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Fuzzy Logic Controller for Boiler Temperature Control using LabVIEW and Matlab

Saad Afzal, Mohsin Jamil, Asim Waris, Shahid Ikramullah Butt and Gussan Mufti

School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), H-12 Islamabad, Pakistan.
saadafzal345@hotmail.com, mohsin@smme.nust.edu.pk, drshahid@smme.nust.edu.pk.

Abstract

The aim of this project is to achieve a precise temperature control of boiler and it can be done by fuzzy logic controller. Fuzzy logic controller is computer generated and is easy to implement. Fuzzy logic controller being more efficient than other conventional controllers provide us with better and accurate results. MatLab simulation and Labview experimental results clearly show the amount of overshoot and settling time are modest, it also makes the boiler cost effective by achieving the target temperature in less time.

***Keywords**: Fuzzy Logic Controller (FLC), Data Acquisition (DAQ), Pulse Width Modulation (PWM), Weighted Average (WA), Inference Engine (IE)*

1. Introduction

Boilers are being used in power plant industry and many other industrial areas from a long time, mainly to generate steam. Steam is generated for different purposes it can be for running the steam turbines or recycling heat energy produced as a result of different power generating processes. Steam is generated by excessive heat provided to boiler which in our case will be from an electric source. As the heat is produced flue gases rise to the upper part of boiler, steam and water go to the steam drum where steam gets transferred to the superheated section of the boiler.

Improving boiler performance has been a topic for many years now, to make it cost effective and less time consuming fuzzy logic seems to be the best option. Over the past years fuzzy logic range has been increasing, from consumer products to industrial process controls. Fuzzy sets, rules and logic are developed to manipulate, analyze, utilize and provide a framework to handle real world problems [1].

In this paper development of temperature control system using fuzzy logic controller will be introduced.

Fuzzy controller calculates value between set point and current value, fuzzification process calculates the member function after that rule base comes in which set rules are defined which leads to defuzzification process where PWM values are set to give exact input to boiler heater.

The practical setup has four parts, boiler, temperature sensor (K type thermocouple), switching circuitry and DAQ card connecting all this to Labview and Matlab. Labview based VI generates PWM to give exact supply to heater after the thermocouple gives input temperature which is being run in both Matlab and Labview based fuzzy logic controller, which actually gives output to run boiler until desired temperature is achieved.

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1.1. Boiler

A boiler is a closed vessel which is used to boil fluid. Fluid doesn't necessarily boils to steam in a boiler, in fact boiled or steamed fluid leaves the boiler for different uses hence we can establish that a boiler can be used either to heat fluids or create steam.

All this heating can only be done by some heat source which is provided by combustion of fuel. *E.g*. wood, coal, oil and natural gas. Heating can also be done by electric heating element and nuclear fission (Nuclear power plants).
The process is further explained in following section.

1.2. Temperature Sensor

A thermocouple is used as a temperature measuring device in this project. A thermocouple consists of two dissimilar conductors that contact each other at one or more spots. When diffused together two dissimilar conductors produce a thermo-electric effect that generates a constant potential difference. The voltage between two contacts is called seebeck effect as a temperature gradient is generated along the conductivity wires producing EMF.
For this project K-type thermocouple is used, which is protected by cover and thermally junction ungrounded.

1.3. DAQ Card

Data acquisition is a process of sampling signals which measure real world physical conditions (Analog signals mostly) and converting the resulting samples into computer readable digital signal (digital numeric values) form.
The DAQ card used in this particular project is USB 6009.

1.4. Switching Circuit

This circuit basically controls the power supply of boiler. It is a relay based in which relay controls the flow of current to the boiler. Its control action is triggered by a PWM signal coming from a 5 V output pin of DAQ card. This signal is generated in accordance to different fuzzy logic rules to control the temperature. This signal can be of 10% duty cycle or 90% duty cycle per the requirement of temperature setting.

2. Fuzzy Logic Controller

Fuzzy logic system contains following parts [5]

- Fuzzifier
- Rules
- Inference engine
- Defuzzifier

2.1. Fuzzy logic Algorithm

Fuzzy logic algorithm is a basic pseudo code of the working principle of the controller program from start to finish.

