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Design Of Fuzzy PI Controller For Room Temperature Control Loop Of HVAC System By Using An Analytical Approach For Selecting The Scaling Factors

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Abstract:

The parameters of Heating, Ventilation and Air-Conditioning (HVAC) system change as a function of load, weather, and building occupancy. Fuzzy logic controllers are believed to be robust when the system encounters large parameter variations. This paper explains the Fuzzy PI control of the room temperature control loop of HVAC system in which an analytical approach is used for selecting the scaling factors of the FPIC. The performances of Fuzzy PI controller are compared with analytically tuned Fuzzy PI controller. The simulation results show that the performances of the analytically tuned FPIC are improved compared to Fuzzy PI controller under normal conditions. Also it exhibits improved robustness when the system encounters large parameter variations.

Key words: HVAC, FLC, Fuzzy PI Controller, room temperature control

1. Introduction:

Processes, with only one output being controlled by a single manipulated variable, are classified as Single Input Single Output (SISO) systems.Many processes, however, do not conform to such a simple control configuration.Systems with more than one control loop are known as Multi Input Multi Output (MIMO) or multivariable systems. Most of the controlled processes in industries are Multi Input Multi Output processes.The control of MIMO systems is a complicated problem due to the coupling that exists between the control inputs and outputs.When MIMO systems are nonlinear and uncertain, their control problem becomes more challenging (Boulkraune 2010) and as such there is a need for an efficient tuning method to control both SISO as well as MIMO processes.

Proportional Integral (PI) / Proportional Integral Derivative (PID) controllers are widely used in process industries due to the simplicity of their design and tuning methods (Mudi and Dey 2011). Now-a-days, Fuzzy Logic Control (FLC) has become an alternative to conventional control algorithms to solve problems dealing with complex processes (Lee 1990). It combines the advantages of classical controllers and human operators. The inputs to the fuzzy controller are the error (e) and change in error (Δe) (Karakya and Karakas 2008, Safarinejadian et al 2012, Sharma et al 2010). PI type FLCs are most commonly used as proportional and integral actions are combined in the Proportional Integral (PI) controller which, in turn, gives the advantages of inherent stability of Proportional controller and the offset elimination by Integral controller. Also the performance and tuning of PI controllers for industrial processes are well known among all industrial operators.However, tuning of PI controller, requires an accurate model of the process and effective design rules (Bai et al 2008).

In this paper, an analytical method is determined for selecting the scaling factors of the FPIC. With the analytically determined values of scaling factors, FPIC is designed, thus, making it Analytically tuned Fuzzy Proportional Integral Controller (AFPIC).The performances of the Analytically tuned FPIC is compared with FPIC for the room temperature control loop of HVAC system..

2. Room temperature loop of HVAC System:

Fig1 shows a typical HVAC system. In HVAC system, room temperatures are fine tuned by regulating the position of two variable air volume (VAV) dampers. When the VAV damper opens wider, more cooling air enters the room and the room temperature will drop, and vice versa. In the room, there are two temperature sensors Tleft and Tright, located at the left-hand and right-hand side, respectively. Also, there are two dampers (VAVleft and VAVright) on the room ceiling. The change in any one damper position will cause the readings of both sensors Tleft and Tright to change. Thus, this forms a coupled process or MIMO process.

The room temperature plant model was estimated as (Bi et al 2000)

$$\begin{bmatrix} \mathrm{Tleft}(s) \\ \mathrm{Tright}(s) \end{bmatrix} = \begin{bmatrix} \dfrac{-0.045e^{-23.2s}}{120s+1} & \dfrac{-0.014e^{-63.3s}}{109s+1} \\ \dfrac{-0.019e^{-15s}}{137s+1} & \dfrac{-0.05e^{-14s}}{96s+1} \end{bmatrix} \begin{bmatrix} V1(s) \\ V2(s) \end{bmatrix} \qquad (1)$$

Where

Tleft - Temperature on the left sensor

Tright - Temperature on the right sensor

V1 - Input voltage of left damper fan

V2 - Input voltage of right damper fan

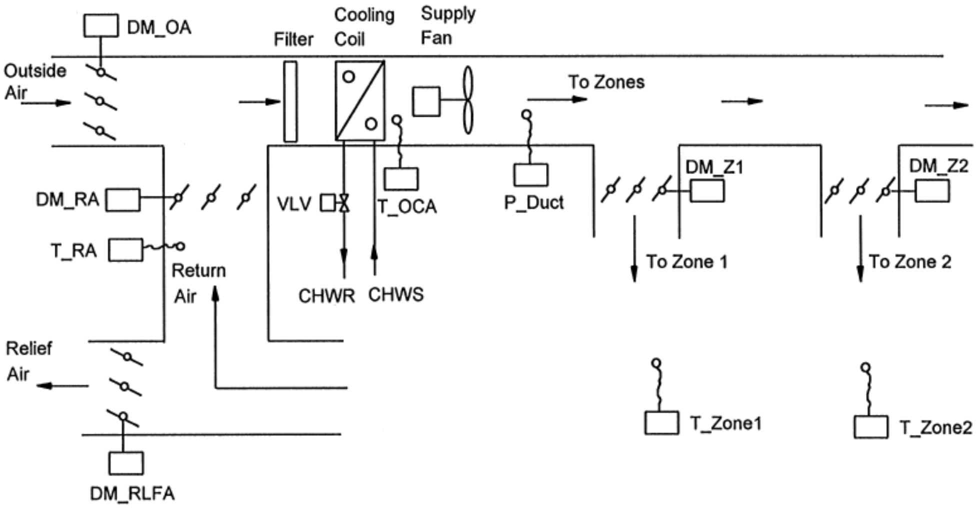

Fig.1. A typical HVAC system

3. FUZZY PI CONTROLLER

3.1. Block Diagram Description

Figure 2 shows the block diagram of Fuzzy PI Controller. It consists of a Fuzzy Logic Controller (FLC), two input scaling factors G_e,$G_{\Delta e}$ and output scaling factor G_u, R the set point, u the controller output and y the process output. Error and change in error are the two inputs to the Fuzzy Logic Controller. The Fuzzy Logic PI Controller generates incremental control output Δu from error (e) and change of error (Δe).The actual value of the controller output (u) is obtained by the accumulation of the incremental change in controller output.

$$u(k) = u(k-1) + \Delta u(k) \qquad (2)$$

where

k is the sampling instant.

Δu (k) is the change in controller output at k^{th} sampling instant.

