International Journal of Advanced Computer Research
ISSN (Print): 2249-7277 ISSN (Online): 2277-7970
Volume-5 Issue-19 June-2015

Investigation of Intelligent Control System for Non-Linear Real Time Pressure Control System

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Received: 03-April-2015; Revised: 26-May-2015; Accepted: 27-May-2015

Abstract

The paper describes a Fuzzy Proportional Integral (PI) controller with Triangular and Gaussian membership functions for controlling pressure in real-time pressure control system having hysteresis error in the control valve. The input scaling factors of controllers are optimized offline by using Genetic Algorithm optimizing technique for minimizing Integral Time Absolute Error on estimated model at specific operating point. The National Instrument based hardware and Matlab/Simulink software have been used for meticulous and perfect pressure measurement, acquisition and control action. The simulation and experimental results of the conventional Proportional–Integral (PI) and Fuzzy PI controllers are analysed. It has been observed that Fuzzy PI controller with Gaussian membership function demonstrate superior set-point tracking performance with minimum overshoot and settling time.

Keywords

Intelligent control techniques, Fuzzy PI controller, Genetic Algorithm, System Identification, Control valve hysteresis, Nonlinearity.

1. Introduction

The classical Proportional, Integral and Derivative (PID) controller has been applied in many process industries. These controllers are still applied in the industries, because of simple structure and based on the fixed gain parameters [1]. The Ziegler-Nicholas (Z-N) tuning rules have dominant to PID controllers. These tuning parameters play a vital role in control action. The parameters gave the best result at the operating point, but have the limitations when the operating range is changed [2-3]. The pneumatic control valves are used as an actuator or final control element in the process industries [4-5]. These control valves show the nonlinearities behaviour because the presence of stiction, dead band, backlash and hysteresis [6-7]. Due to this, it becomes difficult to control the stem movement of the control valve by the conventional PID controller. They need to be returned as parameters change in nonlinear system.

It is desirable to investigate the intelligent controller, which automates the operator task. A Fuzzy Logic technique has been successfully applied in recent years to control the nonlinearity in the various physical processes [8], [9], [10] and [11]. Fuzzy Logic controllers are rule based [12]. The Fuzzy PI controller controls the nonlinear flow through a pneumatic control valve to control the pressure in the pilot pressure tank [13].

Parallel fuzzy proportional plus fuzzy integral plus fuzzy derivative (FP+FI+FD) controller control the highly nonlinear liquid-flow process with a hysteresis characteristic in the pneumatic control valve [14]. The simulation/experiment has been performed on some system (linear/non-linear) and it has been observed that the Fuzzy PI controller performance is preferable than Conventional controller. The fuzzy PI controller has been employed to control the nonlinearity such as hysteresis, backlash, in the Experimental (Physical) system.

In the present work, pneumatic control value of equal percentage characteristics is dominating to control the pressure inside a process tank. The behaviours of control valve are highly nonlinear due to equal percentage characteristics. Conventional controllers (PI, PD, and PID) have limitations to control the nonlinearity in the real-time process system. So, an

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intelligent controller has been used to overcome the nonlinearity in process (experimental) system. A Fuzzy PI controller with Triangular and Gaussian membership functions (MFs) has been applied to control the pressure inside the process tank in the experimental setup. The proposed controller is used to control the pressure at the set level and their real time results are shown by comparing to the traditional PI controller. The gain parameters for conventional and Fuzzy PI controller have been optimized offline by genetic algorithm techniques [15]. National Instrument based hardware has been used for accurate data acquisition. Math Works (MATLAB 2011b) /Simulink software has been used for real time control and controller gain parameters optimization. The paper is organized as follows: Information about experimental setup, Pneumatic control valve's hysteresis error, Transducer and System identification are presented in section 2. Fuzzy PI controller with Triangular and Gaussian membership functions is provided in the section 3. Experimental results of Intelligent and conventional controllers are analysed in section 4. Lastly, conclusions are given in section 5.

