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Comparative analysis of PID and fuzzy logic controller: A case of furnace temperature control

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Abstract

Furnace temperature controller has a large overshoot and constant oscillation error. To solve this problem there are several studies done on the PID type furnace temperature controller with different PID parameters, but this method is not efficient because of the nonlinearity of temperature. Due to this reason, the overshoot happens and steady-state errors are observed. Other researchers have shown that the inclusion of one more controller with a PID controller, such as a fuzzy logic controller can improve the results as compared to the use of the PID controller alone. The objective of this research is to experiment on the PID and fuzzy logic controller hardware and compare the results with those obtained from the simulation. In addition to this, the objective also is to find out the type of controller that would be most efficient in terms of settling time and the overshoot. This paper presents the comparison of PID and fuzzy logic controller simulation and experimentation on the hardware of the same. Results show that the fuzzy logic controller is slightly better than the PID controller in terms of the settling time. The PID controller is better than fuzzy logic in terms of peak overshoot. Better results can be obtained from the fuzzy logic controller by increasing the number of inputs or membership functions.

Keywords*: *fuzzy logic, furnace temperature controller, membership functions, peak overshoot, PID, settling time

1. Introduction

In the olden days, the furnace temperature used to be controlled by human operators, who controlled the furnace temperature by controlling the amount of coal or gas. In the later times, the on/off controller was used, which automatically switched on the heating element when the temperature went below the set-point and switched that off when the temperature went above the set point. The limitation of the on/off controller was that there was a significant overshoot in the whole process. After this, the PID controller came as an alternative, which were more efficient than the on/off controller (Ang, Chong, & Li, 2005). In the PID controller, there are PID parameters known as proportional gain (Kp), integral gain (Ki) and derivative gain (Kd). Also, there are tuning methods such as Ziegler–Nichols (Z-N) method, modified Z-N method, and Tyreus-Luyben method (Kumar, Rajesh, Yugandhar, & Srikanth, 2013), which give optimum values for Kp, Ki, and Kd. The ideal PID controller is no longer used for control of a nonlinear parameter like temperature (Al-Mashakbeh, 2009). However, there is a limitation too, that it is not efficient to control such a nonlinear parameter. There are various methods used to overcome this problem in controlling the furnace temperature. These are cascading PID controller (Kiyak & Gol, 2016), a fuzzy intelligent controller (Bil & Butkiewicz, 1999; Radakovic, Milosevic, & Radakovic, 2002), fuzzy with PI controller (Moon & Lee, 2003) and the fuzzy-PID controller (Wang, Jin, & Zhang, 2017). The fuzzy logic controller is used to overcome some limitations of the traditional PID controller (Kumar, Sujatha, & Anjaneyulu, 2013).

Fuzzy logic is developed to deal with vagueness and uncertainty in the system and it is a soft computing technique (Sakthivel, Snehitkumar, & Ilangkumaran, 2014), which is used to mimic the human reasoning and taking decision according to various inputs. Conventional PID controller and the fuzzy logic controller were used in combination and the results showed improvement in performance as compared to the only conventional controller (Vaishnav & Khan, 2007; Gaurav, 2012; Arulmozhiyal & Kandiban, 2012).

Edalath, Kukreti, and Cohen (2013) showed that in free and forced vibration, fuzzy tune mass damper (TMD) controller performed fundamentally superior to non TMD and most ideal PD controller. Kiyak and Gol (2016) demonstrated that in sun based following framework. The vitality acquired from fuzzy logic controller is expanded to 21.2% in contrast with the non-fuzzy logic controller. Furthermore, FLC was found to be 2.39% productive and steadier than PID controller. Gaurav (2012) showed that by using Simulink model for PID and FLC, the FLC had less settling time and peak overshoot. Transient Behavior in case of FLC was smooth whereas in PID it was Oscillatory. Also, the delay time and rise time in case of FLC was larger as compare to PID controller. Fuzzy logic gives better result than PID but neither fuzzy logic nor PID give as good results as that traditional zero/pole (Jackson, 1994). Munyaneza, Munyazikwiye, and Karimi (2015) showed that fuzzy logic controller had small overshot and small amplitude compared to PID controller. This means that fuzzy controller provides smooth response. Vaishnav and Khan (2007) showed that Fuzzy Logic controller gives no overshoot, zero steady state error and smaller settling time than obtained using Ziegler Nichols tuned PID controller and fine-tuned PID controller. Asere, Lei, and Jia (2015) showed that fuzzy controller has very significant response time, which is 6 seconds, and PI controller took 21 seconds. No overshoot was present in fuzzy controller, which is difficult to achieve in PID controller. Fuzzy logic controller is more robust in case of uncertainty than P-action controller (Ghane & Tarokh, 2013). Xu, L., Xu, T., Wang, and Li, (2017) and Rout, Sain, Swain, and Mishra (2016) showed that the fuzzy PID controller has less overshoot, less settling time and less rise time compared with the traditional PID controller. Previous studies showed that the fuzzy logic controller is more efficient, steadier, and gives fast response time than the PID controller (Rabah, Rohan, & Kim, 2018).