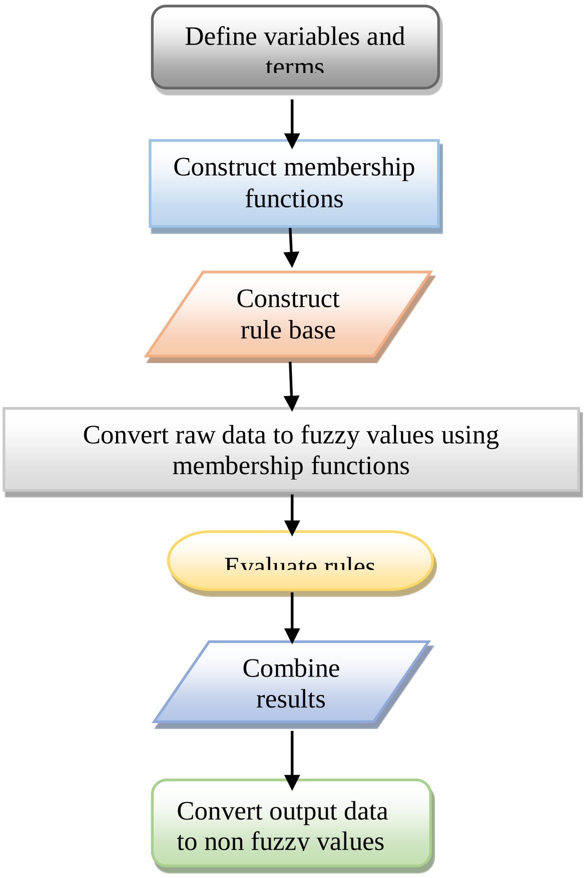
As in the start the variables are defined which basically are set eyeing the limits of experimental setup in this case.

Membership functions are chosen according to the complication of the work controller will do whether to use trapezoidal or triangular *etc*.

Rule base is defined to control the output commands as per the needs, *e.g*. IF temperature is 45°C THEN turn the boiler ON as the target temperature is 50 °C.

Converting raw data into fuzzy values via membership functions, this process is called fuzzification.

Applying rules to the fuzzy values in order to get the desired result.
Results are combined and sent to defuzzifier.
Defuzzifier converts the results into non fuzzy values and sends them in type of output commands [6] [7].



Flowchart 1. Fuzzy Logic Algorithm

2.2. Fuzzy Set

In fuzzy set members membership grade are assigned, for example let's assume a member NS. Temperature is decided between 15-30 °C if temperature is 15°C it is not considered as NS set as in fuzzy logic its membership grade is 0 (zero) if temperature is 17°C membership grade of this set will become 0.134 and if temperature becomes 28°C membership grade becomes 0.867.
0.134 is least likely belonging to NS set and 0.867 is most likely belonging to NS.

2.3. Membership Function

A membership function is implemented for fuzzification and defuzzification. Steps of Fuzzy logic controller to evaluate the fuzzy and non-fuzzy input values include membership functions evaluating linguistic variables. Membership function measure linguistic terms of fuzzy part. In the membership function choice one has to solve a few problems, how to choose general parameters such as number of classes' i-e membership functions to describe all the values of linguistic variables, the position of different membership functions, the width of the membership function and concrete parameters such as shape of a particular membership function, which in this case is triangular membership function [17].

The first step in a width selection should be choice of a parameter to evaluate it. Absolute value if the width is not appropriate as it does not compare the width of separate membership function with the number of classes. Two indices meet this demand, the overlap ratio and overlap robustness. These indices evaluate the width of membership function through the overlap of two functions [10][11].

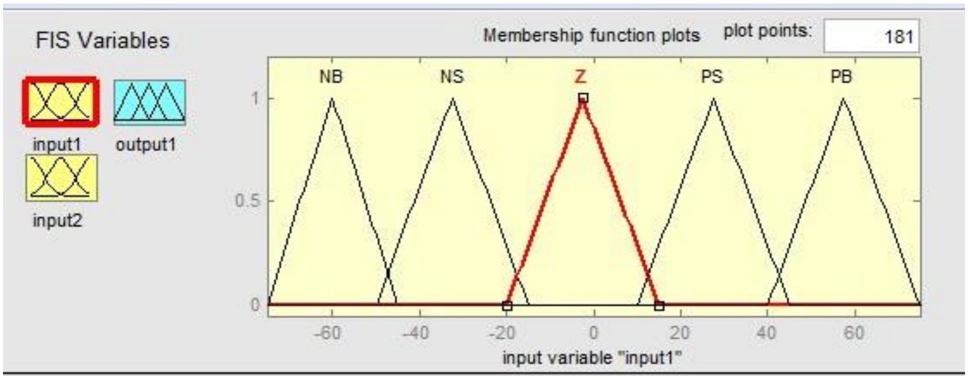


Figure 1. Membership Function

2.4. Fuzzy Rules

Fuzzy rules are considered knowledge of expert in related field of application. Fuzzy logic is defined in terms of IF-THEN sequence, which leads to algorithms describing what actions/output should be taken in the light of present observed information. Observed information includes input and feedback in case of a closed loop control system. The laws of fuzzy rules are different for every system as they depend on each different actual application [21].

