Fuzzy Assisted PI Controller for Pressure Regulation in a Hypersonic Wind Tunnel

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Abstract

Wind tunnels have been used to test race cars, fighter planes etc. The hypersonic wind tunnel can hit the hypersonic speeds necessary to test the latest ultra fast aircraft and space planes. The wind tunnel is a major money saver. It allows us to make a reusable prototype and test it in the tunnel for a few hundred thousand dollars. Maintaining constant pressure in the settling chamber of the hypersonic intermittent blow down type wind tunnel is an important task for its effective performance. Here, a fuzzy assisted PI control system for the hypersonic intermittent blow down type wind tunnel is developed and analyzed.

Key words: *Hypersonic wind tunnel, Mathematical models, Pressure regulation, PI controller, Fuzzy controller.*

1. Introduction

Hypersonic intermittent blowdown-type wind tunnel is a ground based facility to simulate flight conditions of space vehicles in hypersonic flow regime. Block schematic of the tunnel systems are shown below [2]. The different subsystems are high pressure system, wind tunnel system which consists of Pressure regulating valve (PRV), Heater, Settling chamber, Nozzle, Test section, the Diffuser, Vacuum isolation valve After cooler and Vacuum Chamber.

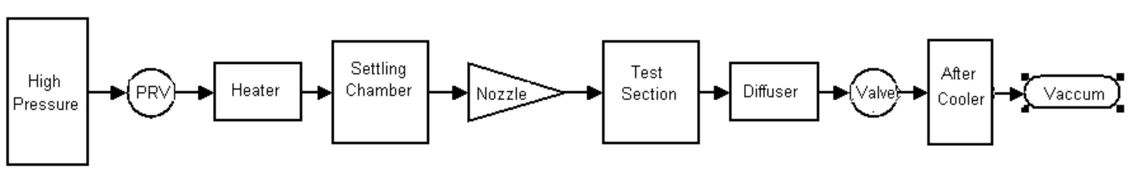

Figure 1. Block schematic of Hypersonic wind tunnel.

Air is compressed and stored in the high pressure system. It is released through a pressure regulating valve to create the desired pressure in the settling chamber. Heater is used to heat the air while passing through the heater bed to avoid liquefaction when it is expanded through the nozzle to get high Mach numbers. The pressure in the settling chamber is controlled by the proper operation of the PRV so that flow through test section meets the Mach number and mass flow rate specified for the test conditions.

Conducting experiments in a large-scale blowdown-type wind tunnels is costly and time consuming. The system is highly uncertain and non linear. The set pressure has to be reached within few seconds. So it is a challenging task to develop a controller that should adapt for different set pressure values and inlet pressure values, mass flow and temperature. These limitations and the need for high reliability systems make the role of controller design important.

Obtaining the mathematical models of the wind tunnel process is very complicated since they involve viscous effects and distributed characteristics. Working with simplified nonlinear model control is mainly used to handle the control problems with varying process parameters. Different non linear adaptive techniques are available in literature.

The specifications of the hypersonic wind tunnel system is available in the directory of wind tunnel facilities in India [8]. In 2008 Mr. Eric M.Braun et.al. developed a supersonic blow down wind tunnel control using LabVIEW [1]. The control algorithm was based on numerically integrating the differential equations used to model the tunnel in which the proportional and integral terms were added and tuned in a simulation to determine their appropriate values. Mr. Varghese Jacob et.al. established a lumped parameter mathematical model for the high pressure systems of hypersonic wind tunnel for designing a controller for pressure regulation [2]. First a classical PI controller is designed and fuzzy controller is added to improve the robustness and performance.Mr. Stanisław Skoczowski et.al proposed an effective method for robust proportional–integral–derivative (PID) control that is easily implementable on commonly used equipment such as programmable logic controller (PLC) and programmable automation controller (PAC) [5]. The method is based on a two-loop model following control (MFC) system containing a nominal model of the controlled plant and two PID controllers.

The fuzzy controller essentially is a kind of non-linear controller, the fuzzy control algorithms are built up based on intuition and experience about the plant to be controlled. The proposed control system for pressure regulation consists of two controllers, the PI controller designed for the nominal plant and the fuzzy controller designed to impart common sense to the control system thereby improving its performance [5].