Furnace Temperature Controller has a significant overshoot and constant oscillation error. There are several studies done on the furnace temperature controller to solve this problem with the PID controller with different PID parameters, but it is not efficient as controlling temperature is nonlinear (Pringsakul, Puangdownreong, Thammarat, & Hlangnamthip, 2019). Due to this reason, there is an overshoot and steady-state error. There are other researches, which show that including one more controller with a PID controller like a fuzzy logic controller can improve the results as compared to alone PID controller (Xu, Di, Lu, Liu, & Yuan, 2019). However, PID controller and fuzzy logic controller research done only on simulation in MATLAB. Therefore, there is no implementation of this algorithm on hardware. Besides, there is no comparison for simulation and hardware for the PID controller. The objective of this study is to implement PID and Fuzzy logic controller hardware and compare simulation as well as hardware results. Also, find out which controller works efficiently.

Organization of the paper is as follows: Section 2 describes objectives of the study. Section 3 explains methodology followed by results in Section 4. Discussion and conclusion is given in Section 5 and 6 respectively.

2. Objectives

There are a good deal of research and comparative studies of PID and Fuzzy-PID controllers but there is not any research or comparative study on the use of PID and Fuzzy logic controller on furnace, as per the best of author’s knowledge. In response to this problem, Research Objectives (ROs) of the study are as follows:

RO1: To implement the PID and fuzzy logic controllers and find the best PID parameter and fuzzy logic membership function.

RO2: To implement PID and fuzzy logic hardware with reference to less overshoot and less settling time as possible and overcome limitation of PID controller.

RO3: To develop PID and Fuzzy logic controller to investigate which controller works efficient PID or Fuzzy in terms of settling time and maximum peak overshoot.

3. Methodology

A Furnace Temperature Controller should control the temperature with minimum overshoot, less or no steady state error and with less settling time. However, the prevailing furnace temperature controllers have large overshoot and constant oscillation error. There are many studies done on the furnace temperature controllers to solve this problem with PID controller with different PID parameters. But this option has been observed to be inefficient due to the controlling temperature being nonlinear. Due to the same reason, the overshoot and steady state error also occur. There are other researches, which have showed that including one more controller with PID controller such as fuzzy logic controller can improve the results as compared to the use of PID controller alone. There is one more problem with PID controller and ON/OFF controller that after reaching set point the power supply to the heating coil cuts off and the temperature decreases rapidly and the temperature doesn't not increase quickly even after powering the heating coil.

Figure 1 (a) shows actual hardware setup of the furnace, whereas Figure 1 (b) shows schematic diagram of the same.

Figure 1 (a) Hardware setup

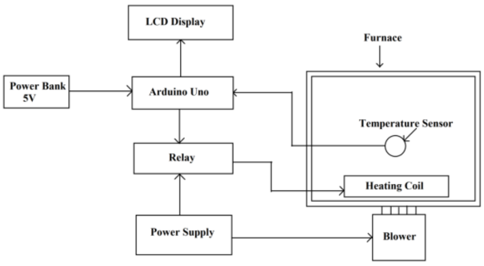

Figure 1 (b) Schematic Diagram of hardware setup

Arduino Uno is the microcontroller which controls the relay, the relay in turn controls the heating coil power and so the temperature. There is a temperature sensor inside the furnace, which measures temperature and sends the signal to Arduino Uno, which decides the relay to be on or off based on the algorithm. Blower is just below the heating coil. LCD display is used to display results and the set point. Arduino Uno is powered with 5V using mobile phone power bank. Transfer function of the system was found using plotting furnace temperature verses time curve, followed by PID Auto tuning. Annexure I details about procedure used to find Transfer Function of Furnace. Figure 2 shows Simulink Model for PID controller.

