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Fuzzy Self-Adaptive PID Controller Design for Electric Heating Furnace

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Abstract*—This paper deals with the importance of fuzzy logic based self-adaptive PID controller in the application of temperature process control of an electric heating furnace [1]. Generally, it is necessary to maintain the proper temperature in the heating furnace. In common, PID controller is used as a process controller in the industries. But it is very difficult to set the proper controller gains. Also because of nonlinear and large inertia characteristics of the controller [2], often it doesn't produce satisfactory results. Hence, the research is going on for finding proper methods for overcoming these problems. Taking this aspect into consideration, this paper proposes methods to choose the optimum values for controller gains (proportional, integral, and derivative), fuzzy logic based intelligent controller and also fuzzy logic based self-adaptive PID controller for temperature process control. This paper comprises the comparison of dynamic performance analysis of Conventional PID controller, fuzzy based intelligent controller and fuzzy based self-adaptive PID controller. The whole system is simulated by using MATLAB/Simulink software. And the results show that the proposed fuzzy based self- adaptive PID controller [3] has best dynamic performance, rapidity and good robustness.

***Keywords*—Electric heating furnace, PID tuning methods, Fuzzy based self-adaptive PID controller, Mat lab, Simulink.**

I. INTRODUCTION

The term electric furnace refers to a system that uses the electrical energy as the source of heat. Electric furnaces are used to make the objects to the desired shapes by heating the solid materials below their melting point temperatures. Based on the process in which the electrical energy converted into heat, electric furnaces are classified as electric resistance furnaces, electric induction furnaces etc. In industries, the electric furnaces are used for brazing, annealing, carburizing, forging, galvanizing, melting, hardening, enameling, sintering, and tempering metals, copper, steel and iron and alloys of magnesium.

Figure.1 shows the schematic diagram for Electric arc furnace. There are three vertical rods inserted into the chamber act as electrodes. When current is passed through them, they produce arc between them. Material to be heated (steel) is placed in between the electrodes touching the arc. This arc is produced until the material reaches the desired temperature. Then the molten steel can be collected at bottom of the chamber. There are two types of arcs. Those are direct arc and indirect arc. The direct arc is produced between the electrodes and the charge making charge as a part of the electric circuit. The indirect arc is produced between the electrodes and heats the material to be heated. Open arc furnaces, DC furnaces, arc-resistance furnace etc. comes under direct arc furnaces.

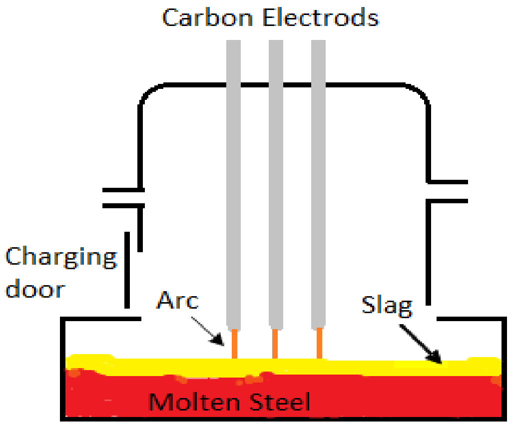


Figure.1 Electric arc furnace

In general, the in industries, PID (Proportional + Integral +Derivative) controller is used for process control because of good characteristics like high reliability, good in stability, and simple in algorithm. However, controlling with PID is a crisp control; the setting of values for gain parameters is quite a difficult and time consuming task. Often, response with PID controller [5] has large peak overshoots. Many papers have proposed different tuning algorithms to reduce this problem. But still it is a challenging task to set PID gains.

PID controller is suitable only for linear systems with known mathematical models. But controlling of temperature of electric furnace is a non-linear, time delay time varying. Hence, conventional PID controllers can't produce satisfactory results when it is used to control the temperature of the electric furnace.

To get rid out of this problem, this introduces fuzzy logic controller to control the temperature. But still it has steady state error. To reduce this error, this paper also introduces self-adaptive PID controller based on fuzzy to get the best performance of the system. In self-adaptive fuzzy controller, PID gain parameters are tuned by fuzzy controller.

The temperature process [1] of an electric furnace is a common controlled object in temperature control system. It can be shown mathematically by a first order system transfer function. This is given by the equation.1

$$G(S)=\frac{K}{TS+1}e^{-\tau S} \tag{1}$$

Hence, the transfer function for the given electric arc furnace system is given by the equation.2

$$G(S)=\frac{1}{11S+1}e^{-1.8S} \tag{2}$$

Where,

Delay time (τ) = 1.8 sec
Time constant (T) = 11 sec
Static gain (K) = 1

II. PID CONTROLLER DESIGN WITH TUNING ALGORITHMS

A simple controller widely used in industries is PID controller. But, the selection of values for the PID gains is always a tough task. Hence, in this paper, some algorithms are discussed to tune the PID gain parameters. They are given below.

- Pessen's tuning algorithm
- Continuous cycling tuning algorithm
- Tyreus-luyben tuning algorithm
- Damped cycling tuning algorithm

The procedural steps for applying pessen's, continuous cycling and damped cycling tuning algorithms are as follows.

Step-1: Design the system with only proportional controller with unity feedback.
Step-2: Adjust the proportional gain value until the system exhibits the sustained oscillations.
Step-3: This gain value represents critical gain (K_C) of the system. Note the time period of oscillations (T_C). This time represents the critical time period.
Step-4: From these K_C and T_C values, calculate PID parameter gains. [7, 15]

The procedural steps for applying damped cycling tuning algorithm are as follows.