The membership functions, the rule bases and tuning of FPIC are explained below:

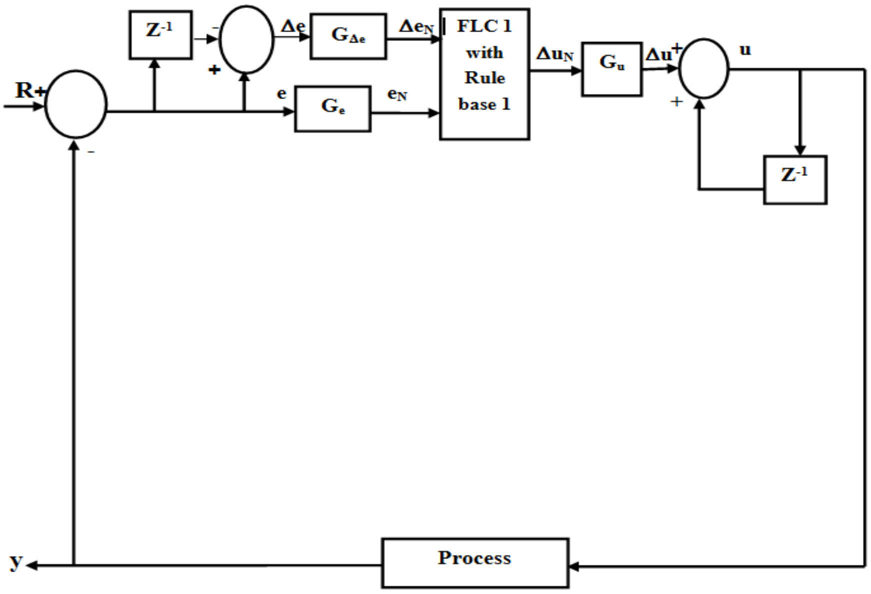

Figure 2 Block diagram of FPIC

3.2. Membership Functions

The Membership Functions (MFs) for: 1) controller inputs, i.e., error and change of error and 2) incremental change in controller output for PI-type FLC are defined on the common interval [-1, 1]. The error and change in error are converted into seven linguistic values namely NB, NM, NS, ZE, PS, PM and PB. Similarly controller output is converted into seven linguistic values namely NB, NM, NS, ZE, PS, PM and PB. Symmetric triangles (except the two MFs at the extreme ends) with equal base and 50% overlap with neighboring MFs are shown in Figure 3

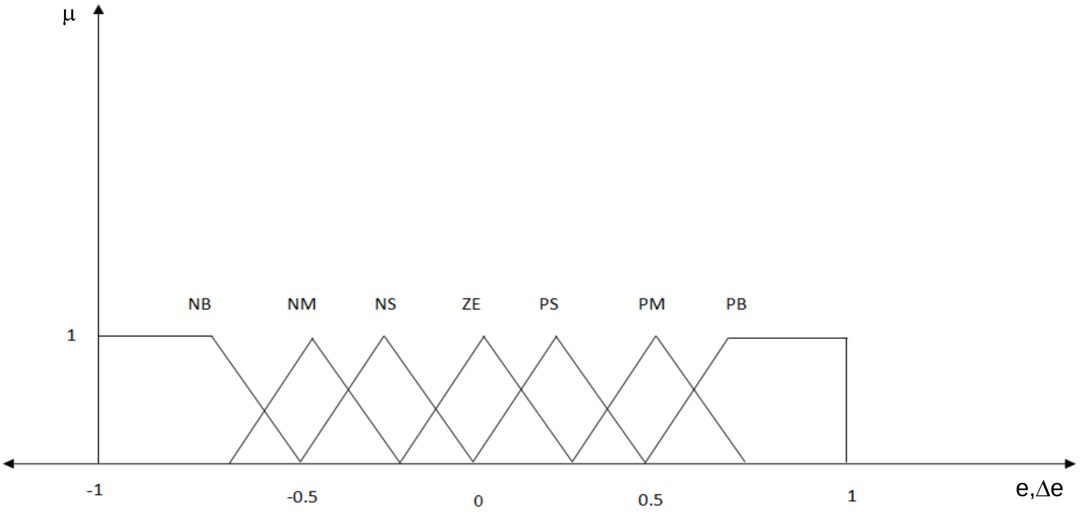

Figure 3 Membership functions for e, Δe and Δu

Where
NB - Negative Big
NM - Negative Medium
NS - Negative Small
ZE - Zero
PS - Positive Small
PM - Positive Medium
PB - Positive Big

3.3. Rule Bases

The control rules are built based on the knowledge about the characteristics of the step response. For example, if the output is falling far away from the set-point, a large control signal that pulls the output toward the set-point is expected, whereas a small control signal is required when the output is near and approaching the set-point. Moreover it is standard rule set available in the literature The rule blocks in the fuzzy logic design contain the actual control strategy.

The incremental change in the controller output (Δu) for a fuzzy PI controller is determined by rules of the form: If e is E and Δe is ΔE then Δu is ΔU.

The rule base for computing Δu is shown in Table 1.

Table 1 Fuzzy rules for computation of Δu

$\Delta e/e$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

3.4. Scaling Factor Determination

The MFs for both scaled inputs (e_N and Δe_N) and output Δu_N of the controller have been defined on the common interval [-1, 1]. The values of the actual inputs e and Δe are mapped onto [- 1, 1] by the input SFs G_e and $G_{\Delta e}$ respectively. The controller output Δu_N is mapped onto the respective actual output Δu domain by the output SF G_u.

The relationship between SFs and the input and output variables of the Fuzzy PI controller are as follows

$$e_N = G_e e \quad (3)$$

$$\Delta e_N = G_{\Delta e}.\Delta e \quad (4)$$

$$\Delta u = G_u.\Delta u_N \quad (5)$$

3.5. Tuning of the controller by trial and error method

Selection of suitable values for G_e, $G_{\Delta e}$ and G_u are made based on the knowledge about the process to be controlled and through trial and error to achieve the best possible control performance.

The SFs of FLC for a given process should be tuned to achieve a reasonably good control performance. In doing so, first G_e should be selected in such a way that the error almost covers the entire domain [-1,1] to make efficient use of the rule bases (Mudi and Pal 1999). Then $G_{\Delta e}$ and G_u are tuned to make the transient response of the system as good as possible. Table 2 shows the tuned scaling factors for Fuzzy PI Controller.