2. Experimental Setup

Figure.1 exhibits the block diagram of pressure control system with pneumatic control valve having equal percentage characteristics as an actuator to control the pressure in the plant. The comparator compares the measured value with set value and generates an error. The error is controlled by the controller and produces an output in the range of 0-2.5 volts. The voltage to current (V/I) converter, convert the voltage signal into a current signal of 4-20 mA. The current to pressure (I/P) converter, converts the current signal into pressure signal in the range of 3-15psi.The pressure signal is fed to the diaphragm that convert the pressure signal into a displacement signal and is attached to the stem and plug assembly of control valve.

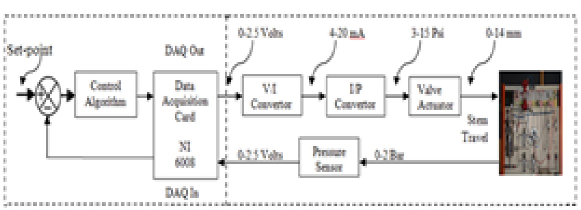

Figure 1: Block diagram of a closed loop pressure control system

2.1 Plant Description

The snapshot of experimental setup of pressure control system is shown in Figure 2. A process tank is incorporated in the experimental system, whose inlet at the bottom is connected to an air compressor through a control valve (V-3) having size of 15mm. A manually operated valve (V-5) is provided at the top of the tank, which can be used to maintain a constant rate of air flow. A piezo-resistive transducer has been used to measure the process tank pressure and provide an output voltage in the range of 0-2.5 volts. To interface the experimental set up with computer a National Instrument (NI-6008) Data Acquisition Card (DAQ) has been used. It is low cost USB type DAQ card having 8 analog inputs and 2 analog outputs channel. The sampling rate is 100 samples per second.

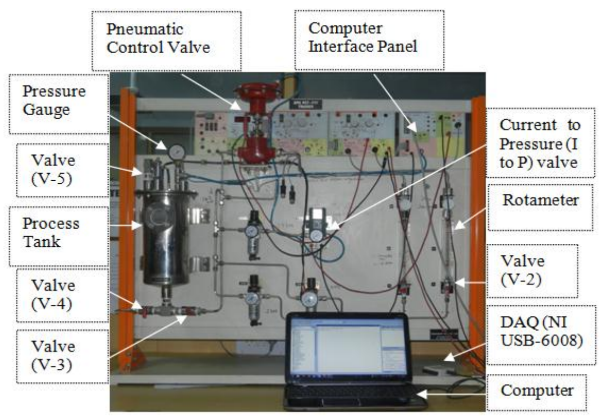

Figure 2: Snapshot of laboratory pressure control setup

2.2 Pneumatic Control Valve

Pneumatic control valve is a device which is used to regulate the pressure throughout the whole process. The equal percentage characteristics control valve is of 0.0125 m (½ inch) port size, 6.0254 m^2 (10 square inch) diaphragm, action-"air-to- close", stroke length 0.014 m (0.551inch), air supply = 137895.1459 Pascal (20 psi) and Valve flow coefficient "C_V" = 0.44. The hysteresis curve of control valve, having the percentage change in controller output and stem position is shown in Figure 3. From the curve it clear that for a controller output forward and backward position of stem movement are not same, it shows the hysteresis curve. The main cause of the hysteresis is the friction between stem and packing of control valve. So, pneumatic control valve makes the system nonlinear and highly complex.