2. System model

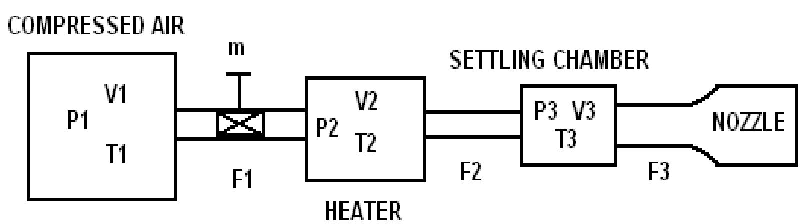

Figure 2. Block diagram of system to be modeled.

Models of different components are developed to obtain the process model of the wind tunnel system for designing a controller. We consider total system as three pressure vessels. The continuity equation of the pressure vessels are used to develop the non linear model assuming constant temperature. Block diagram of systems to be modeled is given before. The modeling equations are as given below [2]. Assuming that the compressed air behaves as an ideal gas its mass in the tank at time‘t’ is given by

$$m_1(t) = \frac{V_1 P_1(t)}{RT_1\{t\}}$$

where $m_1(t)$ is the mass of air contained in the compressed air storage tank, V_1 is the volume of the storage tank, R is the gas constant for air, $P_1(t)$ and $T_1(t)$ are the pressure and temperature in the compressed air storage tank.

Flow rate of compressible fluid [6] F1 is given by

$$F_1 = mC_v N_8 F_p P_1 Y \sqrt{\frac{XM}{T_1 Z}}$$

Where 'm' is the position of the valve, C_v is the valve coefficient, N_8 is the constant for engineering units, Fp is the constant for pipeline geometry, M is molecular weight of air, Z is the compressibility factor,

Expansion factor $Y = 1 - \frac{X}{3F_k X_t}$

where X_t is critical pressure drop ratio factor and F_k is the ratio of specific heats factor and $X = \frac{P_1 - P_2}{P_1}$, where P_2 is the downstream pressure of PRV.

Heater chamber is considered as one pressure vessel and connected pipelines and settling chamber together considered another pressure vessel. The outflow from heater F_2 is given by

$$F_2 = C_v N_8 F_p P_2 Y \sqrt{\frac{XM}{T_2 Z}}$$

Where the Expansion factor $Y = 1 - \frac{X}{3F_k X_t}$ and

$X = \frac{P_2 - P_3}{P2}$ where P_3 is the settling chamber pressure.

For different Mach number simulations we use fixed nozzles with different cross section area. It always maintains a choked flow through nozzle. The mass flow rate through nozzle, F_3 is given by

$$F_3 = \frac{K_n P_3}{\sqrt{T_3}}$$

Where k_n is the nozzle constant and P3 is the settling chamber pressure and T_3 is the settling chamber temperature.

The continuity equations for three pressure vessels may be written as

$$C_1 \frac{dP_1}{dt} = -F_1$$

$$C_2 \frac{dP_2}{dt} = F_1 - F_2$$

$$C_3 \frac{dP_3}{dt} = F_2 - F_3$$

where $C_1 = \frac{V_1}{nRT_1}$, $C_2 = \frac{V_2}{nRT_2}$, $C_3 = \frac{V_3}{nRT_3}$

For nominal test condition, P_1=300bar, T_1=300 K; T_2=700 K; T_3=529 K [8].

3. PI Controller.

Cohen coon method is used for tuning the PI controller [10]. The process reaction curve is plotted by giving a step change. From the graph a delay time of 0.5 sec, time constant of 14 sec and Gain of 4.6 is obtained

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The proportional gain is given by

$$K_c = \frac{\tau}{Kt_d}(0.9 + \frac{t_d}{12\tau}) \text{ and}$$

The integral time is given by

$$.\tau_i = \frac{30 + 3(t_d / \tau)}{9 + 20(t_d / \tau)}$$

Using these equations, we obtained the proportional gain as K_c=5.3 and integral time as τ_i=1.6 sec.

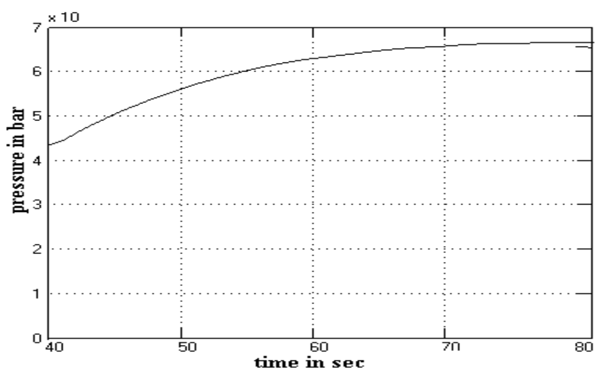

Figure 3 Process reaction curve.