A fuzzy IF-THEN system associates a condition which is decreased using linguistics and fuzzy sets to output. The IF part is usually the gathering information part and the THEN part is used to give output in the linguistic variable form [18].

Table 1. Fuzzy Rules

S.no	Fuzzy Rules
1	If the temperature is NS or NB and target is Z then the command will be NS
2	If the temperature is PS or PB and target is Z then the command will be PS
3	If the temperature is Z and target is also Z then the command will be Z or OFF

And in matrix representation fuzzy rules are as follows

Table 2. Matrix Representation of Fuzzy Rules

e/de	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	NS
Z	NS	NS	Z	PS	PS
PS	PS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

Fuzzy mapping rules provide a functional mapping between inputs and outputs using linguistic variables. These rules are based on a graph defining relationship between fuzzy input and fuzzy output. In real applications input and output links are very complicated hence fuzzy mapping rules are defined to solve these kind of problems [20].

Fuzzy mapping rules work similar to human insight. Each fuzzy map covers limited number of elements of the function. Entire function is approximated by a set of fuzzy mapping rules. Row captions show value of the current temperature, column captions show the target temperature and the cells in the middle show command which generates the output. Commands are taken as input which collects row and column and particular cell data to drive the program.

E.g. cell (3, 4) of above rule table show entry of PS and Z. The cell entry is PS which means the output is positive signal from the output pin which triggers the switching circuit ON until the temperature is set according to the target temperature. Until then the heating element will be kept ON with a low duty cycle usually 60 % duty cycle in this case.

2.5. Defuzzification

The outputs derived from inputs, outputs, membership function and fuzzy rules is still a fuzzy element. To make this data available to real applications a defuzzification process is needed. This process converts the fuzzy output back to the crisp output. The fuzzy output is still a linguistic variable and is needed to be convert into crisp variables via defuzzification.

3. Implementing the Fuzzy Logic

The following steps are carried during temperature control of the boiler by fuzzy logic controller.

3.1. Fuzzification of the Input

Scalar value changes into a fuzzy value, scalar value is the temperature reading from thermocouple or is also a feedback to the controller. Fuzzification ensures that the scalar temperature reading changes into fuzzy value. The resulting fuzzy values are called linguistic terms [12].

The linguistic term show difference between set point and is also expresses measured and calculated signals from the temperature sensor.

For fuzzified input triangular functions are used to calculate the range of fuzzy variables [13].

3.2. Fuzzy Rules

As soon as fuzzification process is complete the controller moves onto the next phase which are rules that decide what action to take in order to bring temperature of boiler to the target temperature or set point. These actions can only be initiated if initial temperature is measured low [20].

The rules are simply stated by IF-THEN statements. IF reflects the input or feedback from the thermocouple and THEN has an answer to IF.

E.g. IF temperature is NS and the target temperature is PS then output will be Z.

3.3. Defuzzification

The output is in the form of numeric data so that it commands directly in the form of PWM wave to switching circuit which is used to turn the boiler ON/OFF.

The fuzzified value can be converted back to numeric output data with the help of a MatLab/ LabView code, which also are running the complete program [16].
The defuzzified output is applied to the switching circuit which will control its PWM.

3.4. Pulse Width Modulation (PWM)

The boiler's input is electricity, it has an electric heating element that boils the fluid. To control the temperature heating element is switched ON/OFF via the switching circuit, which is relay operated so whenever boiler temperature goes below target temperature relay is switched and current flows to the boiler, when desired temperature is achieved the relay is switched again and the current supply is restrained. This whole process is done by PWM [15].

Below are a few frequency values corresponding to the duty cycle at which the relay connection is stable.

S.no	Duty cycle	Frequency	Connection of relay (ON/OFF)
1	10	10	Not settled, to and fro relay movement
2	20	182 404	Connects but not settled Full vibration
3	30	112 150 190 367 500	To and fro Full connection stable
4	40	Nil	Nil
5	50	Nil	Nil
6	60	340 345 500	Fast connection Connects or vibrates faster Full connection
7	80	14 40 99 125 397 407	Connects but not stable Stable connection (connects for more time then disconnection time) Complete connection achieved Complete connection Complete connection

Table 3. PWM Chart for Different Duty Cycle and Frequency Values

For example

90% duty cycle indicates that the boiler is ON 90% of the time and is OFF for the rest 10% of time. Duty cycle is directly proportional to T_{ON} so in basic words a high duty cycle means boiler heats fluid quickly and low duty cycle means boiler has to work for larger period of time to achieve desired result, but will be more accurate and overshoot will be less.