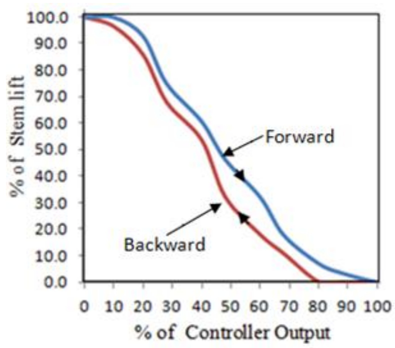

Figure 3: Hysteresis error in control valve

2.3 Transducer

A Piezo-resistive type pressure sensor is used as a transducer to measure pressure in the process control unit. Input range of pressure sensor is 0 to 30 psi, which converts the pressure into an electrical signal in the range of 0 to 2.5 volts. The range of pressure in the process tank is 0 to 2 bars. It is calibrated with the help of a pressure dial gauge as shown in Figure 4. When the pressure at 0 bars the output voltage is 0 volts and at 2 bars the output voltage is 2.5 volts.

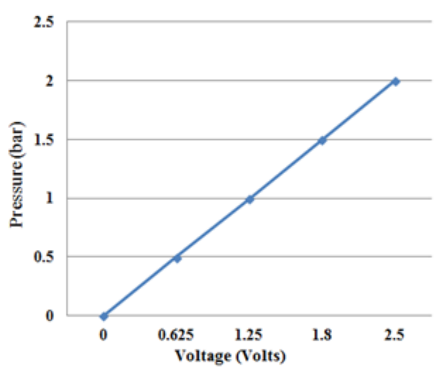

Figure 4: Calibration of pressure sensor with output voltage

2.4 System Identification

The System identification toolkit in Matlab has been used for model estimation of pressure control system. The plant modeling has been done by considering the plant as an open loop system as shown in Figure 5.

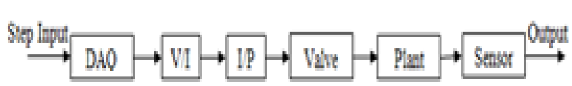

Figure 5: Open loop system of plant

Data for model estimation is taken from an experimental work on the pressure control unit. The plant is excited with 02 volt in an open loop system having sample time 0.01 second. The input (u1) and output (y1) signals obtained from the real data algorithm has been used in the system identification tool kit for getting the accurate modeling of the plant. Based on the output model curve the transfer function from input "u1" for output "y1" is obtained as shown below.

$$\frac{y1(s)}{u1(s)} = \frac{367.854s + 0.49644}{625.029s^2 + 276.477s + 1}$$

3. Fuzzy PI Controller

In the time domain, conventional PI controller is described by

$$u_{PI}(t) = K_C e(t) + K_I \int e(t)dt \qquad (1)$$

Where e(t) is the error signal, $u_{PI}(t)$ is the output of conventional PI controller, K_C is the proportional constant and K_I is the integral constant.
In velocity form, the “(1)” can be represented as

$$\frac{du_{PI}(t)}{dt} = K_C \frac{de(t)}{dt} + K_I e(t) \qquad (2)$$

In discrete form,

$$\frac{u_{PI}(k) - u_{PI}(k-1)}{T} = K_C \frac{e(k) - e(k-1)}{T} + K_I e(k) \qquad (3)$$

where, T is sampling time. Further, the “(3)” becomes

$$\Delta u_{PI}(k) = K_C r(k) + K_I e(k) \qquad (4)$$

where, $r(k) = \frac{e(k)-e(k-1)}{T}$ (5)

and, $\Delta u_{PI}(k) = \frac{u_{PI}(k)-u_{PI}(k-1)}{T}$ (6)

$r(k)$ is the rate of change of the error and $\Delta u_{PI}(k)$ is the incremental output of the discrete PI controller. The Fuzzy PI controller is designed based on “(4)”. Input to the Fuzzy PI controller are error signal ‘$K_I e(k)$’ and rate of change of the error ‘$K_C r(k)$’and the corresponding control action is ‘$\Delta u_{PI}(k)$’.
Rewriting “(5)” and “(6)”, for implementation of the Fuzzy PI controller

$$r(k) = \frac{(1-z^{-1})}{T} e(k) \qquad (7)$$

$$u_{PI}(k) = \frac{T}{(1-z^{-1})} \Delta u_{PI}(k) \qquad (8)$$

The term ‘$T\Delta u_{PI}(k)$’ is replaced by ‘$K_{UPI}\Delta u_{PI}(k)$’. Thus, “(8)” becomes

$$u_{PI}(k) = \frac{K_{UPI}}{(1-z^{-1})} \Delta u_{PI}(k) \qquad (9)$$

where K_{UPI} is the gain of the output of the fuzzy PI controller. It is introduced to increase the degree of freedom of the Fuzzy PI controller.