Table 2 Tuned scaling factors for FPIC determined by trial and error method

Process	**Process variable**	G_e	$G_{\Delta e}$	G_u
Second order MIMO process	Tleft	0.1	150	-0.3
	Tright	0.1	100	-0.3

4. Fuzzy PI Controller(Analytically tuned)

4.1. Model Approximation

Standard method of finding controller gains has been developed for first order plus time delay model (FOPTD). Mostly to design a controller for higher order system, the system is reduced to a FOPTD model. Many methods are available for reducing the higher order system. Among these Sundaresan and Krishnaswamy method is used for approximating the higher order system. (Bequette 2006). In this method, two time instants t_1 and t_2 must be estimated from the step response curve corresponding to the response times 35.3% and 85.3% respectively, as illustrated in Figure 4. The reduced transfer function is represented as

$$G(s) = \frac{K}{(\tau s + 1)} e^{-\theta s} \tag{6}$$

Where,

Process Gain $K = \Delta y / \Delta u$ (7)

Time constant $\tau = 0.67\,(t_1 - t_2)$ (8)

Time delay $\theta = 1.3t_1 - 0.29t_2$ (9)

t_1 - time at 35.3% of unit step response

t_2 - time at 85.3% of unit step response

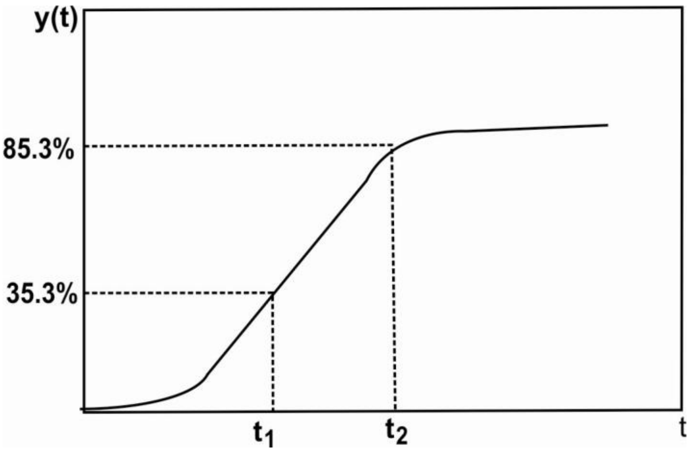

Figure 4 Step response of the system with times $t_{35.3\%}$ and $t_{85.3\%}$ marked

4.2. Determination of PI Controller Gain

Determination of PI controller gains directly for FOPTD model is given by SIMC approach (Skogested 2003). Here the SIMC method is used to derive the PI controller gains. The proportional gain Kp and integral time constant τ_I are obtained using the Equations (10) and (11).

$$K_p = \frac{0.5\tau}{K\theta} \quad (10)$$

$$\tau_I = \tau \quad (11)$$

$$K_I = \frac{K_p}{\tau_I} \quad (12)$$

where,

K_p	- Proportional gain
K_I	- Integral gain
τ_I	- Integral time constant
K	- Process gain
τ	- Time constant
θ	- Time delay

4.3. Determination of Scaling Factors

The PI controller produces an output signal proportional to the error signal and proportional to the integral of the error signal and is given by Equation 13 (Coughenour 1991, Stephanopolous 1984, Ogata 1997, Gopal 1992, Shinsky 1998) The conventional PI controller is expressed mathematically as,

$$u(t) = K_p e(t) + K_I \int e(t)dt \quad (13)$$

Where,

K_p	- Proportional gain
K_I	- Integral gain
$u(t)$	- Controller output as a function of time

e(t) - Error as a function of time

Differentiating Equation 13,

$$\frac{du(t)}{dt} = K_p \frac{de(t)}{dt} + K_I e(t) \tag{14}$$

Discretizing Equation (14) by backward difference approximation

$$\frac{u(k) - u(k-1)}{T_S} = K_p \frac{e(k) - e(k-1)}{T_S} + K_I e(k) \tag{15}$$

where

Ts - Sampling time

$$\Delta u(k) = K_P \Delta e(k) + K_I T_S e(k) \tag{16}$$

Fuzzy controller will generate Δu_N as a function of normalised error and normalised change of error.

$$\Delta u_N(k) = f(e_N, \Delta e_N) \tag{17}$$

Actual output of fuzzy controller is a function of error and change of error

$$\Delta u(k) = f(G_e \times e, G_{\Delta e} \times \Delta e) G_u \tag{18}$$

The function ‘f’ is the fuzzy input-output map of the fuzzy controller. It is possible to construct a rule base with a linear input-output mapping that acts like a summation and is shown in Equation 19 (Silver and Ying 1989, Qiao and Mizumoto 1996)

$$f(G_e \times e, G_{\Delta e} \times \Delta e) = G_e \times e(k) + G_{\Delta e} \times \Delta e(k) \tag{19}$$

Therefore using linear approximation given in Equation (19), Equation (18) can be approximated as a linear combination of error and error change

$$\Delta u(k) = G_e \times G_u \times e(k) + G_{\Delta e} \times \Delta e(k) \times G_u \tag{20}$$

Comparing Equations (16) and (20) the following relation is obtained,

$$G_{\Delta e} \times G_u = K_p \tag{21}$$

$$G_e \times G_u = K_I T_S \tag{22}$$

There are four unknowns in the Equations 21 and 22 Sampling time Ts is fixed for the fuzzy controller. From the literature and also from simulation study, it is found that variation of G_e, does not affect the rise time and settling time. So in this study, G_e is assumed and the other two parameters $G_{\Delta e}$ and G_u are found using Equations 21 and 22.

4.4. Tuning of the controller by analytical method

Using the Equations 21 and 22 G_e, $G_{\Delta e}$ and G_u are calculated analytically. Table 3 shows the scaling factors of Fuzzy PI Controller obtained by analytical calculation.

Table 3 Tuned scaling factors for FPIC determined by analytical calculation

Process	**Process variable**	**G_e**	**$G_{\Delta e}$**	**G_u**
Second order MIMO process	Tleft	0.1	120	-0.478
	Tright	0.1	96	-0.28

5. RESULTS AND DISCUSSION

This section of the study describes the simulation results obtained for both FPIC and Analytically tuned FPIC for second order MIMO process.

The output responses for unit step input and their interaction responses, output responses with disturbance at 850 sec. for unit step input, output responses with 20% variation in gain, with 10% variation time constant and output responses with step change in set point at 1000 sec. for the process variables temperature on left (Tleft) and temperature on right (Tright) are shown below:

Figure 5 shows the output responses of the temperature on the left (Tleft) for both FPIC and AFPIC for unit step input. However, the settling time of FPIC and AFPIC are 744.6 sec. and 536.6 sec. respectively and AFPIC provides improved performance compared to FPIC.