3.5. Mathematical Model

The inference engine of fuzzy logic controller works on different formula one of them is weighted average, weighted average calculates the weight of output according to the

desired set point using membership function in which the value lies and using the value of μ respective of the set point value [11].
The weighted mean of a non-empty set of data is

$$\{X_1, X_2, \dots, X_n\} \quad (1)$$

Once we add weight to it it becomes

$$\bar{X} = W_1X_1 + W_2X_2 + \cdots + W_nX_n \quad (2)$$

The formulae can be simplified by addition of summation

$$W = \sum_{i=1}^{N} W_i = 1 \quad (3)$$

Weighted mean for such normalized weights is

$$\bar{X} = \sum_{i=1}^{N} W_i X_i \quad (4)$$

Weights can always be normalized by making the following transformation on weighted means

$$W_i^` = \frac{W_i}{\sum_{j=1}^{N} W_j} \quad (5)$$

Using the normalized weights we get

$$\bar{X} = \sum_{i=1}^{N} W_i^` X_i \quad (6)$$

$$\bar{X} = \sum_{i=1}^{N} \frac{W_i}{\sum_{j=1}^{N} W_j} X_i \quad (7)$$

And

$$\bar{X} = \sum_{i=1}^{N} \frac{W_i X_i}{\sum_{j=1}^{N} W_j} \quad (8)$$

Which leads to

$$WA = \frac{\sum_{i=1}^{N} W_i X_i}{\sum_{i=1}^{N} W_i} \quad (9)$$

Hence

$$WA = \frac{\sum \mu_f X}{\mu_f} \quad (10)$$

4. Analysis by Labview, Matlab and Results:

4.1. Methodology

The proposed method detects the temperature of boiler water. The model will be programmed with a fuzzy rule base, thermocouple reads the temperature and sends it to the controller. The controller will read the sensor feedback as an input for fuzzy inference system. After fuzzification of the input and applying fuzzy rules an appropriate output is generated in the form of a control signal.

4.2. MatLab Model

Temperature monitoring:

The temperature is measured with a thermocouple. Feedback from thermocouple is used for comparison with the set value. The error from the set value is called deviation and is sent as an input to the fuzzy logic control system

Temperature control:

The fuzzy inference system fuzzifies the feedback applies rule to the fuzzified temperature deviated value and results in a defuzzified value which will correct the deviation or error.

Defuzzified value will then lead to the decision of picking suitable control action to be performed. That action is in the form of a PWM signal which turns boiler ON/OFF. Membership functions of both (inputs) error, change in error and output are as follows