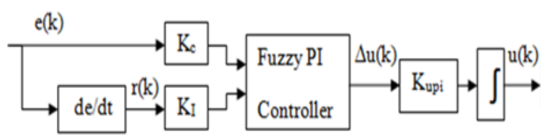

Figure 6: Block diagram of Fuzzy PI controller

Figure 6. Shows the block diagram of pressure control system with the Fuzzy PI controller. Where e(k), r(k) is the error and rate of change of error. Kc, K_I and Kupi are gain parameters of Fuzzy PI Controller. When the pressure in the process tank is measured by the pressure sensor, it is compared with the set pressure. As a result the error e(k) and rate of change of error r(k) will be got; these are the input parameters of Fuzzy PI controllers. In order to minimize the output error, the Fuzzy gain factors Kc, K_I and Kupi are tuned by Genetic Algorithm (GA) optimization technique. The output of the controller varies between -100 to 100 in Matlab/Simulink and is mapped between values of 0 to 2.5 volts. At 0 volts, the valve is in a fully open state having the air pressure across valve diaphragm has a minimum value (3 psi) and at 2.5 volts, the valve is in an approximately shut state having air pressure has the maximum value (15 psi).

3.1 Fuzzification

Fuzzy PI controllers with Gaussian and Triangular membership functions (MFs) are applied to pressure control system. The universe of discourse of each input and output variables to be within range of (-1, 1). For the sake of simplicity, a simple rule based controller is considered which employs only three values of the variables error e(k), rate of change of error r(k) and output Δu(k). Negative (N), Zero (Z), Positive (P) are the linguistic variables for error (e) and rate of change of error r(k) and output Δu(k). Figures 7 & 8 shows the Triangular and Gaussian membership function, for error (e), rate of change error r(k) and output ΔuPI(k). The Triangular MFs are simple; whereas the Gaussian MFs are smooth and none zeroes at all the operating point.

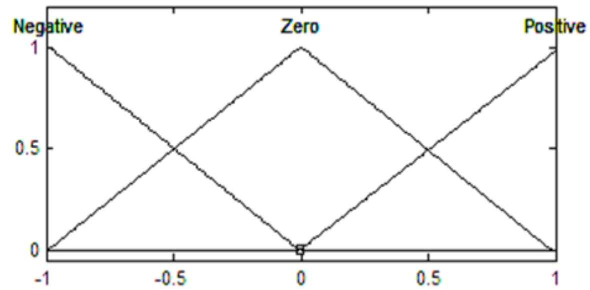

Figure 7: Triangular membership function (MFs) for e(k), r(*k*) and Δu(k)

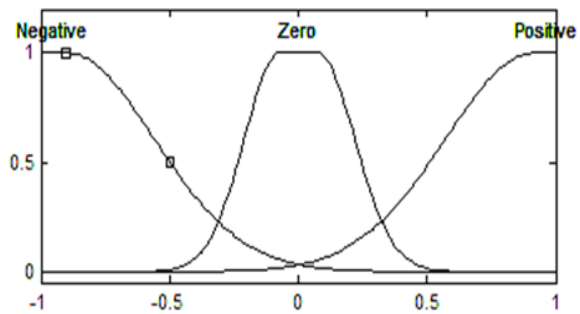

Figure 8: Gaussian membership function (MFs) for e(k), r(*k*) and Δu(k)

3.2 Rule Base

The rules are defined on the basis of process reaction curve [16]. The structures of the control rules of the Fuzzy PI controller have two inputs and one output. The rows and columns represent the linguistic values of error e(k) and rate of change of error r(k) as shown in table 1. The intersection of the first row and first column represents the following rule as;

IF e(k) is Negative and r(k) is Negative THEN output Δu(k) is Negative.