Figure 6 shows the interaction responses of the temperature on the right (Tright) for both FPIC and AFPIC for unit step input to Tleft. From Figure 6, it is clear that there occurs a small amount of interaction in temperature on the right (Tright) due to unit step input in Tleft under both FPICs. However, AFPIC gives lesser interaction than FPIC.

Figure 7 shows the output responses of the temperature on the right (Tright) for both FPIC and AFPIC for a unit step input. Simulation result shows clearly that under both FPICs the temperature on the right (Tright) tracks the set point without steady state error. However, the settling time of FPIC and AFPIC are 532.4 sec. and 415.3 sec. respectively. Hence AFPIC yields improved performance compared to FPIC.

Figure 8 shows the interaction responses of the temperature on the left (Tleft) for both FPIC and AFPIC for unit step input to Tright. From Figure 8, it is clear that there occurs a small amount of interaction in the temperature on the left (Tleft) due to unit step input in Tright under both FPICs, AFPIC gives lesser interaction than FPIC. However the controller acts on the system and reduces the interaction within a short duration.

Figures 5 to 8 show that under both FPIC and AFPIC, a variation in the temperature on the left (Tleft) affects the temperature on the right (Tright) and vice versa. From table 4, Performance analysis of Tleft shows that FPIC provides IAE of 9.32, ISE of 8.74 and ITAE of 44.55. Analytically tuned FPIC provides IAE of 8.95, ISE of 8.13 and ITAE of 41.62. Performance analysis of Tright shows that FPIC provides IAE of 8.87,ISE of 7.99 and ITAE of 44.44. Analytically tuned FPIC provides IAE of 7.90, ISE of 6.55 and ITAE of 34.41.Hence AFPIC provides more improved performance and lesser interaction compared to FPIC.

Figure 9 shows the output responses of FPIC and AFPIC for the temperature on the left (Tleft) for unit step input. A negative step disturbance of magnitude 2 given at 850 sec., is reflected in the response immediately. However, the responses for the temperature on the left (Tleft) track the set point without steady state error with settling time of FPIC and AFPIC as 1054 sec. and 1051 sec. respectively. Figure 10 shows the output responses of FPIC and AFPIC for the temperature on the right (Tright) for unit step input. A negative step disturbance of magnitude 2.5 given at 850 sec., is reflected in the response immediately. Inspite of the disturbance, the responses for the temperature on the right (Tright) track the set point without steady state error within a short duration, the settling time varies for FPIC and AFPIC with the values 1061sec. and 954.9 sec. respectively. Hence AFPIC evokes improved performance compared to FPIC.

From Table 5 Performance analysis of Tleft shows that inspite of a negative step disturbance of magnitude 2 given at 850 sec., FPIC provides IAE of 10.78, ISE of 9.81 and ITAE of 60.65, Analytically tuned FPIC provides settling time of 1051 sec., IAE of 10.16, ISE of 8.87 and ITAE of 54.97. Performance analysis of Tright show that inspite of a negative step disturbance of magnitude 2.5 given at 850 sec., FPIC provides IAE of 10.15, ISE of 8.80 and ITAE of 55.40. Analytically tuned FPIC provides IAE of 8.77, ISE of 6.94 and ITAE of 43.98.

Figure 11 shows the output responses of FPIC and Analytically tuned FPIC for the temperature on the left (Tleft) for unit step input with 20% variation in gain. Eventhough the gain varies by 20%, the responses for the temperature on the left (Tleft) track the set point without steady state error. However, the settling time varies for FPIC and AFPIC with the values 767 sec. and 547.9 sec. respectively.Figure 12 shows the output responses of FPIC and AFPIC for the temperature on the right (Tright) for unit step input with 20% variation in gain. Eventhough the gain varies by 20%, the output responses for Tright track the set point without steady state error. However, the output responses of the temperature on the right (Tright) show that AFPIC provides settling time of 405 sec. and FPIC provides settling time of 557.1 sec. Hence, AFPIC yields improved performance compared to FPIC and the system is robust.

From table 6,Despite the 20% variation in gain performance analysis of Tleft shows that FPIC provides IAE of 9.26, ISE of 8.64 and ITAE of 44.13. Analytically tuned FPIC provides IAE of 9.02, ISE of 8.26 and ITAE of 42.27. Performance analysis of Tright shows that FPIC provides IAE of 8.97, ISE of 8.13 and ITAE of 42.12. Analytically tuned FPIC provides IAE of 8.03, ISE of 6.74 and ITAE of 35.34.

Figure 13 shows the output responses of FPIC and AFPIC for the temperature on the left (Tleft) for unit step input with 10% variation in time constant. Inspite of 10% variation in time constant the output responses of the temperature on the left (Tleft) track the set point without steady state error and provides a settling time of 730 sec. and 525.4 sec. for FPIC and AFPIC respectively.Figure 14 shows the output responses of FPIC and AFPIC for the temperature on the right (Tright) for unit step input with 10% variation in time constant. Inspite of 10% variation in time constant, the output responses of the temperature on the right (Tright) track the set point without steady state error and provides a settling time 518 sec. and 409.1 sec. for FPIC and AFPIC respectively.From table 7 performance analysis of Tleft shows that FPIC provides IAE of 9.37, ISE of 8.82 and ITAE of 44.92. Analytically tuned FPIC provides IAE of 9.02, ISE of 8.24 and ITAE of 42.18. Performance analysis of Tright shows that FPIC provides IAE of 8.95, ISE of 8.10 and ITAE of 41.92. Analytically tuned FPIC provides IAE of 7.99, ISE of 6.68 and ITAE of 35.02. Hence AFPIC yields improved performance compared to FPIC. Hence the system is robust.

Figure 15 shows the output responses of Tleft for FPIC and AFPIC for two different set points. The responses for the temperature on the left (Tleft) track the set point without steady state error and at 1000sec.,there occurs a response change to a given input change, and a similar tracking of set point happens again without steady state error. However, the settling time varies for FPIC and AFPIC with the values 1627 sec. and 1453 sec. respectively and the response shows that AFPIC brings in better improvement than FPIC.Figure 16 shows the output responses of the temperature on the right (Tright) for FPIC and AFPIC for two different set points. The responses for the temperature on the right (Tright) track the set point without steady state error and at 1000sec. there occurs a response change to a given input change,and a similar tracking of set point happens again without steady state error. However, the settling time varies for FPIC and AFPIC with the values 1448 sec. and 1348 sec. respectively.From table 8,Inspite of set point change, performance analysis of Tleft shows that FPIC provides IAE of 25.35, ISE of 34.5 and ITAE of 122.09. Analytically tuned FPIC provides IAE of 23.57, ISE of 29.6 and ITAE of 111.90. Analysis of Tright shows FPIC provides IAE of 23.75, ISE of 30.19 and ITAE of 112.82. Analytically tuned FPIC provides IAE of 21.03, ISE of 23.86 and ITAE of 97.65. AFPIC brings in better improvement than FPIC.