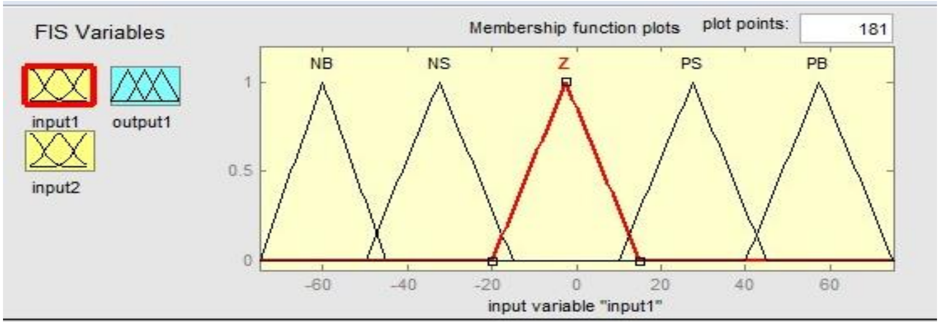


Figure 2. Input 1 Error Membership Function

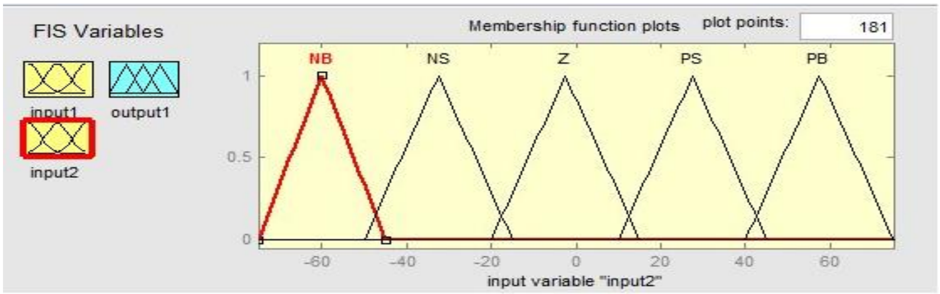


Figure 3. Input 2 change in error Membership Function

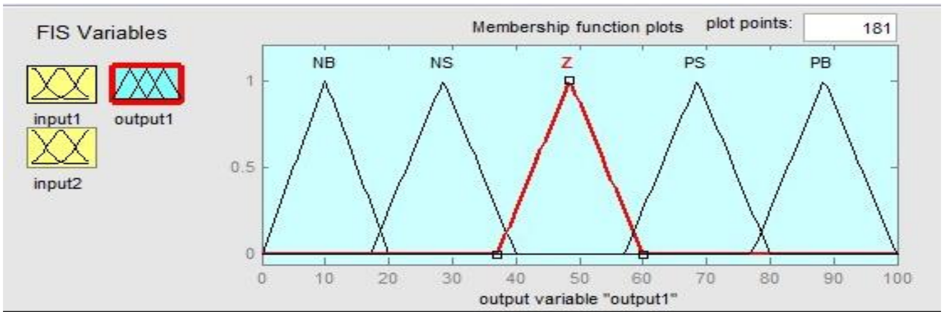


Figure 4. Output Membership Function

The surface view of controller is as follows, this 3D view of output is against both inputs showing the wider picture of what output can be for the corresponding input values.

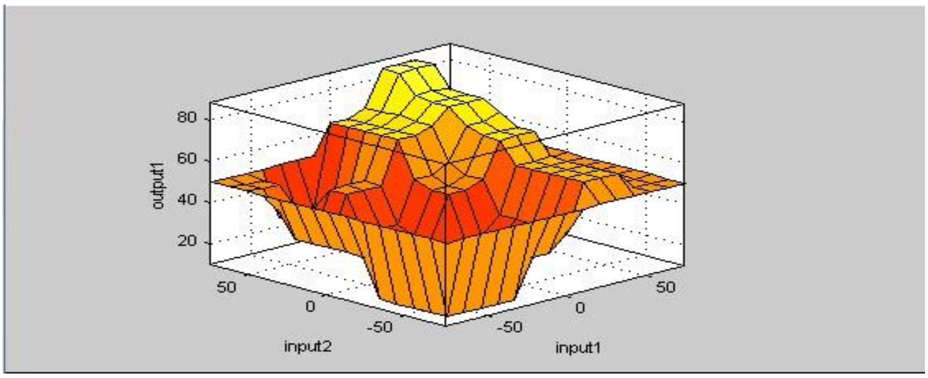


Figure 5. Surface View

LabView Model:

The Fuzzy logic controller is designed with two input variables error and Δ error and an output variable, the controlled temperature of boiler. In the mamandi base fuzzy inference system for fuzzy logic controller the input variables are error and rate of error, e and Δ e. output variable is controlled temperature Δy.

Membership functions are triangular rule base and linguistic variables for rule base are as follows

Table 4. Input Linguistic Variables

S.no	terminology	Fuzzy variable
1	Negative big	NB
2	Negative small	NS
3	Zero	Z
4	Positive small	PS
5	Positive big	PB

Rule base besides providing all the rules and ways to control the temperature also provides a negative feedback to maintain stability in any condition.

The labView models of Temperature control by fuzzy logic are shown as follows,

Input membership functions show both error andchange in error triangular membership function drawn against value of μ from 0 to 1. As we know that fuzzy logic is a controller which deals with values between 0 to 1. Values can be 0.2 or 0.5 corresponding to desired output.

The range of both inputs is selected in equal amount on both positive and negative side because the error can be negative or positive. Therefore it ranges from -75 to 75.