Step-1: Design the system with only proportional controller with unity feedback.
Step-2: Make sure that the P-control is working with SP changes as well as with preset value changes.
Step-3: Put controller in automatic mode to obtain damped cycling.
Step-4: Apply a step change to the SP and observe how the preset value settles.
Step-5: Adjust the proportional gain of the system until damped oscillations occurs. This gain value represents K_C
Step-6: From the response, note the values of first and second peak overshoots and then calculate PID gain parameters. [15]

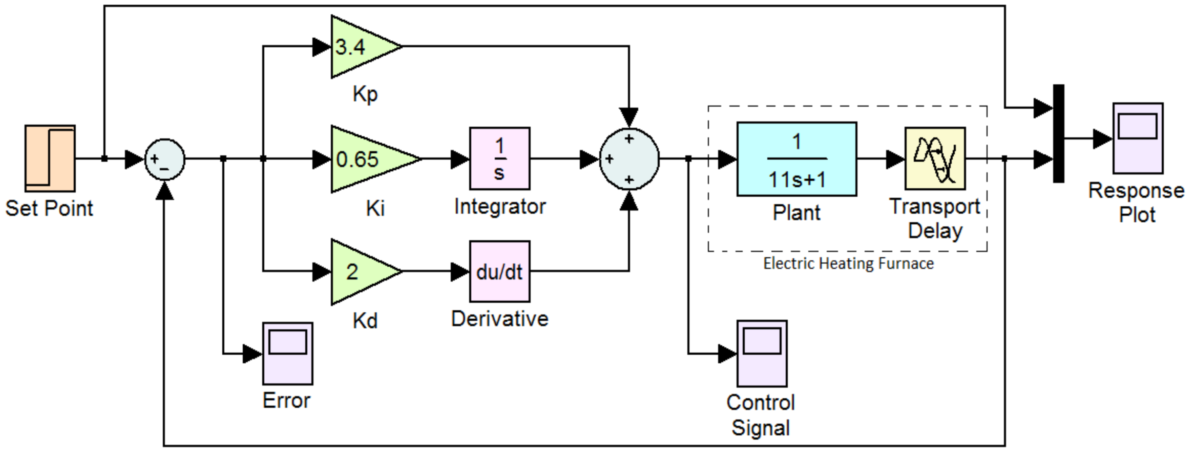


Figure.2 Conventional PID controller design

Figure.2 shows the conventional PID controller design. The values of K_P, K_I and K_D that are calculated from the algorithms are applied to the model and observed the responses. Table.1 gives the values for PID gain parameters calculated from all tuning methods. The responses with different algorithms are shown in figures [11-15].

TABLE.1 PID GAIN PARAMETER VALUES

S. No.	Method Name	K_P	T_I	K_I	T_D	K_D
1	Pessen's method	3.432	3.4	1.009	2.266	7.776
2	Continuous cycling	2.08	6.8	0.305	3.266	4.713
3	Tyreus-luyben	4.68	14.96	0.312	1.079	50.127
4	Damped cycling	9.324	2.33	2.354	0.252	5.484

III. SYSTEM DESIGN WITH FUZZY LOGIC CONTROLLER

Fuzzy logic control [14] can be used even when the process is a non-linear, time varying. The control temperature of the electric furnace is a non-linear. Hence, we can apply fuzzy control to the temperature process control. Fuzzy control has become one of the most successful methods to design a sophisticated control system. It fills the gap in the engineering tools which are left vacant by purely mathematical and purely intelligent approaches in the design of the system. A fuzzy control system is the one that is designed on fuzzy logic. The fuzzy logic system is a mathematical system that analyses the input analog values in terms of logical values between 0 and 1 as shown in figure.3

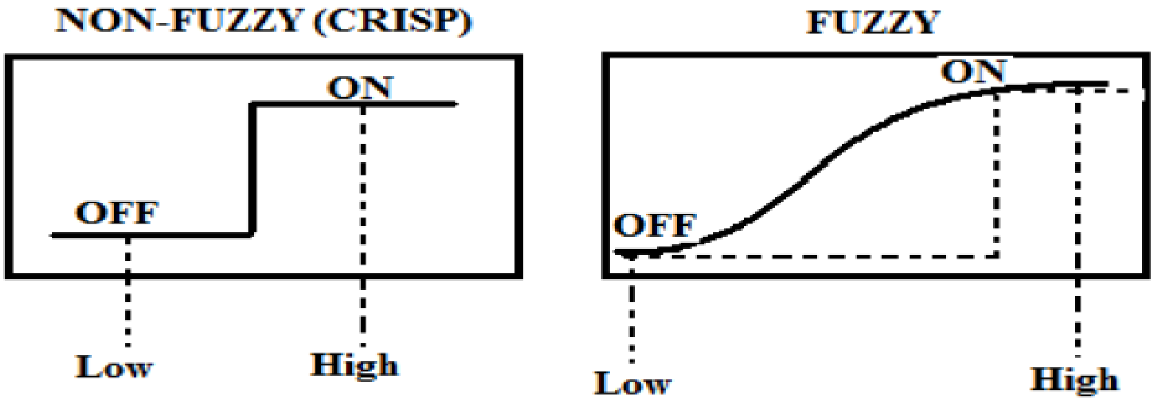


Figure.3 Difference between crisp and fuzzy

Figure.4 shows the elements of a fuzzy logic system. Fuzzy logic defines the control logic in a linguistic level. But the input values (Measured variables) are generally in numerical. So, Fuzzification needs to be done. Fuzzification is a process of converting numerical values of measured variable to the linguistic values. Fuzzy inference structure converts the measured variables to command variables according its structure.

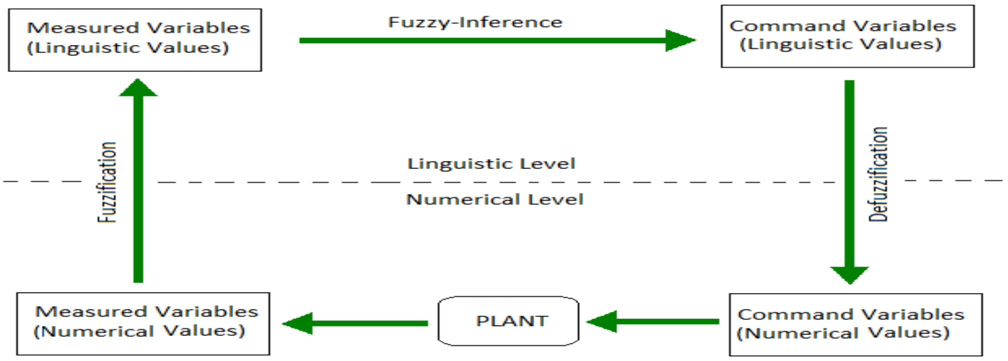


Figure.4 Basic elements of a fuzzy logic system

Figure.5 shows the MATLAB model of the system fuzzy logic controller. It takes two inputs namely error signal and change in error.