From Figures 5 to 16 it is inferred that AFPIC provides more improved performance compared to FPIC under all the conditions discussed hence the system is robust.

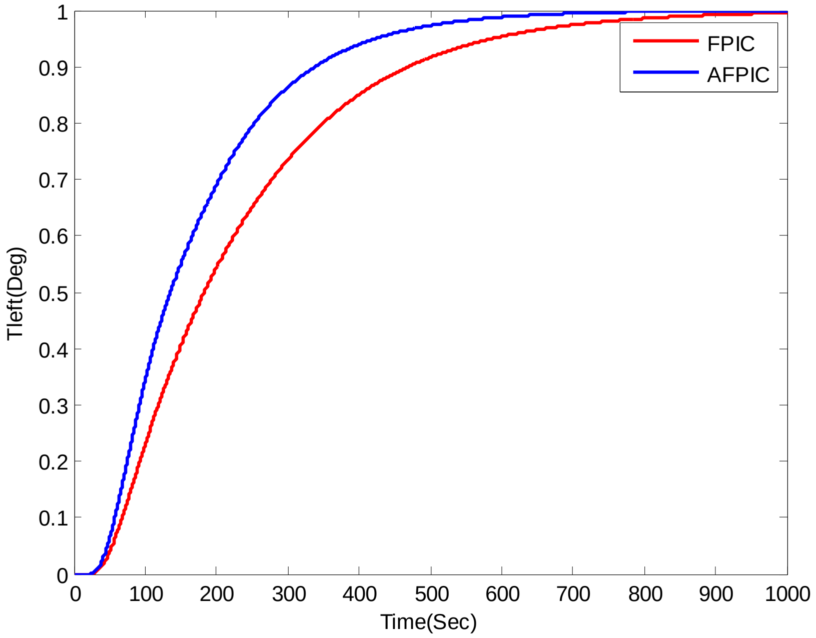

Figure 5 Output responses of Tleft for unit step input (FPIC and AFPIC)

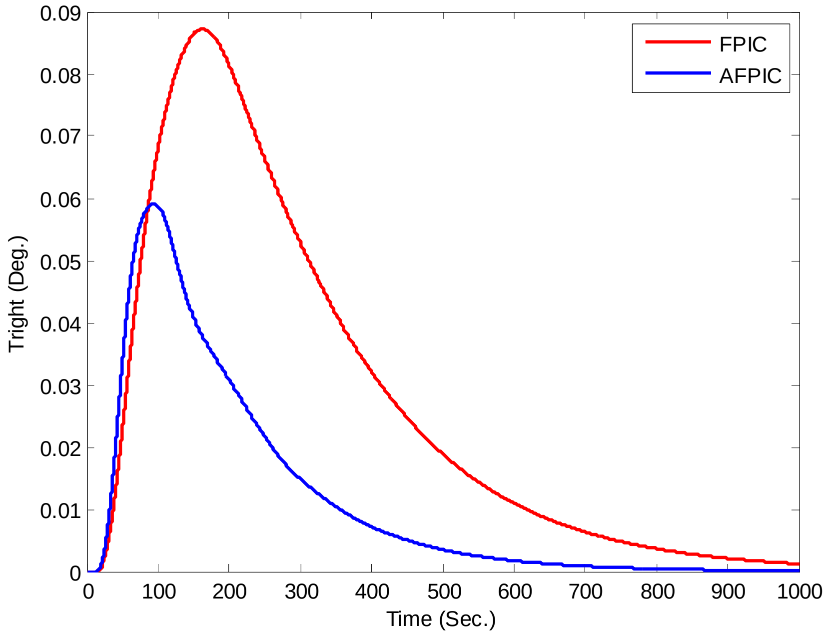

Figure 6 Interaction responses of Tright for unit step input to Tleft (FPIC and AFPIC)

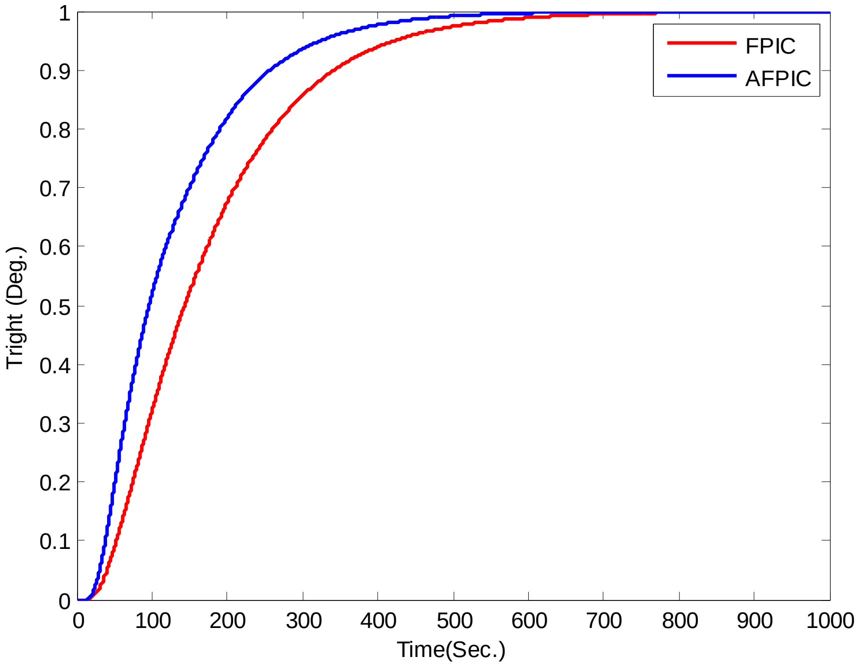

Figure 7 Output responses of Tright for unit step input (FPIC and AFPIC)