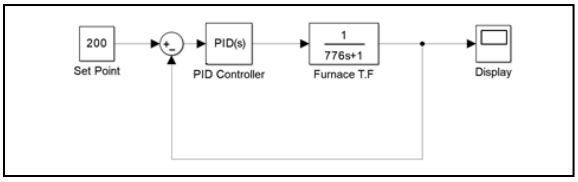

Figure 2 Simulink Model for PID Controller

Development of membership function for Fuzzy Logic Controller was done through three experiments. The first experiment with 5-singleton membership functions, second with 6-singleton membership functions and the third with 7-singleton membership functions. Singleton membership was shown by a spike and used to compare results between simulation and hardware (Arya, 2007). MATLAB software supports different membership functions such as triangular, trapezoidal, sigmoidal etc. (Elias, Yahya, & Sing 2018). It was difficult to implement these membership functions in hardware (Ersoyoglu, Ata, Dincer, Önal, & Yilmaz, 2017). Thus this study uses singleton membership function Figures 3 and 4 show the input and output membership functions respectively for 7-singleton membership functions.

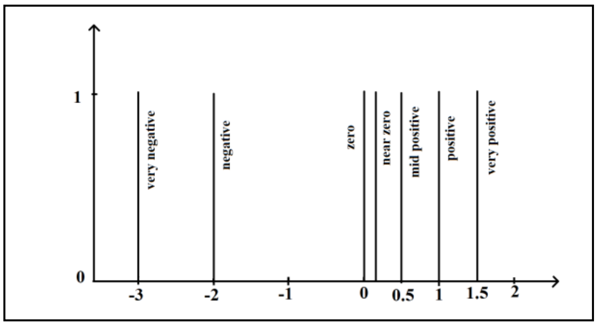

Figure 3 Input membership function

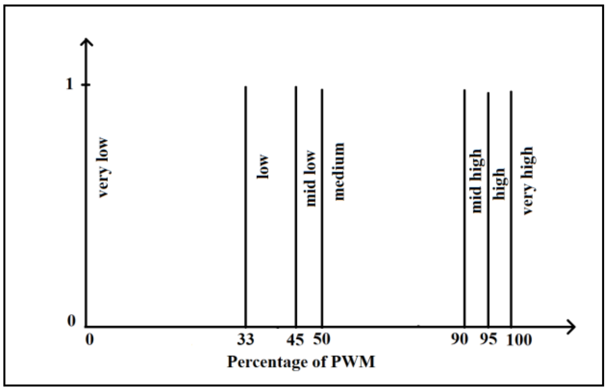

Figure 4 Output membership function

Finding a membership function and rule base for fuzzy logic controller is main task. Without this fuzzy logic controller cannot exist. While doing experiment of PID controller, it is observed that when temperature reaches set point PID algorithm turn off relay hence heating coil. Even for few seconds heating coil is off. It dropped temperature significantly. Therefore, it is known that where to make changes to hold that temperature. So this changes implemented inform of membership function. As it is known that when it hit set point or overshoot, it should turn off relay and hence heating coil. Based on this rule base is created. There is one input, which is error in temperature, and output is percentage of plus width modulation (PWM). Output controlling relay, which switch on and off heating coil hence, it controls furnace temperature.

Rule base was developed followed by three hardware experiments for Fuzzy Logic controller. First experiment with 5-singleton membership function functions, Second with 6-singleton membership function functions and the Third with 7-singleton membership function functions. Figure 5 shows temperature v/s time graph for fuzzy logic controller for 7-singleton membership functions. It also shows the maximum overshoot from set point.

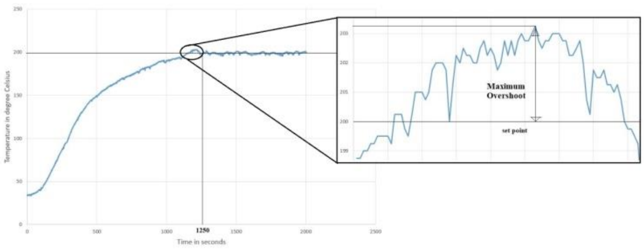

Figure 5 Fuzzy Logic Controller Response for 7-singleton M.F.