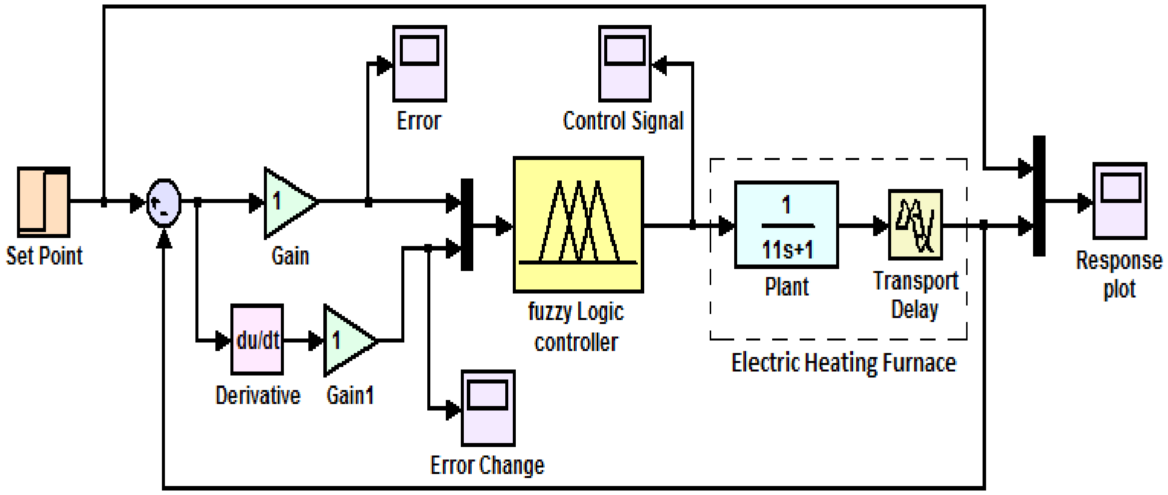


Figure.5 MATLAB/Simulink model for Fuzzy logic controller

[1] Fuzzy membership functions

Fuzzy set is described by its membership functions [16]. It categorizes the element in the set, whether continuous or discrete. The membership functions can be represented by using graphs. There are some constraints regarding usage of the shapes. The rules that are to be written to characterize the fuzziness are also fuzzy. The shape of the membership function to be considered is one of the important criteria. Membership function is represented by a Greek symbol “µ”. The commonly used shapes for the membership functions are triangular, Gaussian and trapezoidal. Gaussian shape membership function is preferred for temperature process control. But for temperature control in electric furnace it is better to consider the triangular membership functions which is similar to Gaussian function to make the computation relatively simple. Figure.6 shows the selection of membership functions for the input and outputs for the fuzzy logic controller. Figure.7 shows the input membership function editor for fuzzy logic controller.

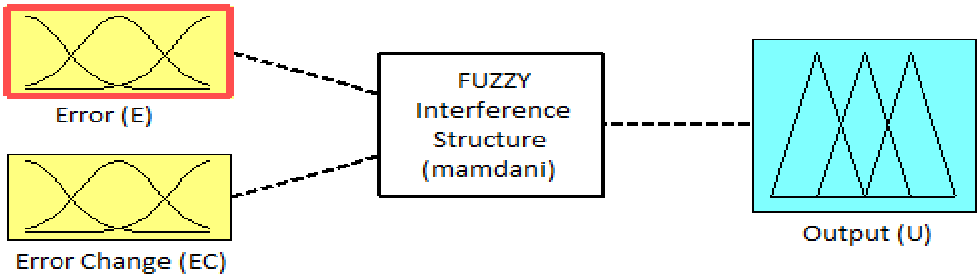
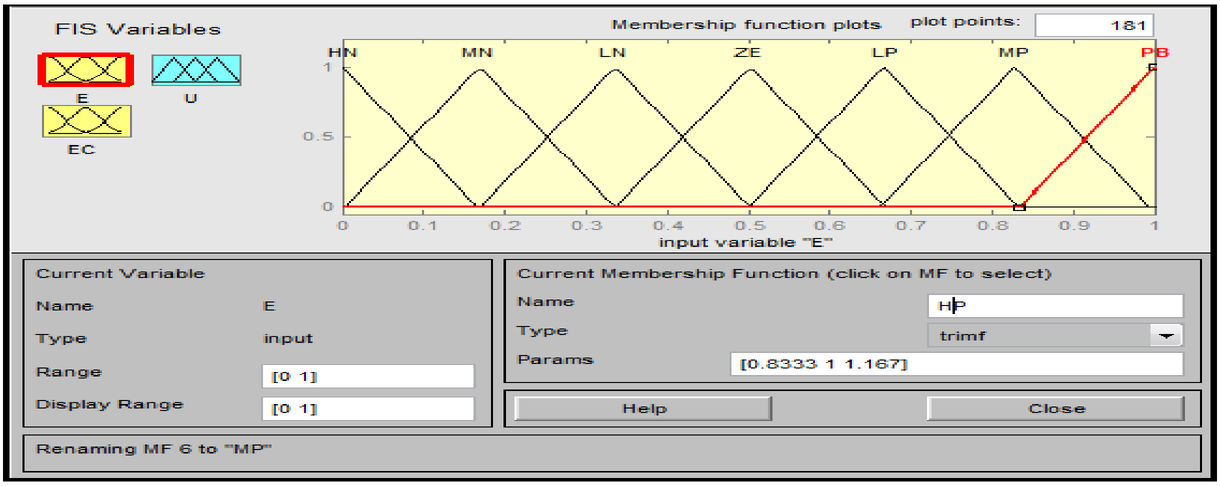


Figure.6 Selection inputs/outputs for designing fuzzy inference structure for fuzzy logic controller



plot points: 181

Current Variable
Name E
Type input
Range [0 1]
Display Range [0 1]

Current Membership Function (click on MF to select)
Name HP
Type trimf
Params [0.8333 1 1.167]

Renaming MF 6 to "MP"

Figure.7 Membership function editor for fuzzy logic controller

The basic methods for fuzzification are sugeno and mamdani. And some defuzzification methods are middle of maximum, quality method, mean of maxima, first of maximum, semi linear defuzzification, last of maximum, center of gravity, fuzzy clustering defuzzification, and adaptive integration. This paper uses the mamdani fuzzification method.