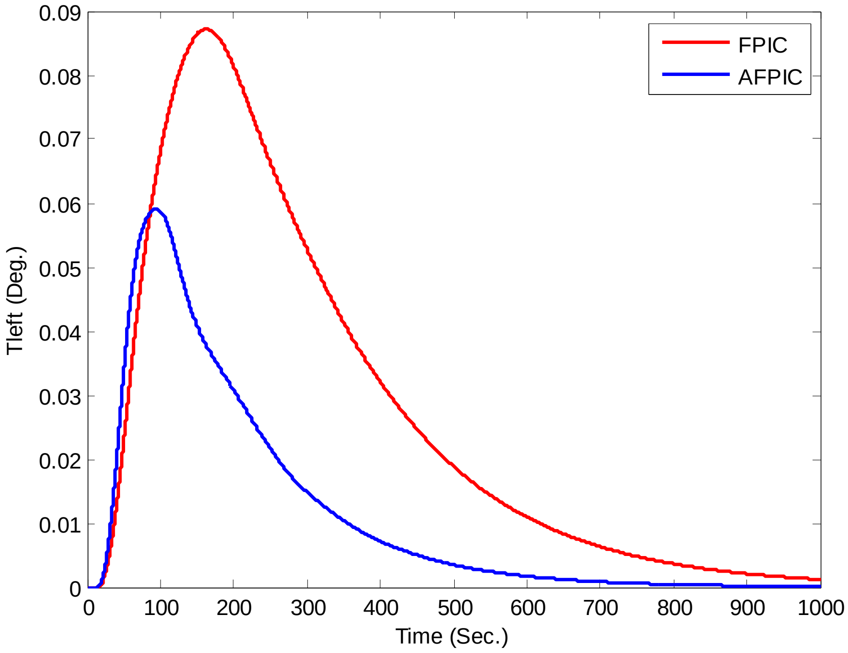

Figure 8 Interaction responses of Tleft for unit step input to Tright (FPIC and AFPIC)

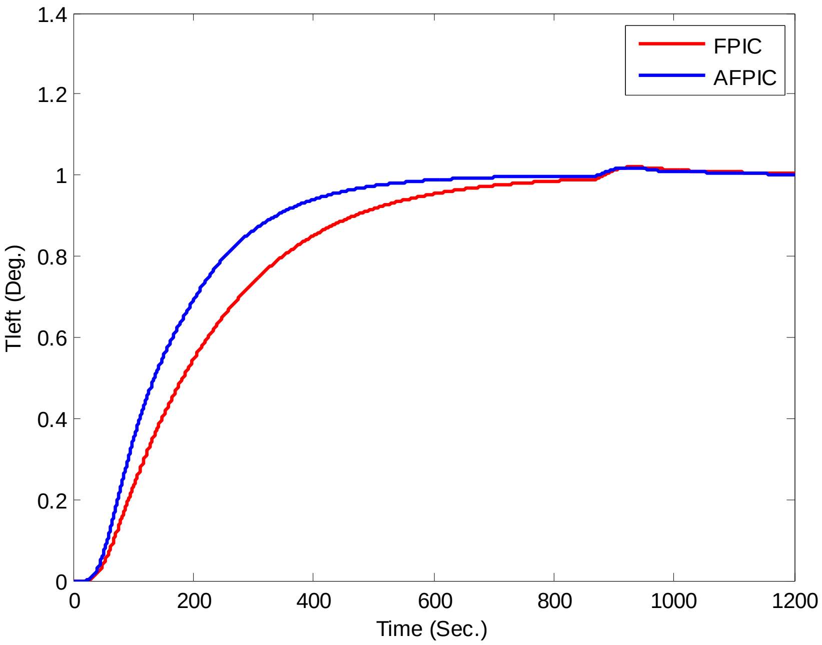

Figure 9 Output responses of Tleft with disturbance for unit step input (FPIC and AFPIC)

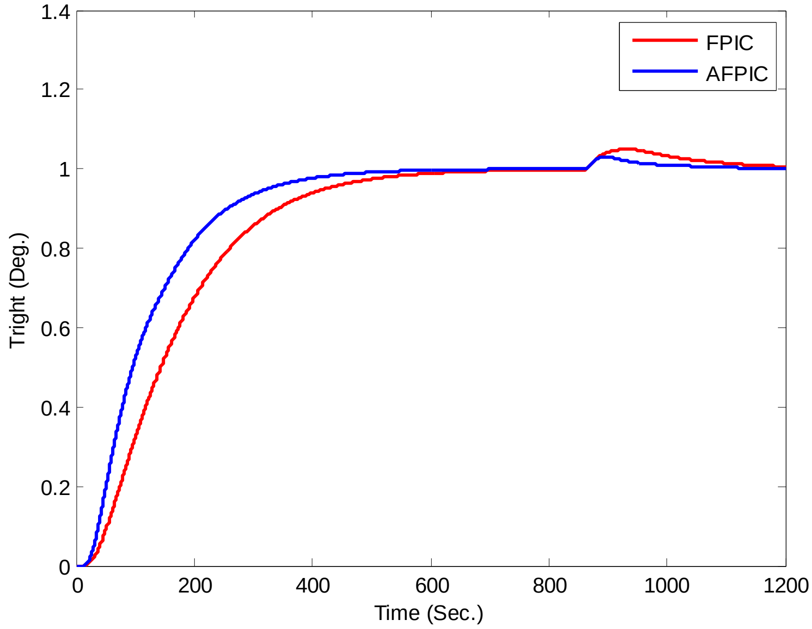

Figure 10Output responses of Tright with disturbance for unit step input (FPIC and AFPIC)

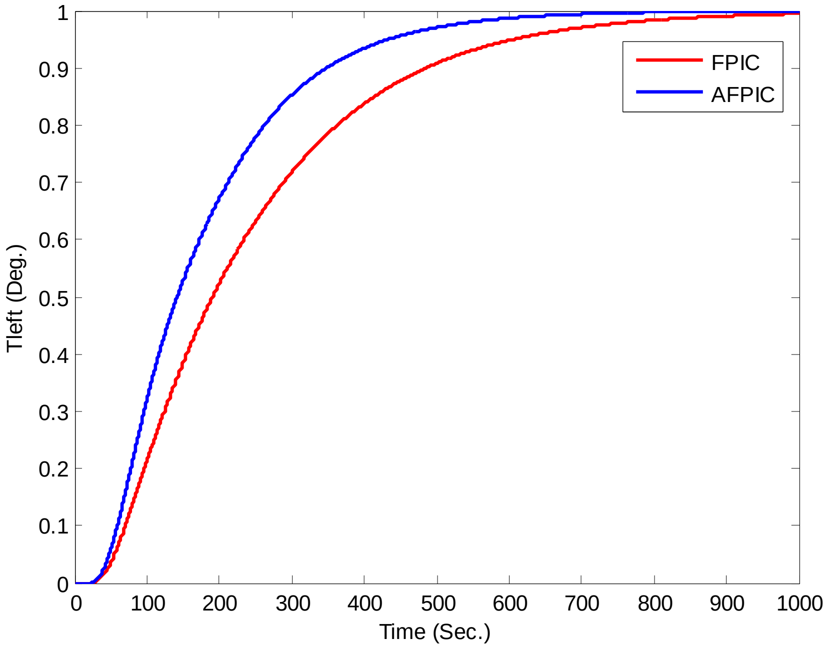

Figure 11 Output responses of Tleft with 20% variation in gain for unit step input (FPIC and AFPIC)