Simulink is used for simulating the controllers. Figure below shows the simulink program of the system with PI controller.

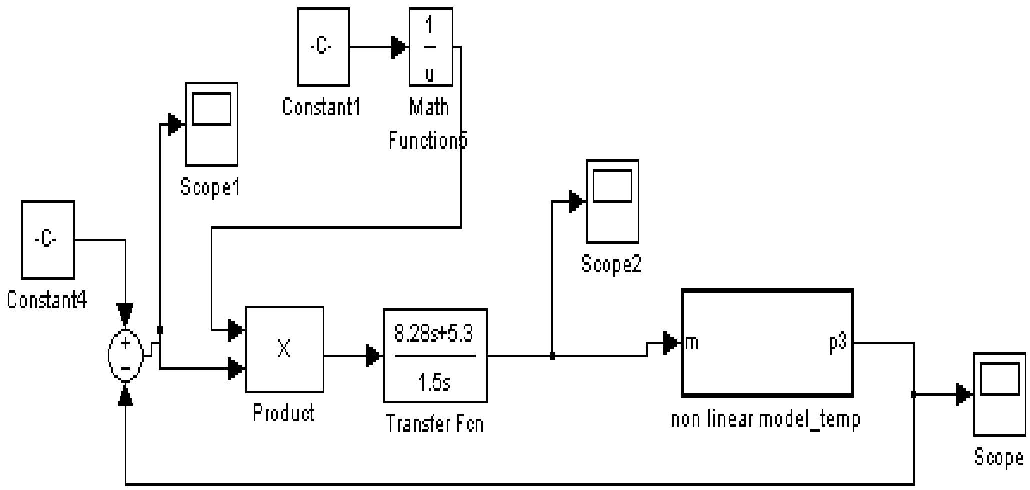

Figure 4. Simulink program of the system with PI controller.

4. Fuzzy Assisted PI Controller.

The error(e) and error rate(e_r) are the input variables, f is the output variable. Fuzzy relations between e,e_r and f is formed. Then f can be changed on line according the rules, current error and error rate. The block diagram of the system is shown below.

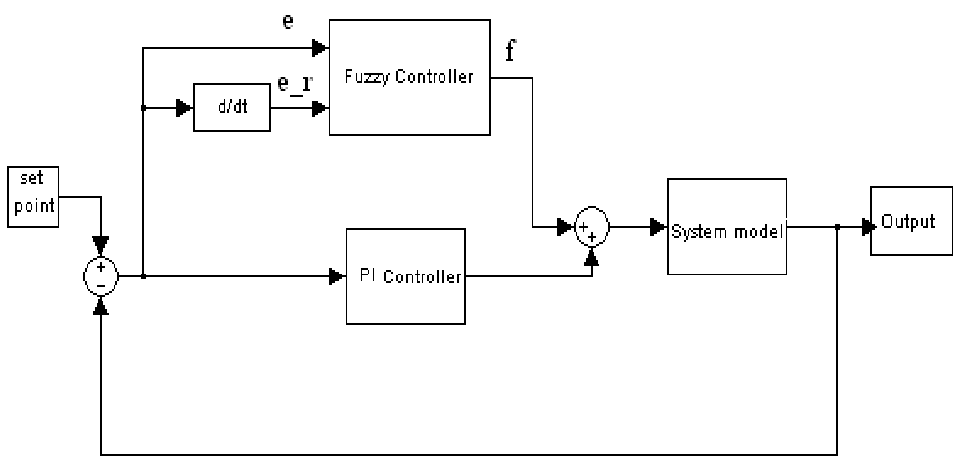

Figure 5. Block diagram of system with Fuzzy assisted PI Controller.

The membership functions are defined based on the two inputs of the fuzzy system, error e and error rate e_r. Seven triangular membership functions are defined for both input and output. The membership function is given below.