[2] Fuzzy inference structure

The steps performed by the fuzzy rule based inference structure are given as follows [13]

Fuzzification: It is a mapping from the observed input to the fuzzy sets. The input data match the condition of the fuzzy rules. Therefore, fuzzification is a mapping to the unit hypercube 0 and 1.

Inference Process: It is a decision making logic which determines fuzzified inputs corresponding to fuzzy outputs, according with the Fuzzy rules.

Defuzzification: It produces a non-fuzzy output, for application purpose that needs a crisp output. This process is used to convert a Fuzzy conclusion into a crisp.

[3] Fuzzy rules for developing FIS

Generally human beings take decisions which are like if-then rules in computer language. Suppose, it is forecasted that the weather will be bad today and fine tomorrow then nobody wants to go out today and postpones the work to tomorrow. Rules associate with ideas and relate one event to the other.

TABLE.2 IF-THEN STATEMENTS FOR FUZZY INFERENCE SYSTEM FOR FUZZY CONTROLLER

1. If E = HN and EC = HN Then U = HP
2. If E = HN and EC = MN Then U = HP
3. If E = HN and EC = LN Then U = HP
4. If E = HN and EC = ZE Then U = HP

……..

……..

……..

47. If E = HP and EC = LP Then U = HN
48. If E = HP and EC = MP Then U = HN
49. If E = HP and EC = HP Then U = HN

The decision makings are replaced by fuzzy sets and rules by fuzzy rules. Table.2 shows some fuzzy rules written for the fuzzy inference structure.

TABLE.3 FUZZY RULES FOR DEVELOPING FUZZY INFERENCE STRUCTURE (FIS) FOR FUZZY LOGIC CONTROL

E EC U	**HN**	**MN**	**LN**	**ZE**	**LP**	**MP**	**HP**
HN	HP	HP	HP	HP	MP	LP	ZE
MN	HP	HP	MP	MP	LP	ZE	LN
LN	HP	HP	MP	LP	ZE	LN	MN
ZE	HP	MP	LP	ZE	LN	MN	HN
LP	MP	MP	ZE	LN	MN	HN	HN
MP	LP	ZE	LN	MN	MN	HN	HN
HP	ZE	LN	MN	HN	HN	HN	HN

Where, HP - High Positive; MP - Medium Positive; LP - Low Positive; ZE - Zero Value; LN - Low Negative; MN - Medium Negative; HN - High Negative.

IV. SYSTEM DESIGN WITH FUZZY-PID CONTROLLER

The conventional PID controller [12] parameter gains are always obtained by some testing methods. These methods have low precision and takes long time for debugging. In the recent years, several approaches are proposed PID design based on intelligent algorithms mainly the fuzzy logic method. This method takes the advantage of both conventional PID control and fuzzy logic control. Figure.8 shows the design of the system with fuzzy-PID controller.

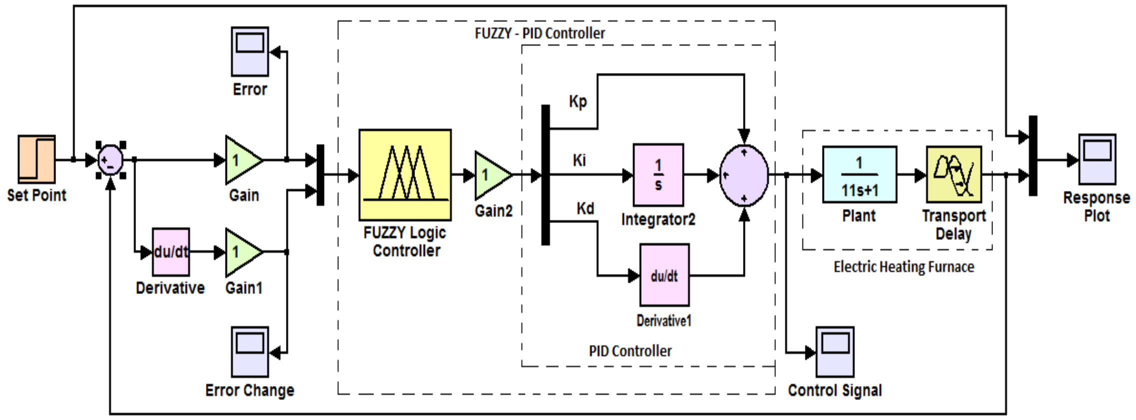


Figure.8 MATLAB/Simulink model with fuzzy-PID controller

Figure.9 shows the selection of inputs and outputs for design of FIS for fuzzy-PID controller. In this error and error change in error are considered as inputs, PID controller parameter gains (proportional + integral + derivative) are considered as the outputs for fuzzy logic control. These PID parameter gains are given to the conventional PID control block. Figure.10 shows the membership function editor for fuzzy-PID controller.