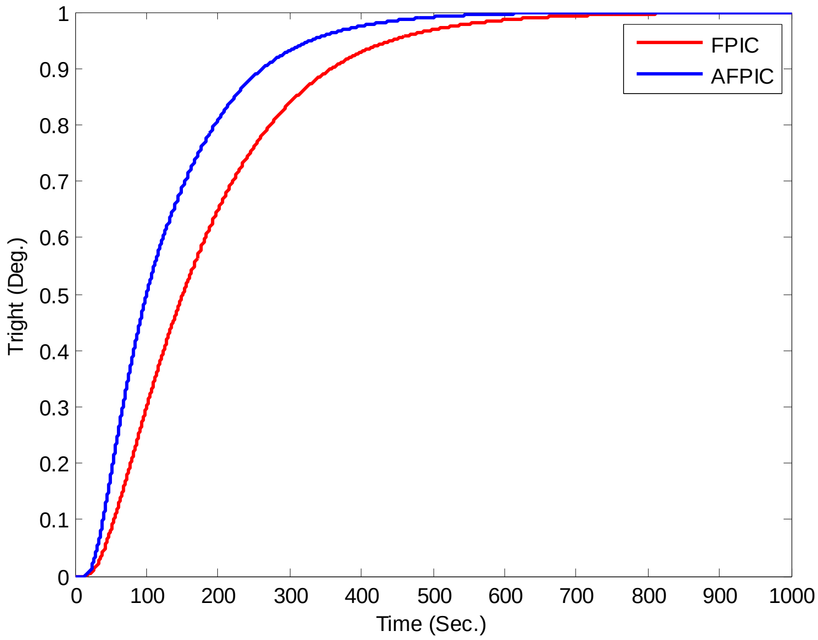

Figure 12 Output responses of Tright with 20% variation in gain for unit step input (FPIC and AFPIC)

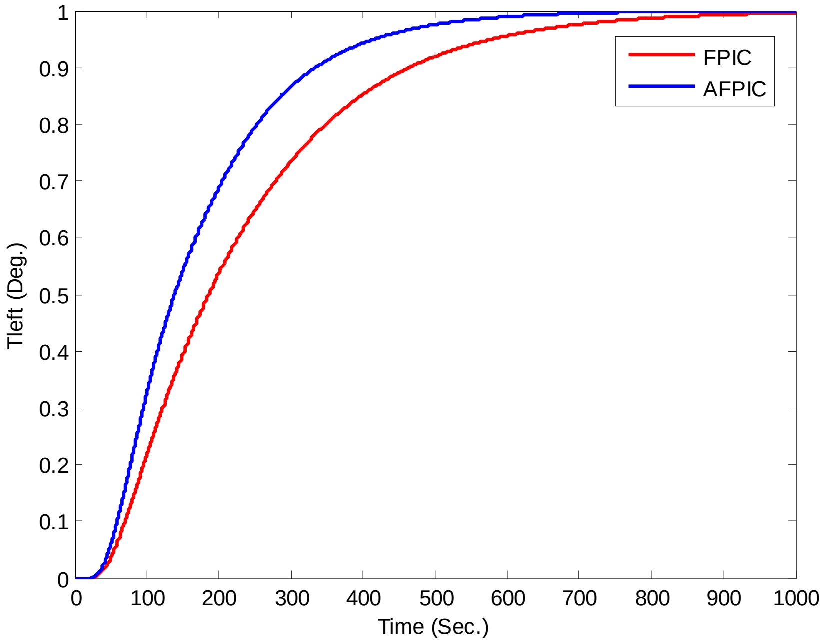

Figure 13Output responses of Tleft with 10% variation in time constant for unit step input (FPIC and AFPIC)

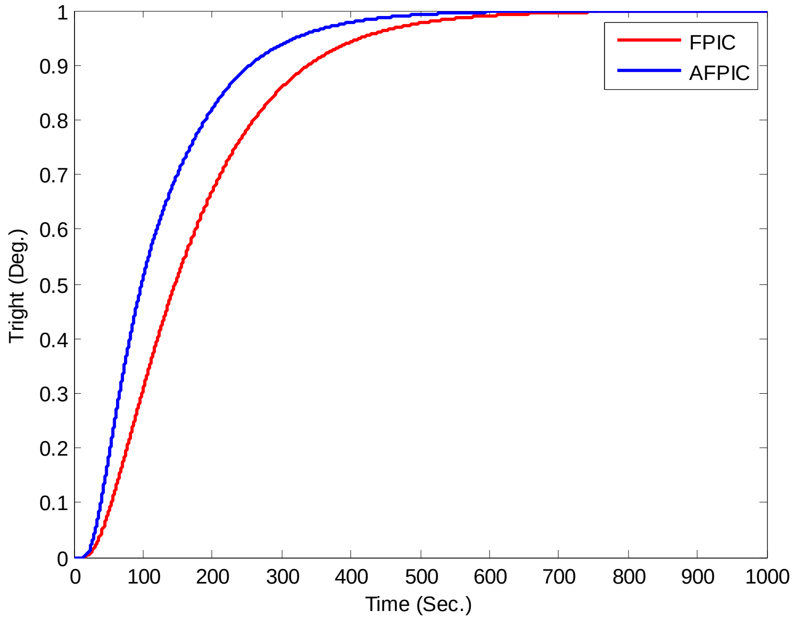

Figure 14 **Output responses of Tright with 10% variation in time constant for unit step input (FPIC and AFPIC)**