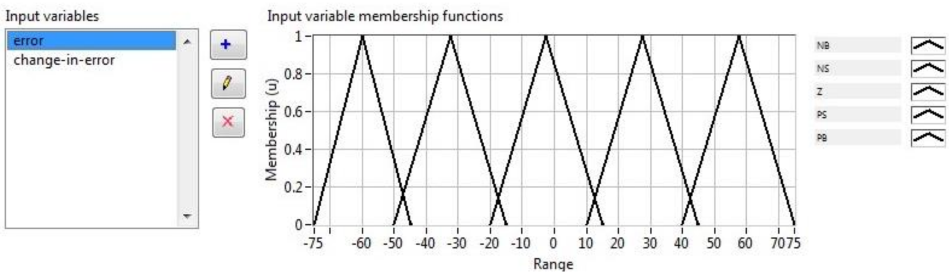


Figure 6. Input Membership Function Error

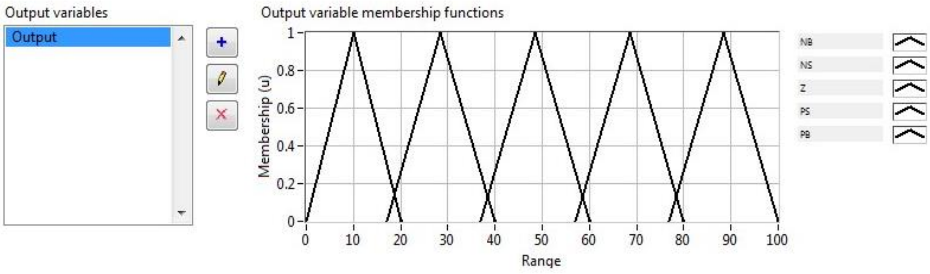


Figure 7. Output Membership Function

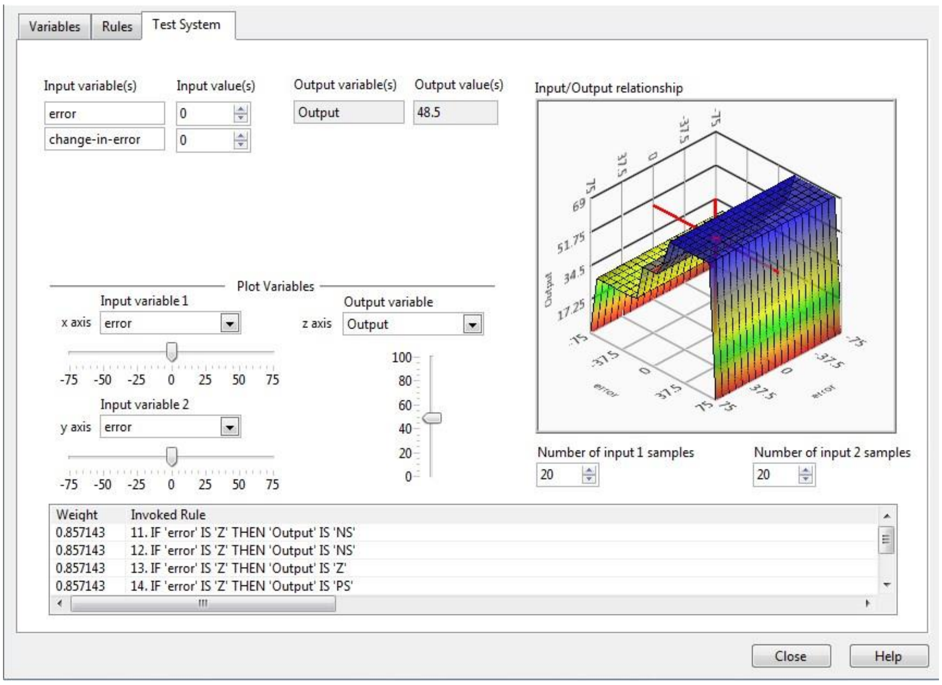


Figure 8. Test System

In test system the rules are thoratically tested against membership functions of error and change in error. The output is shown in the surface view.

Results and discussion:

Figure 9 and Figure 10 shows comparison graphs between LabView and MatLab output temperatures, these output temperatures are basically the desired temperatures. LabView and MatLab both store data in the form of a spread sheet for temperature at respective time values. In LabView experimental waveform temperature is achieved rather quickly then MatLab but the MatLab waveform is a simulation result which was run with extra care for overshoot. Both waveforms clearly show that there is no overshoot at all and the set point temperature is achieved accurately with minimal error.