4. Results

Results of the PID controller simulation and hardware experiments are compared and percentage error is determined. In the way the PID and fuzzy logic controller results are also compared. Simulation results are taken from Simulink MATLAB model and hardware results are taken from the furnace through Teraterm software. Table 1 shows comparison between simulation and hardware results of the PID controller. As the table shows, results are nearly the same. Settling time in hardware PID controller is slightly more than simulation time. Overshoot percentage is more in the hardware of PID controller. However, from the results of simulation and hardware, it is clear that the highest peak overshoot is 1.5%. The Table1 also shows percentage error with respect to simulation.

Table 1 Comparison between Simulation and Hardware Results of PID controller

Set-up No.	PID Parameters	Settling Time (Sec)		Peak Overshoot (%)		Percentage Error w.r.t Simulation
		Simulation	Hardware	Simulation	Hardware	
1	Kp= 1.94 Ki= 0.003 Kd=103.92	1400	1300	1.35	0.75	-7.14
2	Kp= 1.0605 Ki= 0.0018 Kd= 0	1950	2100	1.325	1.5	7.69
3	Kp= 1.6944 Ki= 0.00263 Kd= 86.8548	1650	1700	1.20	1.5	3.03

PID controller parameters were found by Ziegler–Nichols tuning method. Further auto tuner inbuilt function of Simulink MATLAB was used to validate the parameters. Refer Annexure II for Simulation Results of PID Controller.

Table 2 shows hardware results of Fuzzy Logic Controller. A number of experiment are conducted before performing these three experiments for finding right membership function and the rule base. In each experiment, the number of singleton membership functions is increasing and it is seen that with this increase the results improve. Also, this decreases the settling time but slightly increase overshoot percentage the overshoot percentage slightly increases.

Table 2 Hardware results of fuzzy logic controller

Set-up No.	Number of Singleton Membership Function	Settling Time (Sec)	Peak Overshoot (%)
1	Five	2500	1.25
2	Six	1950	1.375
3	Seven	1250	1.625

Table 3 shows comparison between hardware results of PID and Fuzzy Logic controller. From table the minimum settling time for PID controller is 1300 seconds and minimum peak overshoot percentage is 0.75 and for fuzzy logic controller minimum settling time is 1250 seconds and minimum peak overshoot percentage is 1.25. There is no steady state error but the temperature fluctuate constantly between 2 to 3 degrees Celsius from the set point.

Table 3 Comparison between hardware results of PID and fuzzy logic controller

Specifications	PID Controller	Fuzzy Logic Controller
Minimum settling time (sec)	1300	1250
Minimum Peak Overshoot (%)	0.75	1.25

Refer Annexure III for detailed results

5. Discussion

While experimenting on the hardware of PID controller, an observation has been made. When the set point is reached, the PID algorithm turns off the relay which turns off the heating coil and thus the temperature of the furnace is controlled. But when the heating coil is turned off, the temperature drop of about 3 to 4 percent takes place, which is quite significant. This cycle of temperature reaching the set point and then dropping and again rising to set point repeats itself continuously. This problem is proposed to be solved with the application of fuzzy logic controller hardware. The membership function is so chosen that it holds the temperature near the set point and minimizes the overshoot. Increasing the number of membership functions further can improve the results.

From results it is obvious that one input fuzzy logic controller gives slightly better results than the PID controller. With more number of membership functions or increased number of inputs, the results can be further improved. In addition, the main advantage of using fuzzy logic controller is it can be given any membership where control should be taken. It is observed that more meticulous controlling with fuzzy logic and membership function may lead us to desired results. This will require a lot of trial and error but the outcome also will be commensurate with the efforts. Pulse Width Modulation (PWM) is not possible without a proper circuit. Moreover, in this study, relay was used which turns the heating coil on and off. What exactly happening in the study set-up is that the pulse generated by PID algorithm that plus percentage is nothing but the ON time. For example, 40% duty cycle means that the controller is ON for 40% time and OFF for 60% time. Same is the convention for controlling the relay. When PID or Fuzzy Logic controller gives PWM to relay, it knows as for how much time the heating coil is required to be kept ON or OFF. Thus there was the significant of the improvement over settling time and peak overshoot of the furnace.