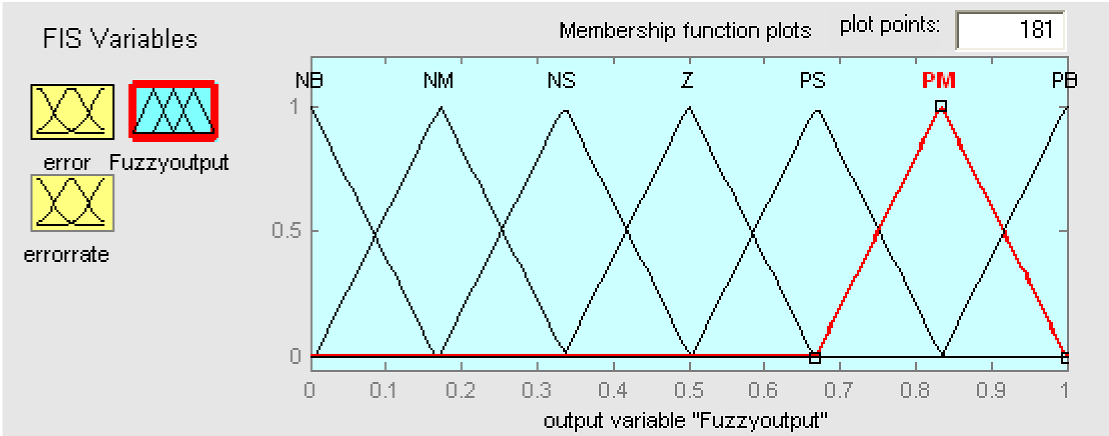

Figure 6. Fuzzy membership function.

The seven fuzzy subsets assigned for input and output variables are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The rule table for fuzzy controller is shown below.

e_r	e						
	PB	PM	PS	Z	NS	NM	NB
PB	PB	PB	PM	Z	Z	Z	Z
PM	PB	PB	PM	PS	Z	Z	NS
PS	PB	PM	PS	PS	Z	NS	NM
Z	PB	PS	Z	Z	Z	NS	NB
NS	PM	PS	Z	Z	NS	NM	NB
NM	PS	Z	Z	NS	NM	NB	NB
NB	Z	Z	Z	NS	NM	NB	NB

Table 1. Fuzzy rule table.

The defuzzification method used is centroid. The fuzzy controller is designed using fuzzy tool box in Matlab [3]. Figure below shows the simulink block diagram of the system with fuzzy assisted PI controller.

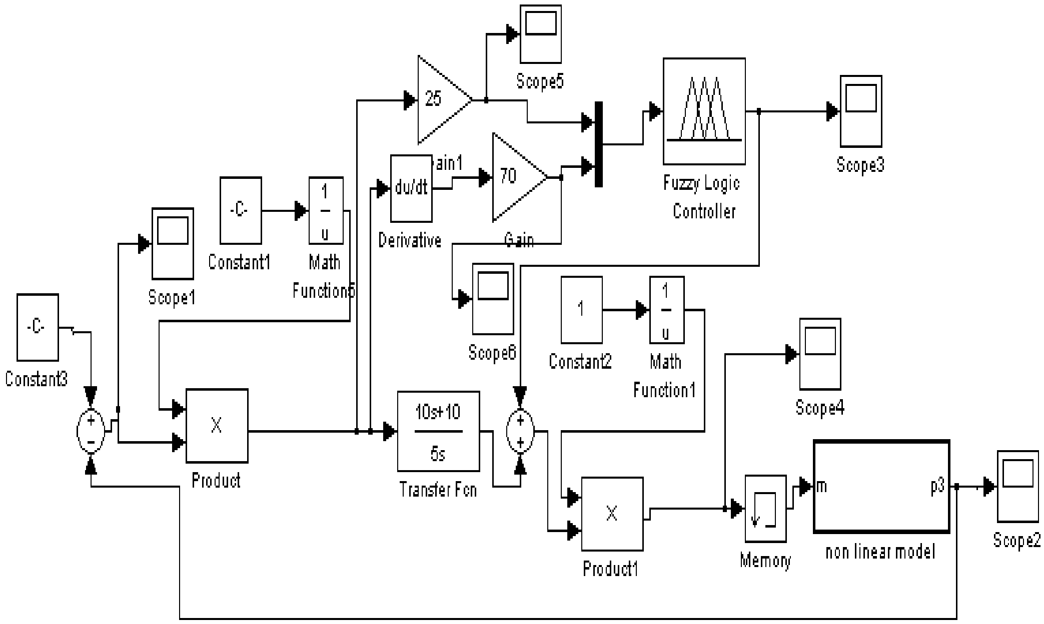

Figure 7. Simulink program of the system with fuzzy assisted PI controller.