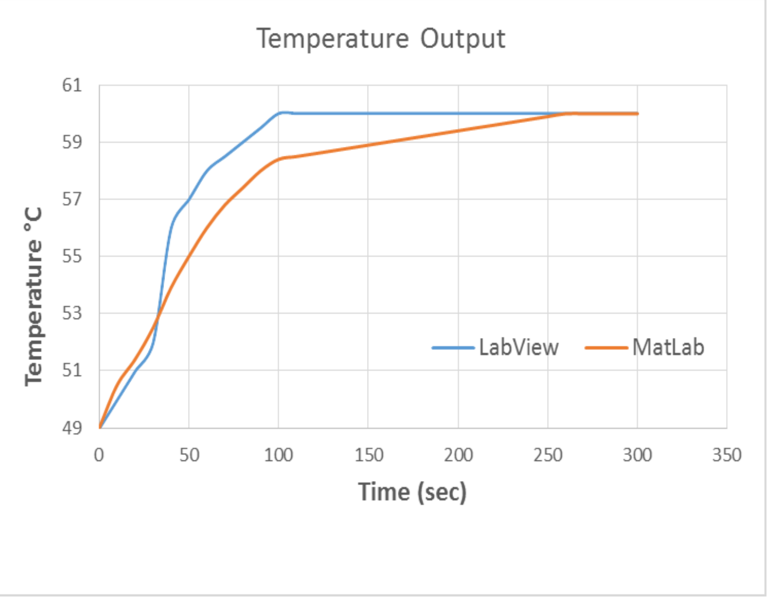


Figure 9. Output Temperature at 60 °C

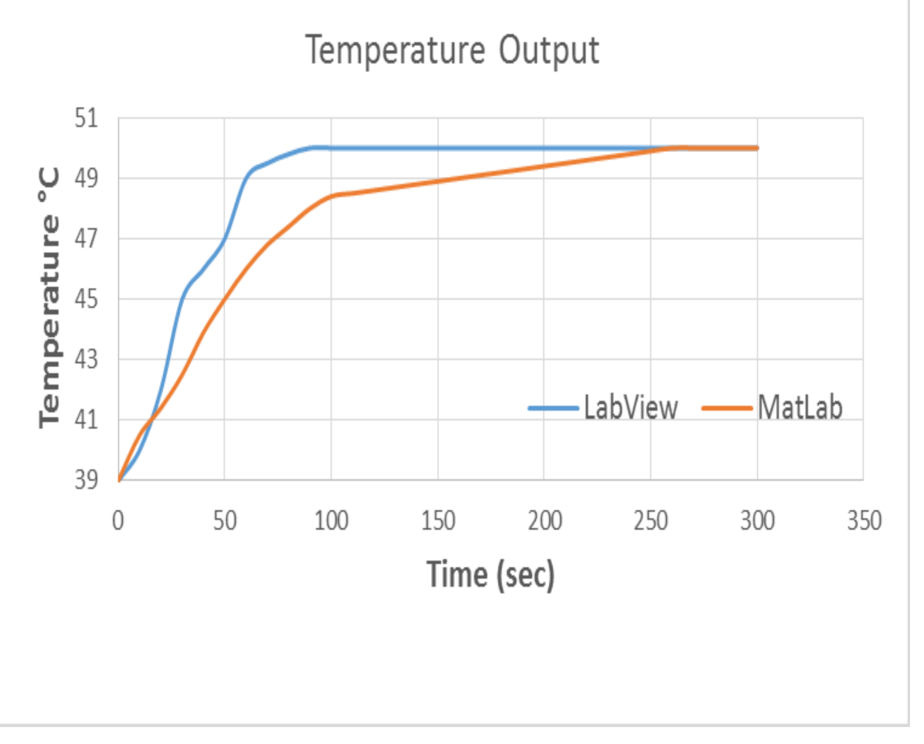


Figure 10. Output Temperature at 50 °C

The output PWM for switching circuit has the following waveform, its amplitude is 5 volts and it depends totally on the duty cycle and frequency.

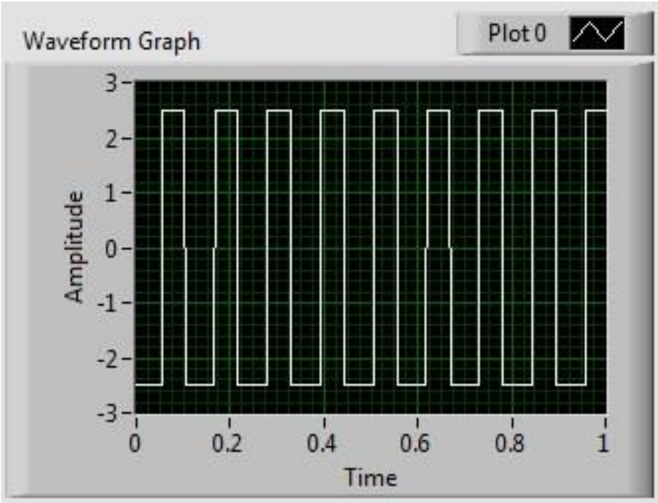


Figure 11. PWM as Input to Switching Circuit

The fuzzy logic controller achieves any required temperature in a step response, but its real graph shows an inclined output until it reaches the target temperature and settles, sometimes it overshoots if the duty cycle is high and sometimes it steadily reaches to target temperature if duty cycle is low. As shown in following graphs