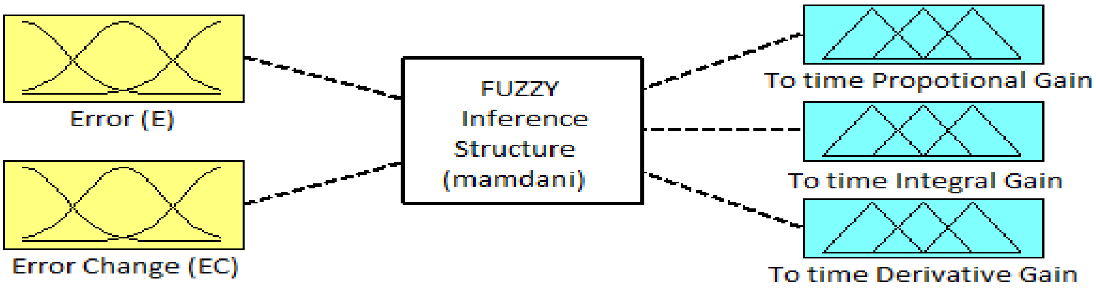
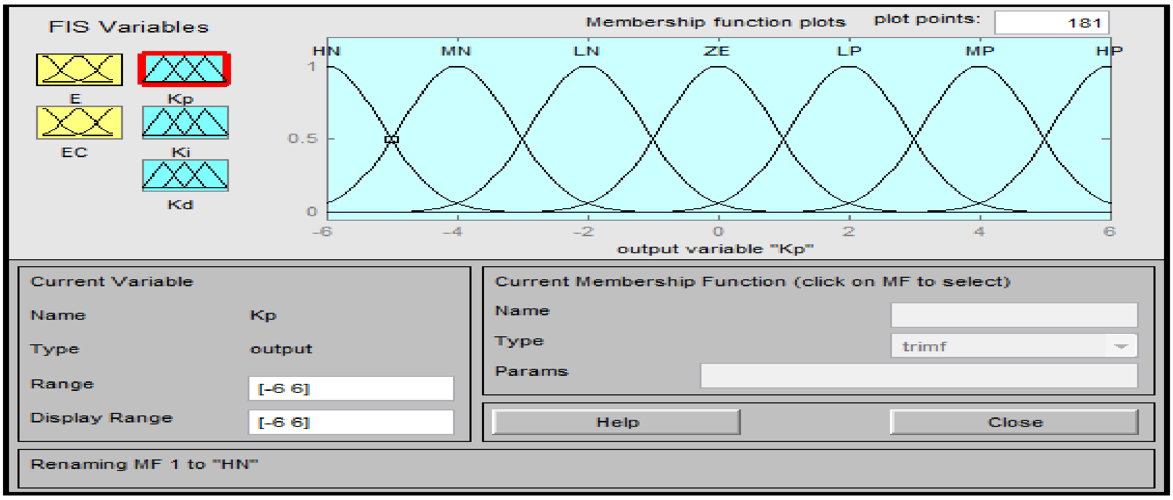


Figure.9 Selection inputs/outputs for designing fuzzy inference structure for fuzzy-PID controller



plot points: 181

Current Variable

Name Kp

Type output

Range [-6 6]

Display Range [-6 6]

Current Membership Function (click on MF to select)

Name

Type trimf

Params

Renaming MF 1 to "HN"

Figure.10 Membership function editor for fuzzy-PID controller

TABLE.4 IF-THEN STATEMENTS FOR FUZZY INFERENCE SYSTEM FUZZY-PID CONTROLLER

1) If (E is HN) and (EC is HN) then
(K_P is HP) (K_I is HN) (K_D is LP)
2) If (E is HN) and (EC is MN) then
(K_P is HP)(K_I is HN)(K_D is LP)
………….
49) If (E is HP) and (EC is HP) then
(K_P is HN)(K_I is HP)(K_D is HP)

TABLE.5 FUZZY RULES FOR DEVELOPING FUZZY INFERENCE STRUCTURE (FIS) FOR FUZZY-PID CONTROLLER

	E	HN	MN	LN	ZE	LP	MP	HP
Ec	K_P K_I K_D							
HN		HP HN LP	HP HN LN	MP MN HN	MP MN HN	LP LN HN	ZE ZE MN	ZE ZE LP
MN		HP HN LP	HP HN LN	MP MN HN	LP LN MN	LP LN MN	ZE ZE LN	LN ZE ZE
LN		MP HN ZE	MP MN LN	MP LN MN	LP LN MN	ZE ZE LN	LN LP LN	LN LP ZE
ZE		MP MN ZE	MP MN LN	LP LN LN	ZE ZE LN	LN LP LN	MN MP LN	MN MP ZE
LP		LP MN ZE	LP LN ZE	ZE ZE ZE	LN LP ZE	LN LP ZE	MN MP ZE	MN MP ZE
MP		LP ZE HP	ZE ZE LN	LN LP LP	MN LP LP	MN MP LP	MN HP LP	HN HP HP
HP		ZE ZE HP	ZE ZE MN	MN LP MP	MN MP MP	MN MP LP	HN HP LP	HN HP HP

The output variables and certainty outputs are given by the equation. (3-5) from those values, the PID gain parameters based on fuzzy-PID control are given by the equations.(6-8)

$$K_P^{*} = f_1(E,Ec) = \frac{\sum_{j=1}^{n} \mu_j(E,Ec) K_{Pj}}{\sum_{j=1}^{n} \mu_j(E,Ec)} \tag{3}$$

$$K_I^{*} = f_2(E,Ec) = \frac{\sum_{j=1}^{n} \mu_j(E,Ec) K_{Ij}}{\sum_{j=1}^{n} \mu_j(E,Ec)} \tag{4}$$

$$K_D^{*} = f_3(E,Ec) = \frac{\sum_{j=1}^{n} \mu_j(E,Ec) K_{Dj}}{\sum_{j=1}^{n} \mu_j(E,Ec)} \tag{5}$$