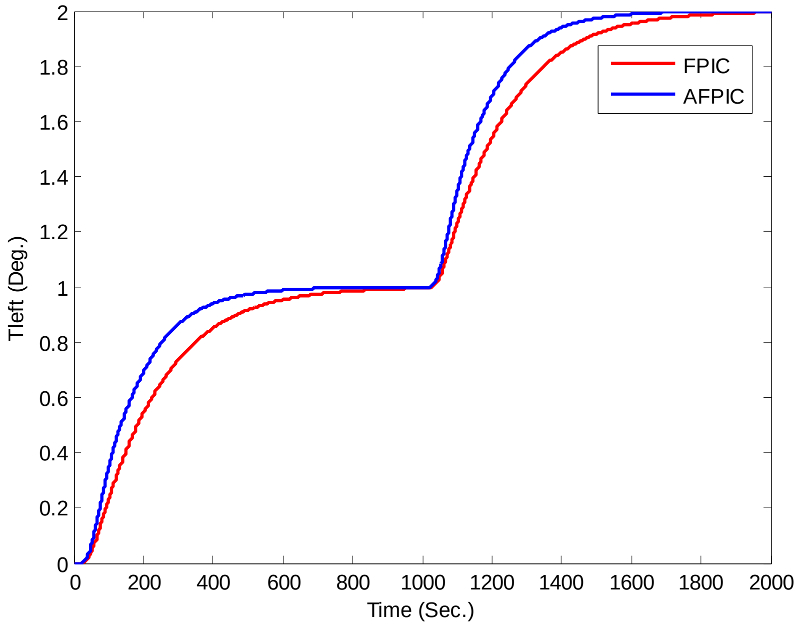

Figure 15 **Output responses of Tleft for different set points (FPIC and AFPIC)**

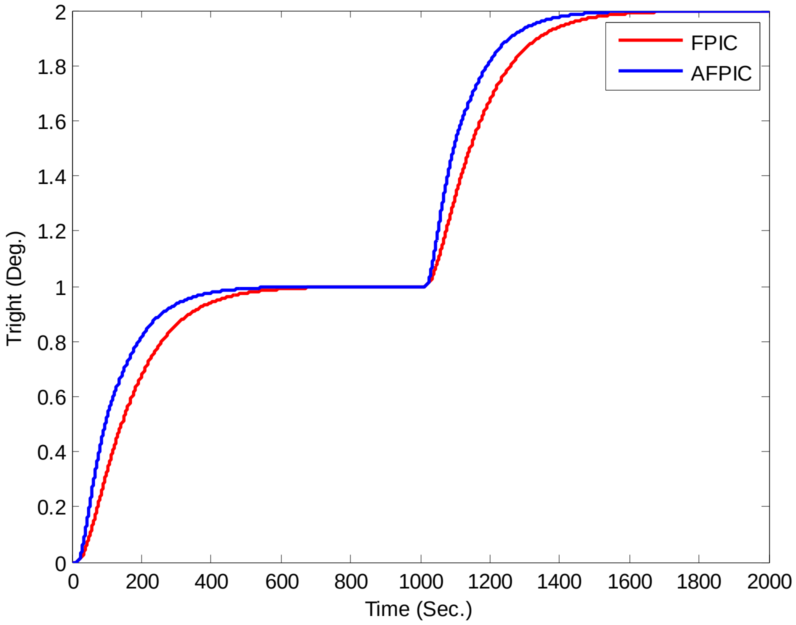

Figure 16Output responses of Tright for different set points (FPIC and AFPIC)

Table 4 Performance analysis of FPIC and AFPIC for unit step input

Process variable	**Type of Controller**	**Performance Measures**			
		IAE	**ISE**	**ITAE**	**Settling time ts (Sec.)**
Tleft	FPIC	9.32	8.74	44.55	744.6
	AFPIC	8.95	8.13	41.62	536.6
Tright	FPIC	8.87	7.99	44.44	532.4
	AFPIC	7.90	6.55	34.41	415.3

Table 5Performance analysis of FPIC and AFPIC with disturbance for unit step input

Prcess variable	**Type of Controller**	**Performance Measures**			
		IAE	**ISE**	**ITAE**	**Settling time ts (Sec.)**
Tleft	FPIC	10.78	9.81	60.65	1054
	AFPIC	10.16	8.87	54.97	1051
Tright	FPIC	10.15	8.80	55.40	1061
	AFPIC	8.77	6.94	43.98	954.9

Table 6Performance analysis of FPIC and AFPIC with 20% variation in gain for unit step input

Process variable	Type of Controller	Performance Measures			
		IAE	ISE	ITAE	Settling time ts (Sec.)
Tleft	FPIC	9.26	8.64	44.13	767.0
	AFPIC	9.02	8.26	42.27	547.9
Tright	FPIC	8.97	8.13	42.12	557.1
	AFPIC	8.03	6.74	35.34	405.0

Table 7 Performance analysis of FPIC and AFPIC with 10% variation in time constant for unit step input

Process variable	Type of Controller	Performance Measures			
		IAE	ISE	ITAE	Settling time ts (Sec.)
Tleft	FPIC	9.37	8.82	44.92	730.0
	AFPIC	9.02	8.24	42.18	525.4
Tright	FPIC	8.95	8.10	41.92	518.0
	AFPIC	7.99	6.68	35.02	409.1

Table 8 Performance analysis of FPIC and AFPIC with set point change

Process variable	Type of Controller	Performance Measures			
		IAE	ISE	ITAE	Settling time ts (Sec.)
Tleft	FPIC	25.35	34.50	122.09	1627
	AFPIC	23.57	29.60	111.90	1453
Tright	FPIC	23.75	30.19	112.82	1448
	AFPIC	21.03	23.86	97.65	1348

6. CONCLUSION

The output responses of FPIC and Analytically tuned FPIC have been simulated using MATLAB for the room temperature control loop of HVAC system (second order MIMO process). The controller is subjected to set point changes, disturbances as well as subjected to variations in gain and time constant. The performance comparison is made in terms of the performance measures, settling time, IAE, ISE and ITAE to demonstrate the effectiveness of the proposed controllers.

The FPIC behaves effectively and maintains the set point inspite of the input set point variations, disturbances and variations in gain and time constant. Its settling time, ISE, IAE and ITAE at the time of parameter variation are also less. The FPIC tracks the set point without steady state error.The Analytically tuned FPIC behaves effectively and gives an improved performance by minimum settling time and minimum IAE,ISE and ITAE both under normal as well as at the instant of parameter variation. The Analytically tuned Fuzzy PI Controller provides quick settling time under set point changes and under variations in gain and time constant compared to the FPIC.Thus the designed Analytically tuned FPIC when compared with the other FPIC shows improved performance.

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