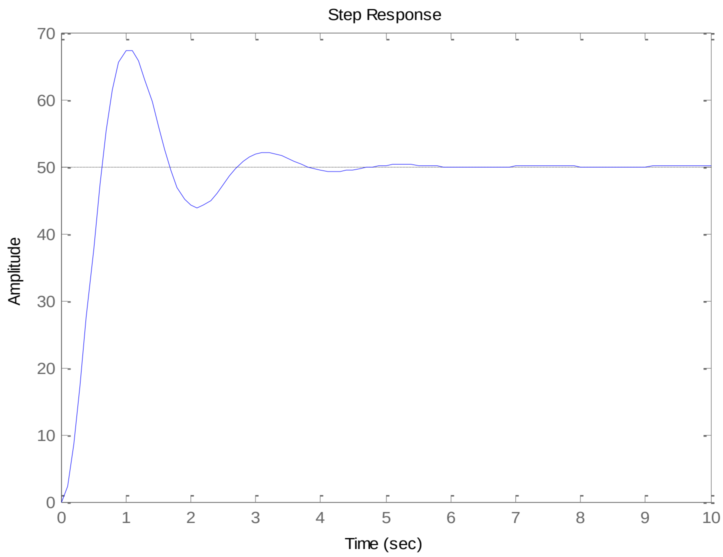


Figure 12. FLC Step Response with Overshoot

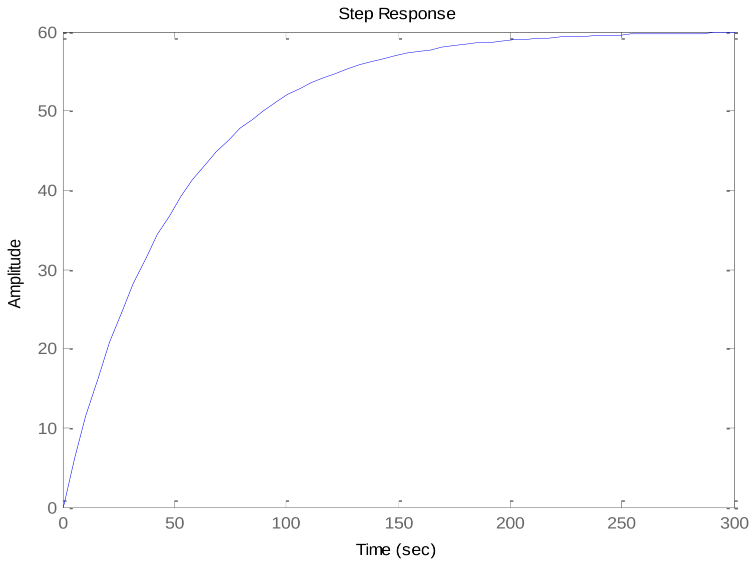


Figure 13. FLC Step Response without Overshoot

In control theory, overshoot refers to an output exceeding its final, steady-state value. For a step input, the percentage overshoot is the maximum value minus the step value divided by the step value.

The time taken for a measuring or control instrument to get within a certain distance of a new equilibrium value without subsequently deviating from it by that amount is called settling time.

In this project control of temperature of a boiler is done by two fuzzy logic controller models, one in Matlab and second in Labview.

Simulation is done for both models in Matlab and Labview. It was done over and over for tuning purpose of parameters, as shown in modelling chapter when PWM was tuned it was tested for different values of duty cycle and frequency. When the response is satisfactory, it was stopped.

In step response overshoot was found which settled quickly as its settling time was very low around 2 to 3 seconds.

The fuzzy logic controller is modelled with five membership function for each variable, there were total 25 rules defined to solve these five membership functions. These membership functions combine with fuzzy rules and solve problems inside the model.

5. Conclusion

A comparative study of LabView and MatLab models is done in this project to control temperature of boiler.

The aim of the fuzzy logic controller is to control the target temperature and achieve it.

It can be done in short period of time or can be done in longer period of time by changing to duty cycle.

Fuzzy logic controller gives quick response without any oscillations, fuzzy logic controller is easy to implement as it is computer generated model.

Adaptive neuro fuzzy and neural networks have better oscillation and settling time, they are advanced type of fuzzy logic and are also computer generated models [12] [17].

Fuzzy logic completely changes the way a controller works, it focuses more on system work than trying to understand how it works and modelling big mathematical problems. It leads to quicker and cheaper solutions.

Compared to conventional PI and PID controllers it has better settling time, less overshoot, cheap and more reliable.

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Authors

Saad Afzal, He is a MS Mechanical Engineering student at SMME, NUST. He has done his graduation in BE- Mechatronics from Air University. His research area includes

Mohsin Jamil, He is serving as Assistant Professor and Deputy Head of Department in the department of Robotics and Artificial Intelligence at National University of Sciences and Technology, Pakistan. He completed his PhD in Electrical Engineering from University of Southampton, U.K. His research area is Control Systems/Power Electronics.

Asim Waris, He did his master’s degree from National University of Sciences and Technology (NUST) in Mechanical Engineering. He did his bachelors from EME College NUST in Mechatronics Engineering. Currently He is PhD student at University of Alborg, Denmark.

Shahid Ikramullah Butt, He is an Associate professor at SMME, NUST. He is a senior faculty member in department of Mechanical Engineering. His area of expertise is Industrial and Manufacturing Engineering with emphasis on Manufacturing Processes, Simulation, Layout Designing, Scheduling and re-Scheduling algorithm, Computer Integrated Manufacturing and so on.

Gussan Mufti, He did his master’s degree from National University of Sciences and Technology (NUST) in Energy Systems Engineering. He did his bachelors from University of Engineering and Technology Peshawar. He is currently serving as a lecturer in Bahria University Islamabad. His research interests include grid connected inverters and power system analysis.