6. Conclusion

The main objective of this project achieved by finding transfer function, simulation of PID and Fuzzy Logic controller, to design hardware for furnace temperature controller, implementation of PID and Fuzzy Logic Hardware, analyzing and finding best parameter and membership function, comparing two-controller performance, developing controller which have less peak overshoot percentage and less settling time, slightly better controller than PID. Results show that the fuzzy logic controller is slightly better than the PID controller in terms of settling time, and the PID controller is better than the fuzzy logic in terms of peak overshoot. Better results can be obtained from the fuzzy logic controller increasing the number of inputs or the membership functions. Temperature error and the rate of change of error may be the two inputs. Similarly, in addition to the heating coil temperature, the blower speed may be the second output. The results can also be improved by increasing the number of inputs, such as error of temperature and rate of error of temperature. As the scope of this study is limited to the implementation of hardware, only one input and one output for fuzzy logic system is considered. Implementation of two inputs and one output fuzzy logic controller is difficult because of the method used for defuzzification, such as centroid method, which requires lot of calculations and coding work. This can be taken up as a future work.

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Annexure I: Finding transfer function of furnace

First step is to find out transfer function because it will help us to find best PID parameter for PID controller. For this, first develop the hardware and heat furnace in open loop. Therefore, graph of Furnace Temperature v/s Time obtained. Figure A1 shows furnace hardware result of temperature v/s time graph. From graph, it is seen that first order system. For this system, constant temperature is 236.50, after reaching constant temperature. It will not increase temperature further. It reaches 236.5 degree Celsius in nearly 3500 seconds.

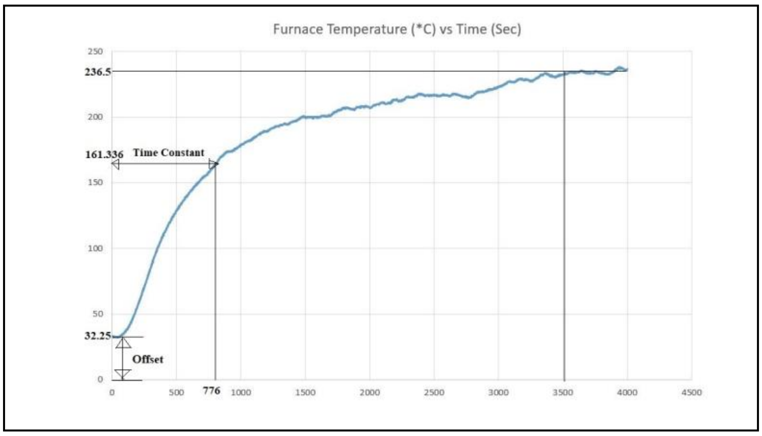

Figure A1 Furnace Temperature v/s Time curve

From general transfer function of first order system is

G(s) = K/ Ts+1

where K is static gain and T is time constant.

K = (Final steady state value- Initial steady state value) / step change

K = (236.5-32.25)/(236.5-32.25)

K = 1

T = Time constant = time for the response to reach temperature T1

T1 = 63.2 % of (change in process variable) + offset

Offset is steady state temperature before starting furnace.

= 63.2 % of (236.5-32.25) + 32.25

= 161.336 degree Celsius

Time constant = 12.93 minutes = 776 seconds

Hence, our furnace transfer function will be

G(s) = 1/ 776s+1

This is the proposed methodology for furnace temperature controller and transfer function.

Annexure II: Simulation results of PID controller

Table A1 shows simulation results of PID controller. PID parameter found with Simulink PID auto tuner. Best PID parameter is taken for simulation.

Table A1 Simulation Results of PID Controller

Setup no.	PID Parameter	Settling Time (sec)	Peak Overshoot (%)
1	Kp= 1.94, Ki= 0.003, Kd= 103.92	1400	1.35
2	Kp= 1.0605, Ki= 0.0018, Kd= 0	1950	1.325
3	Kp= 1.6944, Ki= 0.00263, Kd= 86.8548	1650	1.20

Details are as follows.

Setup 1: This PID parameter is taken from simulation 1, which is generated with PID tuner. Figure A2 shows PID Controller setup 1 graph. X-axis shows time in second and Y-axis shows temperature in degree Celsius. It also shows maximum overshoot from set point.

