 10.5772/52562.

[16] S. Kozak, "From PID to MPC: Control engineering methods development and applications," in *2016 Cybernetics and Informatics (K&I)*, Feb. 2016, pp. 1–7, doi: 10.1109/CYBERI.2016.7438634.

[17] Z. Liying, X. Ting, L. Xuejun, L. Liyan, G. Pan, and Z. Yubao, "Study on nonlinear compensation control method for electronic throttle valve," in *2018 Chinese Automation Congress (CAC)*, Nov. 2018, pp. 1085–1089, doi: 10.1109/CAC.2018.8623743.

[18] Y. Pan, M. J. Er, T. Sun, B. Xu, and H. Yu, "Adaptive fuzzy PD control with stable H ∞ tracking guarantee," *Neurocomputing*, vol. 237, pp. 71–78, May 2017, doi: 10.1016/j.neucom.2016.08.091.

[19] M. M. Mohamed Iqbal, R. Joseph Xavier, and J. Kanakaraj, "A neuro-fuzzy controller for grid-connected heavy-duty gas turbine power plants," *Turkish journal of electrical engineering and computer sciences*, vol. 25, pp. 2375–2387, 2017, doi: 10.3906/elk-1511-242.

[20] M. Pezzetti, C. V. M. Garcia, B. Bradu, and E. Rogez, "Overview of different control strategies for a typical cryogenic warm compressor station at CERN," *IOP Conference Series: Materials Science and Engineering*, vol. 278, Dec. 2017, Art. no. 012079, doi: 10.1088/1757-899X/278/1/012079.

[21] R. Bai, Y. Liu, and S. Wang, "Fuzzy sliding-mode control of the electronic throttle system," in *Proceeding of the 11th World Congress on Intelligent Control and Automation*, Jun. 2014, pp. 747–750, doi: 10.1109/WCICA.2014.7052808.

[22] A. K. Yadav, P. Gaur, and S. Tripathi, "Design and control of an intelligent electronic throttle control system," in *2015 International Conference on Energy Economics and Environment (ICEEE)*, Mar. 2015, pp. 1–5, doi: 10.1109/EnergyEconomics.2015.7235119.

[23] M. A. Saeed, N. Ahmed, M. Hussain, and A. Jafar, "A comparative study of controllers for optimal speed control of hybrid electric vehicle," in *2016 International Conference on Intelligent Systems Engineering (ICISE)*, Jan. 2016, pp. 1–4, doi: 10.1109/INTELSE.2016.7475142.

[24] C.-T. Chao, N. Sutarna, J.-S. Chiou, and C.-J. Wang, "Equivalence between fuzzy PID controllers and conventional PID controllers," *Applied Sciences*, vol. 7, no. 6, Art. no. 513, Jun. 2017, doi: 10.3390/app7060513.

[25] R. Bharti, R. Trivedi, and P. K. Padhy, "Design of optimized PID type fuzzy logic controller for higher order system," in *2018 5th International Conference on Signal Processing and Integrated Networks (SPIN)*, Feb. 2018, pp. 760–764, doi: 10.1109/SPIN.2018.8474202.

[26] R. S. Barbosa and I. S. Jesus, "Fuzzy algorithms for fractional PID control systems," in *Hybrid Intelligent Systems*, Springer International Publishing, 2020, pp. 428–437.

[27] D. Somwanshi, M. Bundele, G. Kumar, and G. Parashar, "Comparison of fuzzy-PID and PID controller for speed control of DC

motor using LabVIEW," *Procedia Computer Science*, vol. 152, pp. 252–260, 2019, doi: 10.1016/j.procs.2019.05.019.

[28] A. Prayitno, V. Indrawati, and I. I. Trusulaw, "Fuzzy gain scheduling PID control for position of the AR.Drone," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 4, pp. 1939–1946, Aug. 2018, doi: 10.11591/ijece.v8i4.pp1939-1946.

[29] M. B. N. Shah *et al.*, "PID-based temperature control device for electric kettle," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 3, pp. 1683–1693, Jun. 2019, doi: 10.11591/ijece.v9i3.pp1683-1693.

[30] G. Prabhakar, S. Selvaperumal, and P. Nedumal Pugazhenthi, "Fuzzy PD plus i control-based adaptive cruise control system in simulation and real-time environment," *IETE Journal of Research*, vol. 65, no. 1, pp. 69–79, Jan. 2019, doi: 10.1080/03772063.2017.1407269.

[31] D. Khamari, R. K. Sahu, and S. Panda, "A modified moth swarm algorithm-based hybrid fuzzy PD-PI controller for frequency regulation of distributed power generation system with electric vehicle," *Journal of Control, Automation and Electrical Systems*, vol. 31, no. 3, pp. 675–692, Jun. 2020, doi: 10.1007/s40313-020-00565-0.

[32] H. K. Tran, P. D. Lam, T. T. Trang, X. T. Nguyen, and H.-N. Nguyen, "Fuzzy gain scheduling control apply to an RC Hovercraft," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, pp. 2434–2440, Jun. 2020, doi: 10.11591/ijece.v10i3.pp2434-2440.

[33] Z. Zhang, Z. Yang, S. Xiong, S. Chen, S. Liu, and X. Zhang, "Simple adaptive control-based reconfiguration design of cabin pressure control system," *Complexity*, vol. 2021, pp. 1–16, Mar. 2021, doi: 10.1155/2021/6635571.

[34] C. Urrea and D. Jara, "Design, analysis, and comparison of control strategies for an industrial robotic arm driven by a multi-level inverter," *Symmetry*, vol. 13, no. 1, Art. no. 86, Jan. 2021, doi: 10.3390/sym13010086.

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