A negative error e(k) implies that controller output Δu(k) above the set-point. If the rate of change of error r(k) is negative at the same time, it means that controller output Δu(k) is moving away from set point. Thus a negative change of controller action Δu(k) is required to reverse this effect. Similarly, other nine rules are defined as shown in Table 1. In the present work, Mamdani inference mechanism has been used because of simple min–max structure. The defuzzification has been done by centroid method

Table 1: Fuzzy Rule

Error, e(k)	Change of error, r(k) N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

4. Experimental and Computer Simulation Results

Simulation and Real time experiments have been conducted in the Matlab/Simulink software. The operating point is kept of a value 1.5 bars, sampling time 0.01 second and ODE4 (Runge Kutta) as an ordinary differential solver. Genetic Algorithm (GA) optimization technique has been applied for getting the gain parameters of conventional and Fuzzy PI controllers. The tuning has been done offline in Matlab environment. The performance of index (PI) is Integral Time Absolute Error (ITAE). The creation, selection, mutation and crossover functions are uniform, tournament, adaptive feasible and arithmetic in GA optimization. The optimized parameters of controllers have been shown in Table 2. The tuning parameters obtained during the simulation have been applied in the simulation and real time. Simulation and Real time experiments have been conducted in process control system by conventional and the Fuzzy PI controller with Gaussian and Triangular membership functions and results are compared. The simulation and experimental output responses of conventional and Fuzzy PI controllers with a set pressure level of 1.5 bars are shown in Figures 9, 10, 11, 12, 13, 14, 15 and 16.

Table 2: Optimize Parameters of Controllers

S. No	Types of Controller	K_C	K_I	K_{upi}
1	Conventional PI	16.98	19.61	
2	Fuzzy PI Triangular MF's	2	400	2.5
3	Fuzzy PI Gaussian MF's	2.35	450	2.45

4.1 Conventional PI Controller Response

The optimized conventional PI controller parameters have been applied to the real time in the plant and estimated model in the Matlab/Simulink. The simulation and real time response of Z-N and GA optimized conventional PI controller are shown in Figures 9, 10, 11 and 12. The dotted line shows the set value of pressure at 1.5 bars and continuous line represents the output of the system with respect to time.

The Z-N tuning method has been applied in the experimental setup to obtain the tuning parameters of conventional PI controller. The value of ultimate gain K_u and oscillation period T_u is obtained by setting the integral and derivative gain to zero. The value of proportional gain K_I is then increased (from zero) until it reaches the ultimate gain K_u. The value of K_u and T_u are obtained as 30 and 01 second.

On the basis of the values of K_u and T_u the gain parameters of Z-N PI Controller are obtained as; K_I = 13.5, K_C = 26. These gain parameters are applied at the set pressure of 1.5 bars. The simulation result shows the rise time 0.4 second, settling time 3 second, overshoot 5% and real time result shows rise time 10 second, settling time 53 second, overshot 36% as shown in Figures 9 and 10.

The gain parameters of optimized conventional PI Controller are, K_I = 19.61, k_C = 16.81, set pressure = 1.5 bars. The simulation result shows the rise time 0.5 second, settling time 3 second, overshoot 4.71% and real time result shows rise time 5 second, settling time 25 second, overshot 35.33 % as shown in Figures 11 and 12.