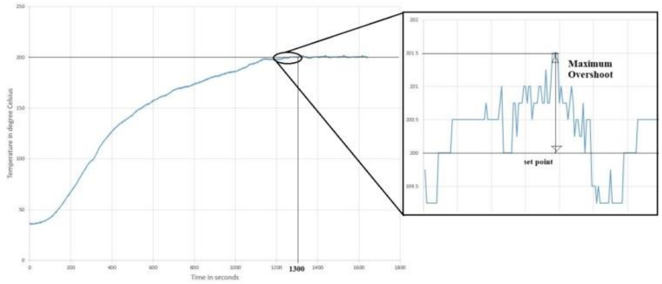

Figure A2 PID Controller Setup 1 graph

Setup 2: This PID parameter is taken from simulation 2, which is generated with PID tuner. Figure 6.19 shows PID Controller setup 2 graph. X-axis shows time in second and Y-axis shows temperature in degree Celsius. It also shows maximum overshoot from set point.

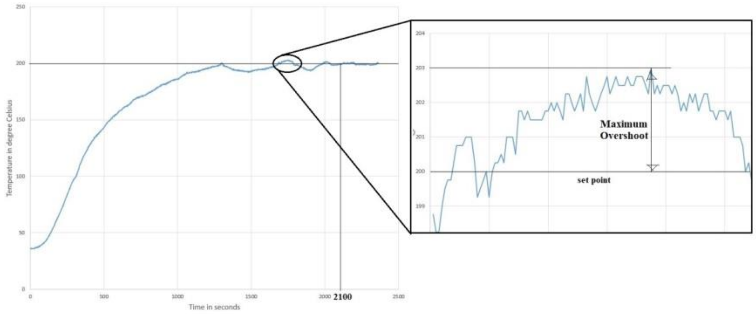

Figure A3 PID Controller Setup 2 graph

Setup 3: This PID parameter is taken from simulation 3, which is generated with PID tuner. Figure A4 shows PID Controller setup 3 graph. X-axis shows time in second and Y-axis shows temperature in degree Celsius. It also shows maximum overshoot from set point.

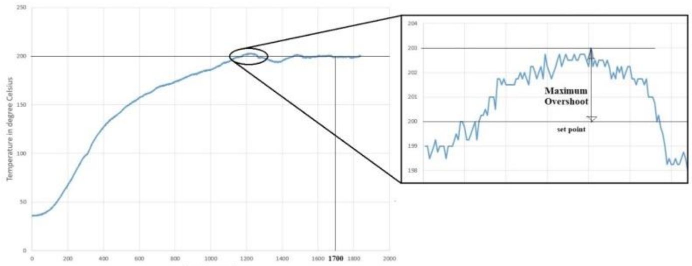

Figure A4 PID Controller Setup 3 graph

Annexure III: Hardware implementation of fuzzy logic furnace temperature

Setup 1: Figure A5 and A6 shows input & output membership function for setup 1 respectively. Singleton membership function is used in input and output. For setup 1 five singleton membership function used. Figure A7 shows temperature vs time graph for fuzzy logic controller setup 1. It also shows maximum overshoot from set point.

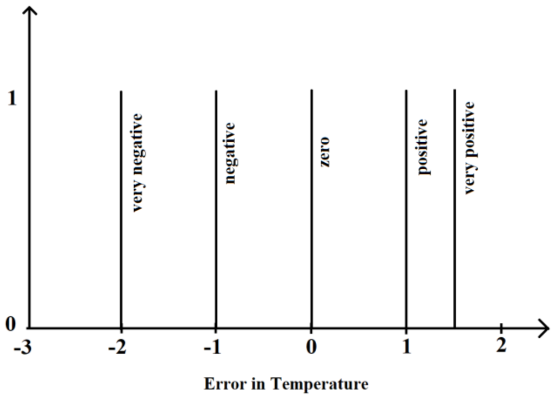

Figure A5 Input M.F for Setup 1

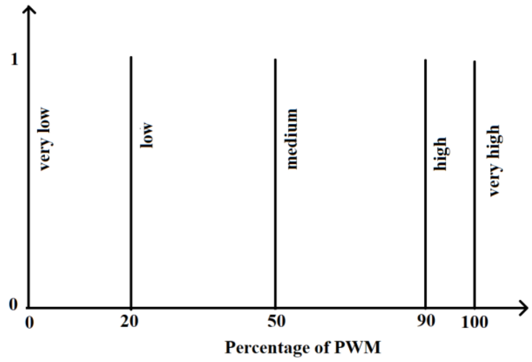

Figure A6 Output M.F for Setup 1

Rule base:

IF *error in temperature* is very positive **THEN** *percentage of PWM* is very high.