5. Simulation Results and Discussion

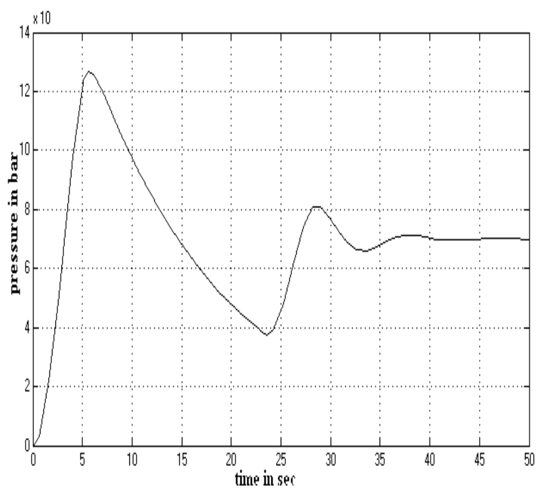

Figure 8. Output response using PI controller for set point 70 bar .

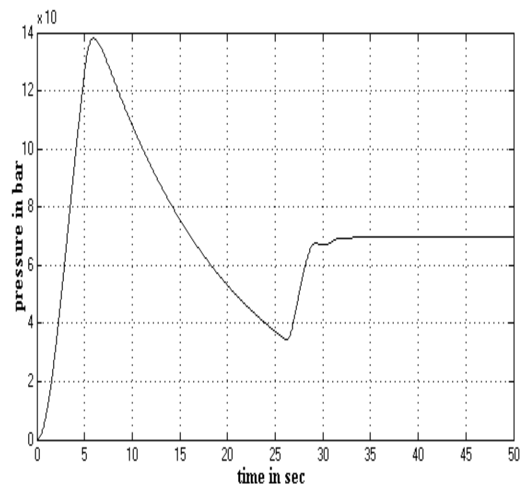

Figure 9. Output response using Fuzzy assisted PI controller for set point 70 bar.

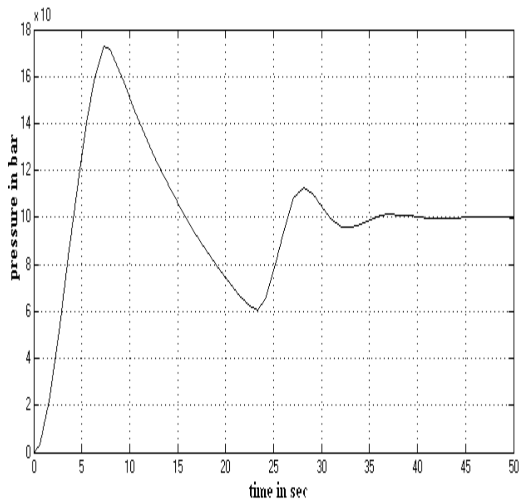

Figure 10. Output response using PI control for set point 100 bar.

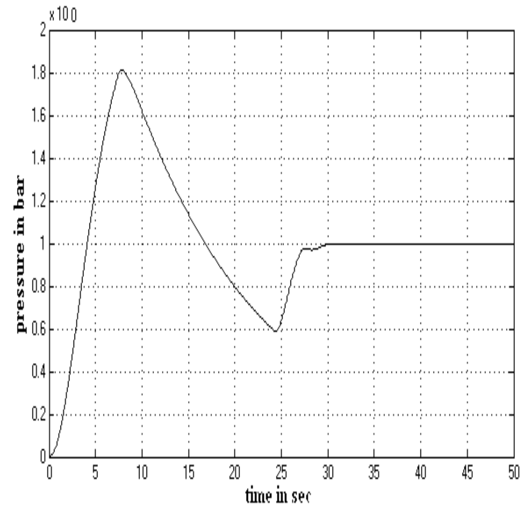

Figure 11. Output response using Fuzzy assisted PI controller for set point 100bar

From the simulation graphs, it is seen that for a set point of 100 bar, the settling time for PI controller is 35 sec and that of Fuzzy Assisted PI Controller is only 27 sec. Similarly, for a set point of 70 bar, the settling time for PI controller is 36 sec and that of Fuzzy Assisted PI Controller is only 30 sec. Clearly, we can say that the fuzzy assisted PI controller has fast settling time. The results are tabulated below.