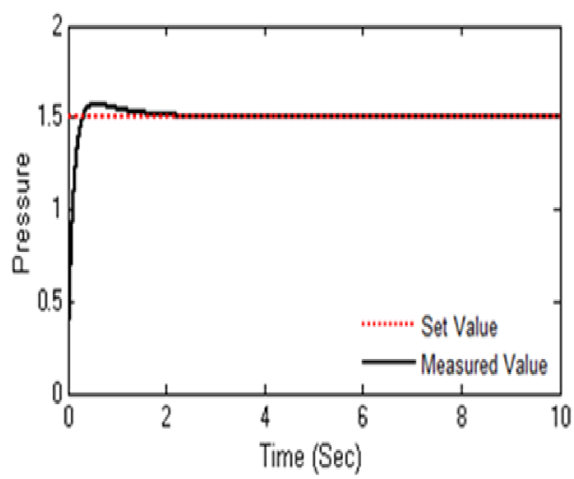

Figure 9: Response of Z-N tuned conventional PI controller in simulation

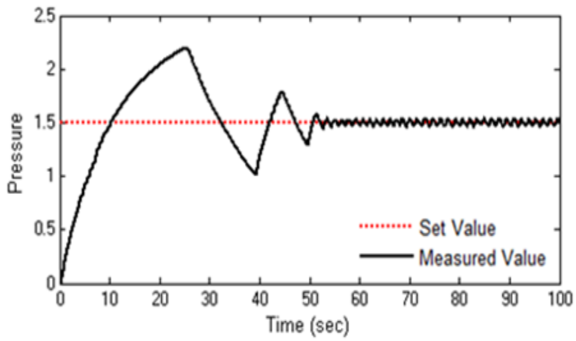

Figure 10: Response of Z-N tuned conventional PI controller in real time

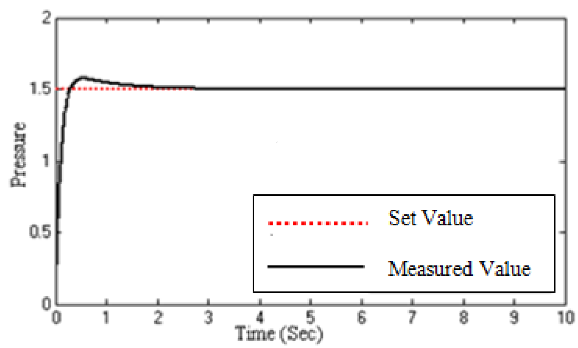

Figure 11: Response of GA tuned conventional PI controller in simulation

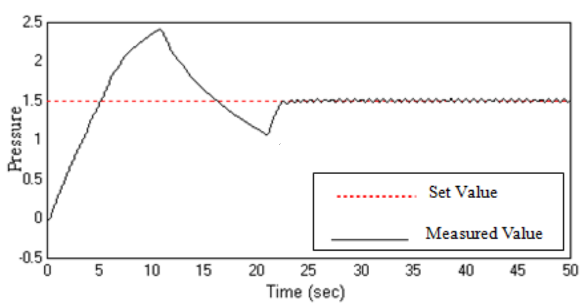

Figure 12: Response of GA tuned conventional PI controller in real time

4.2 Response of Fuzzy PI Controller with Triangular membership function

The Fuzzy PI controller with Triangular MFs has been applied to the real time in plant and estimated model in the Matlab/Simulation. The GA optimized gain parameters are KI = 2, KC = 400, Kupi = 2.5, set pressure = 1.5 bars. The response of the Fuzzy PI controller in simulation and real time are shown in Figures 13 and 14. The dotted line shows the set value of pressure at 1.5 bars and continuous line represents the output of the system with respect to time. The simulation result shows the rise time 3 second, settling time 6 second, no overshoot and in real time the rise time is 1.22 second, settling time 5 second and overshoot 16.66 %.