IF *error in temperature* is positive **THEN** *percentage of PWM* is high.

IF *error in temperature* is zero **THEN** *percentage of PWM* is medium.

IF *error in temperature* is negative **THEN** *percentage of PWM* is low.

IF *error in temperature* is very negative **THEN** *percentage of PWM* is very low.

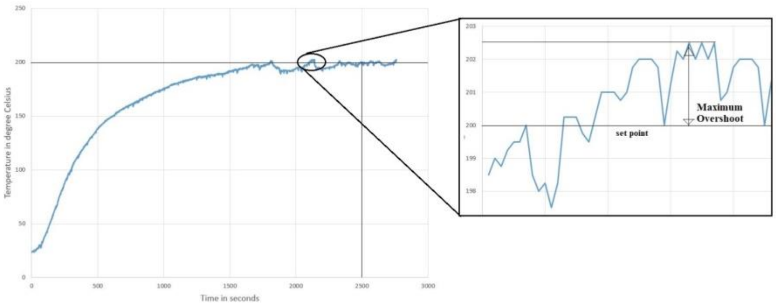

Figure A7 Fuzzy logic controller response for Setup 1

Setup 2: Figure A8 and A9 shows input & output membership function for setup 2 respectively. Singleton membership function used in input and output. For setup 2 six singleton membership function used. Figure A11 shows temperature vs time graph for fuzzy logic controller setup 2. It also shows maximum overshoot from set point.

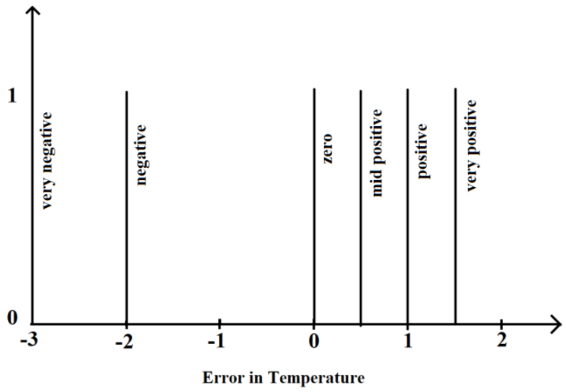

Figure A8 Input M.F for Setup 2

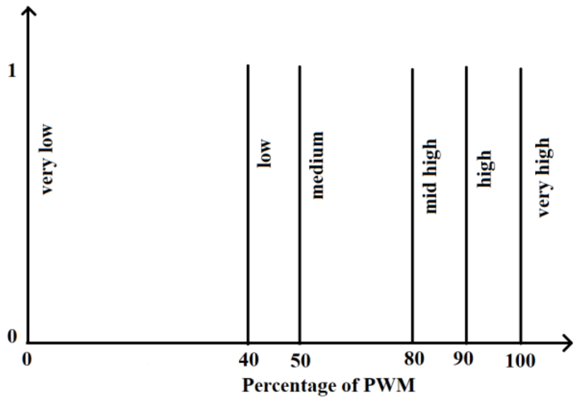

Figure A9 Output M.F for Setup 2

Rule base:

IF *error in temperature* is very positive **THEN** *percentage of PWM* is very high.
IF *error in temperature* is positive **THEN** *percentage of PWM* is high.
IF *error in temperature* is mid positive **THEN** *percentage of PWM* is mid high.
IF *error in temperature* is zero **THEN** *percentage of PWM* is medium.
IF *error in temperature* is negative **THEN** *percentage of PWM* is low.
IF *error in temperature* is very negative **THEN** *percentage of PWM* is very low.

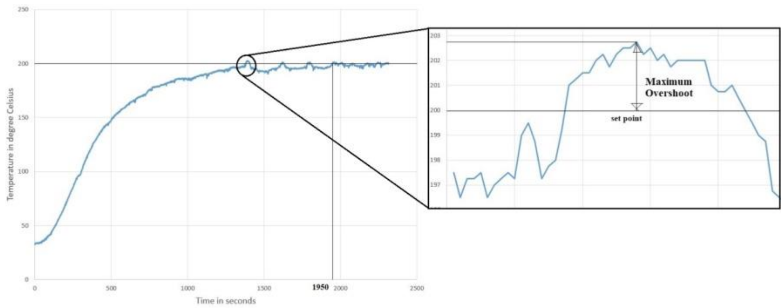

Figure A10 Fuzzy logic controller response for Setup 2