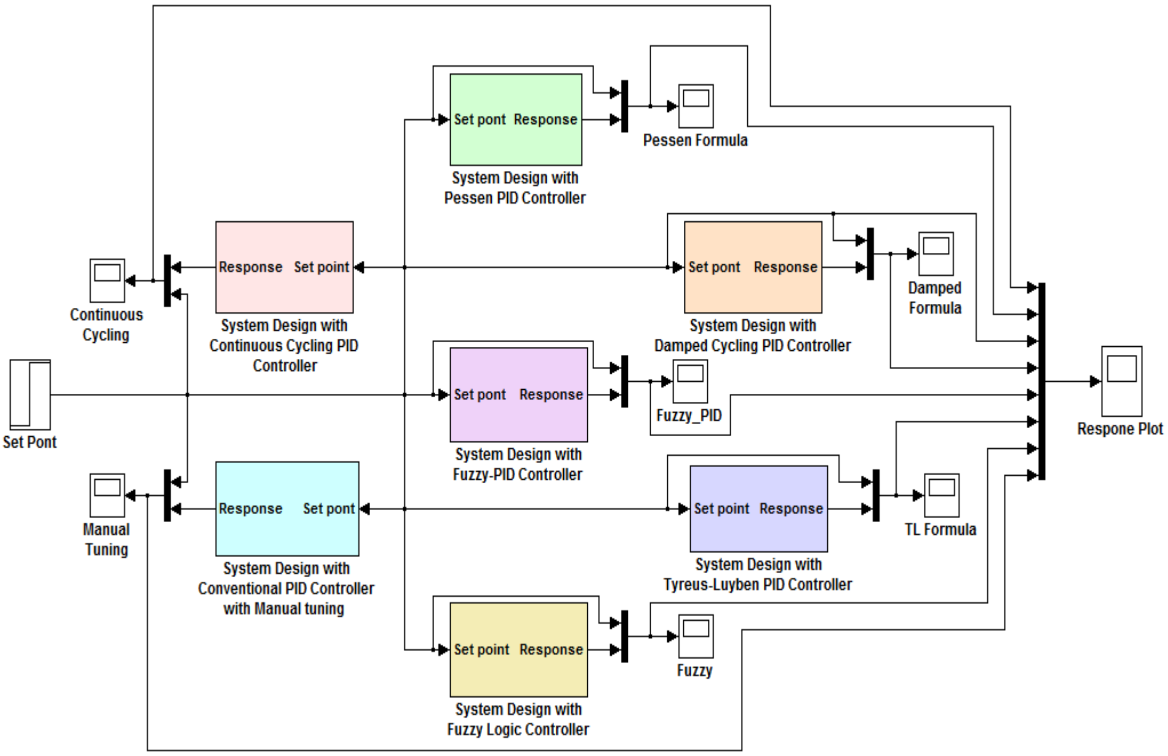


Figure.11 MATLAB/Simulink model for comparison of system responses with different controllers

Here, 'µ' refers to the membership function of fuzzy set; 'n' refers to the number of single-point set. K_{Pj}, K_{Ij} and K_D^* are output variables, K_P^*, K_I^* and K_D^* are certainty outputs. The PID gain parameters can be calculated as follows.

$$K_P = K_P^{!} + K_P^{*} \tag{6}$$

$$K_I = K_I^{!} + K_I^{*} \tag{7}$$

$$K_D = K_D^{!} + K_D^{*} \tag{8}$$

V. SIMULATION RESULTS

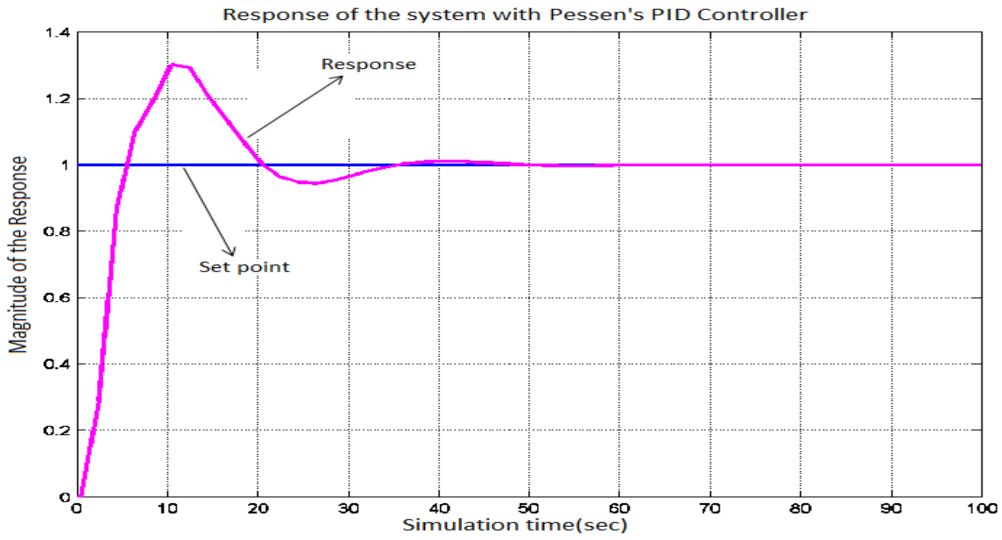


Figure.12 Response of the system with Pessen's PID controller

Figure.11-14 show the responses of the system with conventional PID controller when it is tuned with pessen's, continuous cycling, Tyreus-luyben and damped cycling tuning algorithms. Figure.15 shows the comparison of the responses of the system with above tuning algorithms.

Figure.16 shows the response of the system with fuzzy logic controller. It has some steady state error. But it is eliminated by using with fuzzy-PID controller. Figure.17 shows the response of the system with fuzzy-PID controller. The responses of these two methods are compared in figure.18

Table.6 shows the comparison of the transient response parameters when system is designed with different PID control strategies.