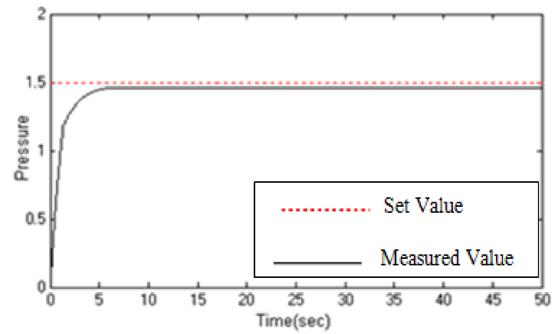

Figure 13: Response of GA tuned Fuzzy PI controller with triangular MFs in simulation

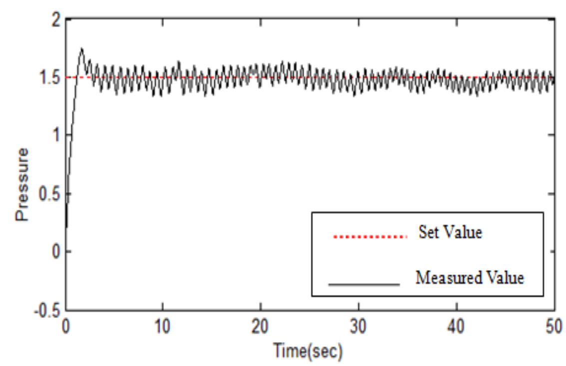

Figure 14: Response of GA tuned Fuzzy PI controller with triangular MFs in real time

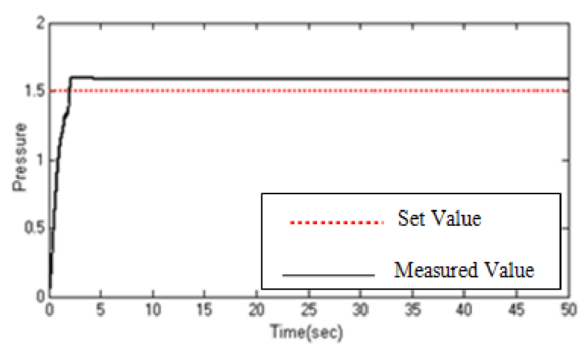

Figure 15: Response of Fuzzy PI controller with Gaussian MFs in Simulation

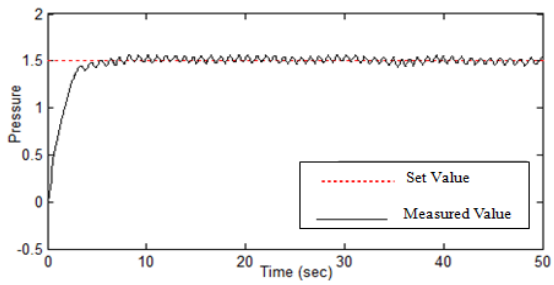

Figure 16: Response of Fuzzy PI controller with Gaussian MFs in Real time

Table 3: Simulation and Real Time Results

Types of Controllers	**Simulation Results**		
	Rise Time (Sec.)	**Settling Time (Sec.)**	**% overshoot**
Z-N tuned PI	0.4	3	5
GA tuned PI	0.5	03	4.71
GA tuned Fuzzy PI Triangular MFs	03	06	Nil
GA tuned Fuzzy PI Gaussian MFs	02	03	6.6
Real Time Results			
Z-N tuned PI	10	53	37
GA tuned PI	6	25	35.33
GA tuned Fuzzy PI Triangular MFs	1.22	05	16.66
GA tuned Fuzzy PI Gaussian MFs	3.4	09	Nil

5. Conclusions

Fuzzy PI controller with Gaussian and Triangular membership function and conventional PI controllers have been successfully implemented, using feedback control loops in real time. The overall performance of the system has been realized in the Matlab (2011b) /Simulink environment. The generated results revealed that the Fuzzy PI controller with Gaussian membership function maintains the process tank pressure at a set level without any overshoot in real time and simulation. It has been observed that the Fuzzy PI controller with Gaussian MFs performed superior than triangular MFs and conventional PI controller in feedback loop configuration. The Fuzzy PI Controller with Gaussian membership is better than others controllers because the Gaussian membership functions have smooth and nonzero at all points.

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