Controller / Parameter	PI Controller		Fuzzy Assisted PI Controller	
	Set point		Set point	
	100 bar	70 bar	100 bar	70 bar
Settling Time	**35** sec	**36** sec	**27** sec	**30** sec
Percentage Overshoot	73%	81%	81%	97%
IAE	230	180	1100	890

Table 2. Result Comparison Table

The graphs below shows the fuzzy controller output for the two pressure set points of 70 bar and 100 bar.

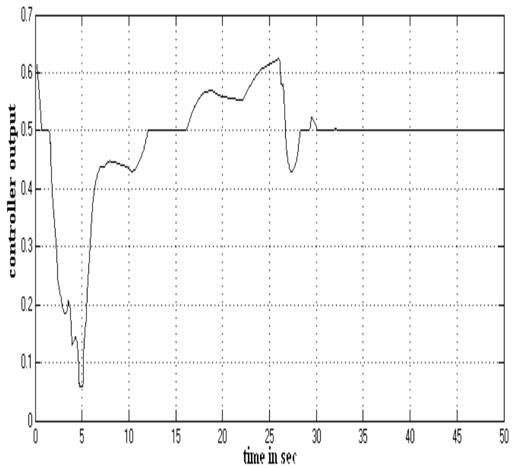

Figure 12. Controller output contribution of the fuzzy block for set point = 70 bar.

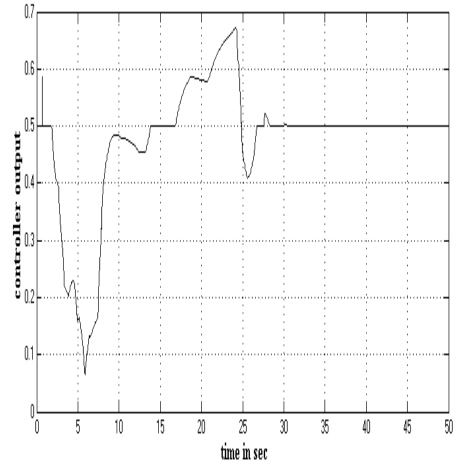

Figure 13. Controller output contribution of the fuzzy block for set point = 100 bar.

Graphs below shows the total controller output of the fuzzy assisted PI controller for the set points of 70 bar and 100 bar.

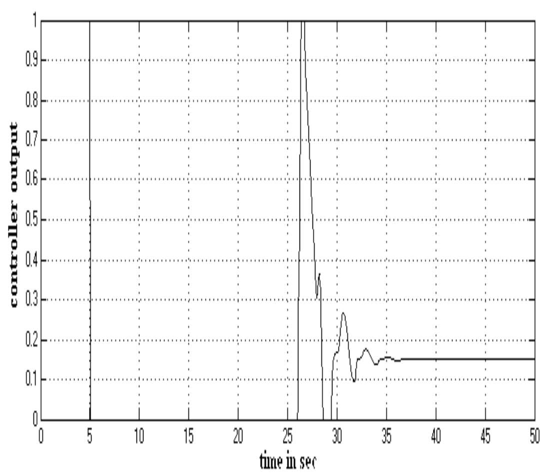

Figure 14. Total controller output of Fuzzy assisted PI controller for set point = 70 bar.

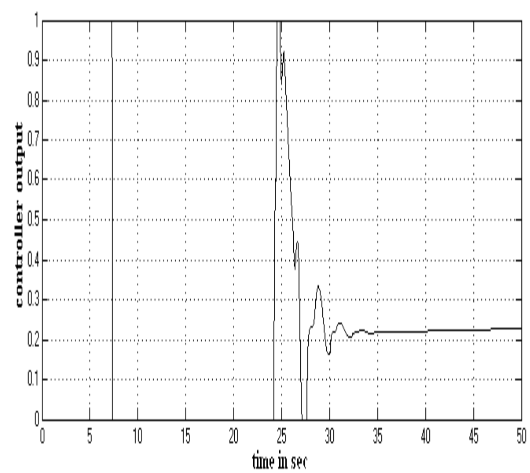

Figure 15. Total controller output of Fuzzy assisted PI controller for set point = 100 bar.

6. Conclusion

The simulation results shows an improvement in the settling time for the fuzzy assisted PI controller compared to the classical PI controller. An improvement in percentage overshoot and IAE can be obtained by modifying the rule base of the fuzzy controller. In this work, error and error rate are taken as inputs to the fuzzy controller. Further works is to be carried out by incorporating more inputs to the fuzzy controller like the pressure in the first vessel, intermediate pressures etc. More investigations in this direction are required for improved performance of the Fuzzy assisted PI controller.

7. References

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