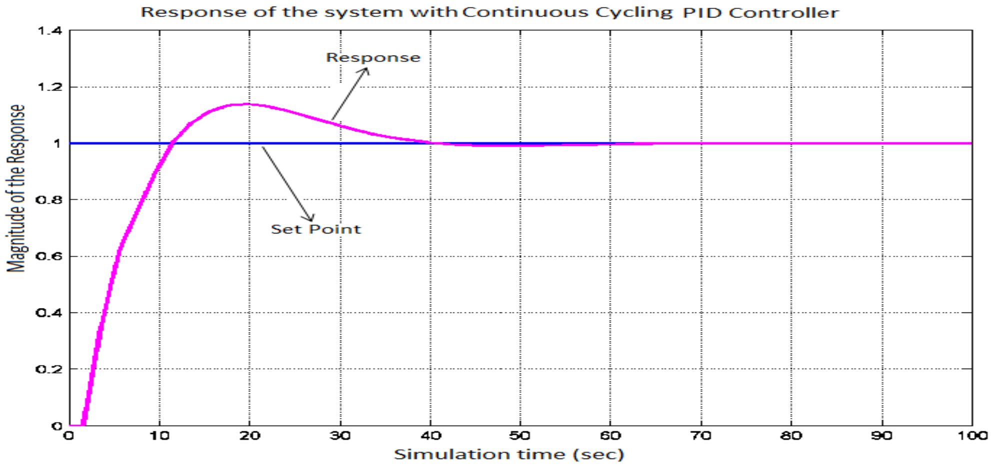


Figure.13 Response of the system with continuous cycling PID tuning method

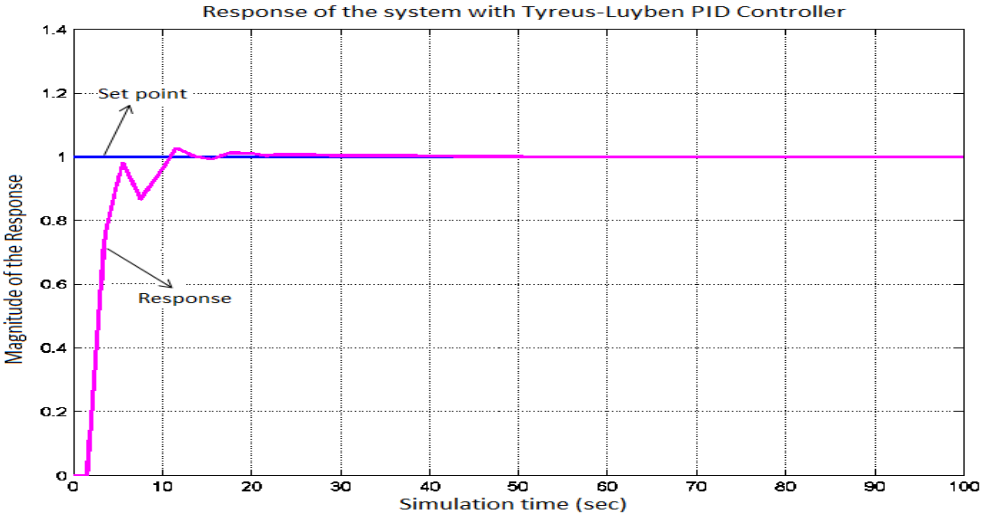


Figure.14 Response of the system with Tyreus-luyben method

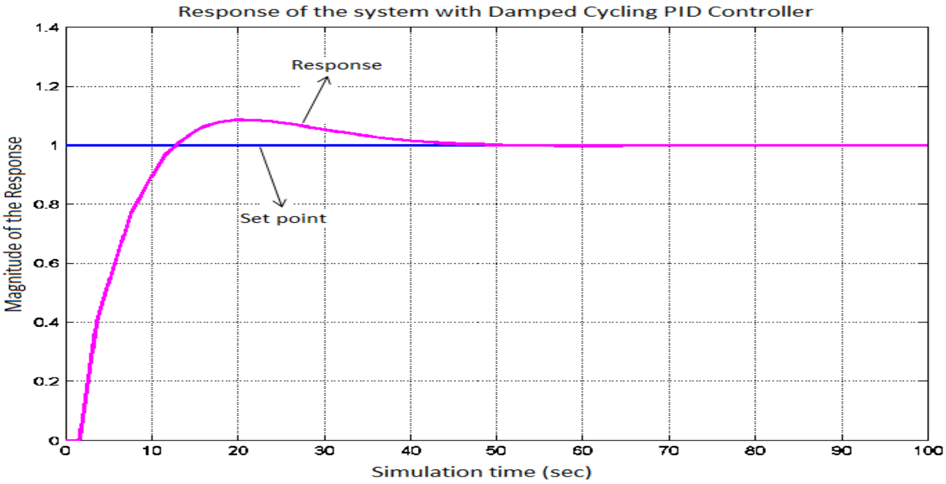


Figure.15 Response of system with damped cycling method

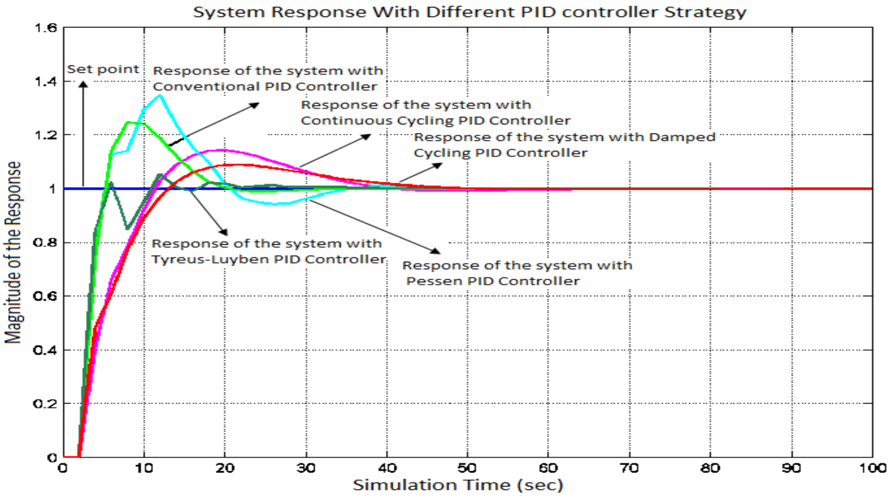


Figure.16 Comparison of responses with various tuning algorithms

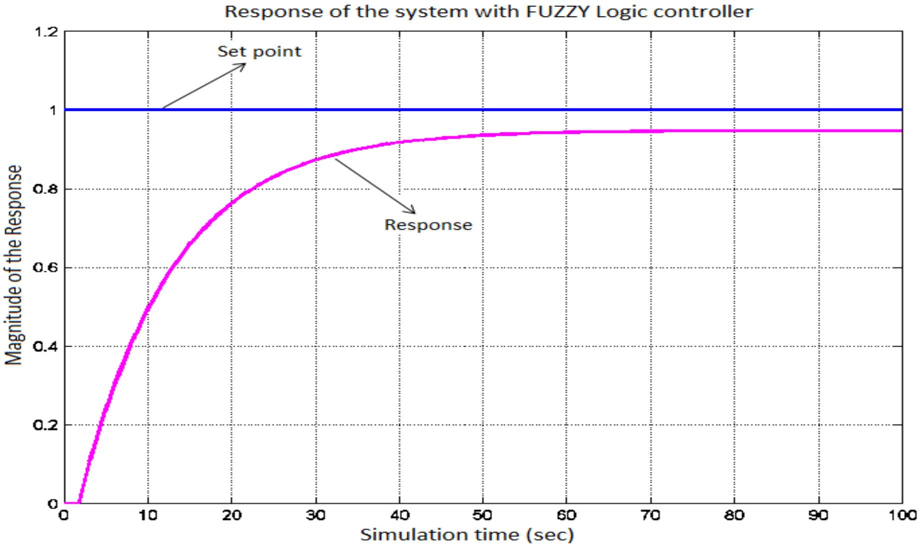


Figure.17 Response of the system with fuzzy logic controller

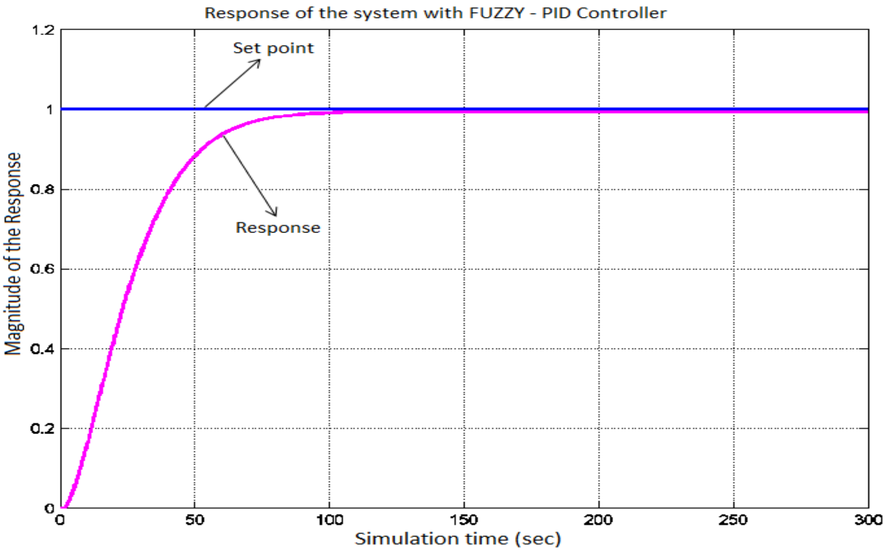


Figure.18 Response of the system with Fuzzy-PID controller

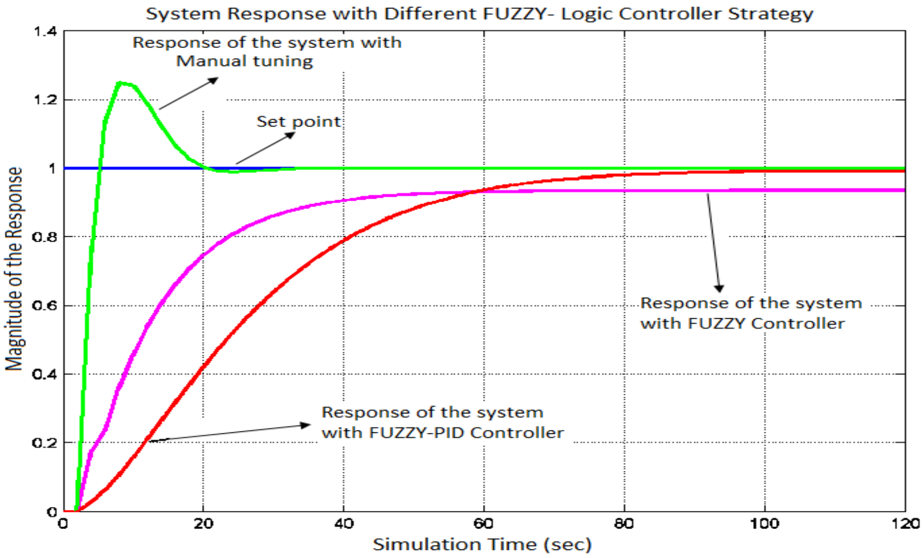


Figure.19 Comparison of responses with fuzzy and fuzzy-PID controllers

TABLE.6 COMPARISON OF TIME DOMAIN PERFORMANCE PARAMETERS FOR VARIOUS CONTROLLING METHODS

S. No.	***Controller Used***	***Time Domain Performance Parameters***					
		Delay Time (T_d) in Sec	***Rise Time (T_r) in Sec***	***Settling Time (T_s) in Sec***	***Peak Overshoot (M_P) in %***	***Transient Behavior***	***% Steady state Error (E_{SS})***
1.	Pessen's PID Controller	2.425	3.408	50.6	33.5	Oscillatory	0
2.	Damped Cycling PID Controller	3.07	7.828	51.6	8.6	No Oscillatory	0
3.	Continuous Cycling PID Controller	3.208	7.644	67.13	13.5	No Oscillatory	0
4.	Tyreus-Luyben PID Controller	1.289	3.131	52.85	2.7	Less Oscillatory	0
5.	Fuzzy Logic Controller	1.382	32.54	123.18	No overshoot	Smooth	5.8
6.	Fuzzy-PID Controller	21.55	45.85	101.53	No overshoot	Smooth	0.2

VI. CONCLUSION

Hence, in this paper firstly, the conventional PID controller is used as temperature process controller for Electric Heating Furnace System. Later on fuzzy logic based intelligent controller is introduced for the same. The performance of both is evaluated against each other and from the Table 6, the following parameters [8] can be observed.

1) Even though, the PID controller produces the response with lower delay time, rise time and settling time, it has severe oscillations with a very high peak overshoot of 2.7%. This causes the damage in the system performance

2) To suppress these severe oscillations Fuzzy logic controller is proposed to use. From the results, it can be observed that, this controller can effectively suppress the oscillations and produces smooth response. But it is giving a steady state error of 5.8%.

3) Furthermore, to suppress the steady state error, it is proposed to use Fuzzy-PID controller, where the PID gains are tuned by using fuzzy logic concepts and the results show that this design can effectively suppress the error to 0.2% while keeping the advantages of fuzzy controller.

Hence, it is concluded that the conventional PID controller could not be used for the control of non-linear processes like temperature. So, the proposed fuzzy logic based controller design can be a preferable choice to achieve this

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