MULTIPOINT TEMPERATURE CONTROL USING MODEL PREDICTIVE CONTROLLER

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology
in
Electrical and Electronics Engineering

with specialisation in

Industrial Instrumentation and Control

Department of Electrical and Electronics Engineering

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JUNE 2023

DECLARATION

I undersigned hereby declare that the project report entitled "**Multipoint Temperature Control using Model Predictive Controller.**", submitted for partial fulfillment the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under the supervision of *Dr. Mathew P Abraham*, Project Internal Supervisor, Assistant Professor, Department of Electrical and Electronics Engineering, *Mrs.M. Mary Jermila* , Project External Supervisor, Scientist Engineer 'SF', ISRO Inertial Systems Unit, Thiruvananthapuram, *Prof. Amal A.*, Project Co-ordinator, Assistant Professor, Department of Electrical and Electronics Engineering, and *Prof. Sumayya Jaleel*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

This is to certify that the report entitled " **Multipoint Temperature Control using Model Predictive Controller** " submitted by **ALIYA N**, **(Reg. No. TKM21EEII02)** of final year to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation Industrial Instrumentation and Control, is a bonafide record of the project work done by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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Finally I thank my parents and friends who directly and indirectly contributed to the successful completion of my project work.

ALIYA N.

ABSTRACT

All spacecraft and equipment include thermal control systems that keep the temperature within the acceptable range for optimum operation. A spacecraft's primary heat sources are its instruments, heaters, or solar absorption, whereas radiation is the sole way for heat to escape from the vessel. Heat is transferred from the primary heat sources of a spaceship onto radiators and away from instruments using thermal control, which also employs heaters, thermal switches, and heat pipes.For simplicity, considering a sensor package system for temperature control.The temperature of system varies with gradient. Multipoint temperature measurement includes the measuring and monitoring temperature at different point of a system.For heating different points different heaters are placed at different locations in the sensor package.

The sensor package includes heaters and sensors with the potential to self-heat. The heaters are powered, which heats the package. A box is used to protect the product from heat loss. The system's temperature profile is tracked over time, and its characteristics, such as delay time, thermal gain, and time constant, are determined from the system's reaction. These parameters are used to create a digital control system that includes an ADC, controllers, a PWM actuator (duty cycle based), a lowpass filter, and these parameters.

A Model Predictive Controller algorithm is used to control multipoint temperature of sensor package.We are using a sensor package having two regions each having its own heaters and thermisters.Interactions are calculated by measuring the temperature of thermister.Using step response model a model predictive control law is applied.In predictive law single and multiple predictions are calculated and a comparison of both single point and multiple point is made.

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ABBREVIATIONS

ARX	Autoregressive Exogenous Model
MLP	Multilayer Perceptron
MPC	Model Predictive Controller
PID	Proportional Integral Derivative
RLG	Ring Laser Gyroscope
SVM	Support Vector Machine

Chapter 1

INTRODUCTION

1.1 GENERAL BACKGROUND

A temperature control system's goal is to keep a device at a consistent temperature. Any circumstance where maintaining a specific temperature is necessary calls for the use of temperature controllers. This may be the case when it is necessary for an object to be heated, cooled, or both while maintaining the desired temperature (setpoint), regardless of the surroundings. The two basic types of temperature regulation are closed loop and open loop. The simplest type of loop, known as a open loop, continuously applies heating and cooling without taking into account the final temperature.

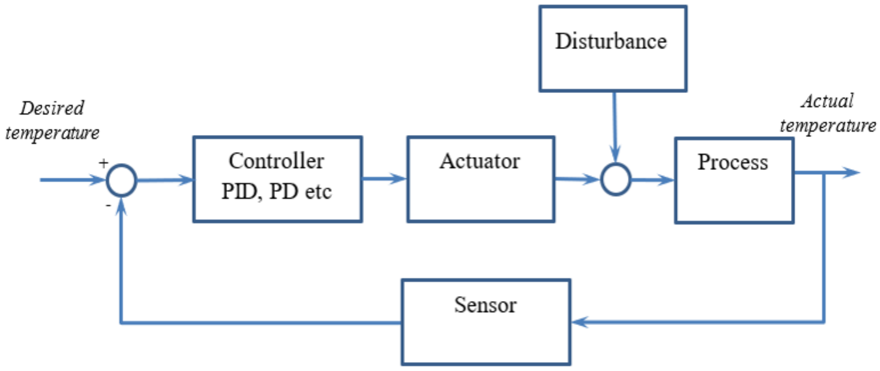

Figure 1.1: Block diagram of temperature control system.

Compared to open loop, closed loop control is far more complicated. A consistent output at the desired temperature is maintained in a closed loop application by continuously measuring and adjusting the output temperature. The output signal is constantly considered by closed loop control, which will feed it back into the control process. Similar to an automobile with an internal climate control system is closed loop control. The temperature control system is used widely in industries. In this, the plant is an electric oven or a heater whose temperature is to be controlled with respect to the reference input and control. All spacecraft and equipment include thermal control systems that keep the temperature within the acceptable range for optimum operation.The basic heat sources in a spacecraft are the instruments, heaters or solar absorption, while the only heat loss mechanism is radiation.Thermal control uses heat pipes, thermal switches, heaters and louvers to move heat from the basic heat sources in a spacecraft onto radiators and away from instruments.

1.1.1 Single Point Temperature

If the gradient shift is very minor, it may be ignored and treated as a single point, but if it is significant, the temperature inside an industrial facility or system will vary as a result.In order to measure, control, and monitor the temperature, only one sensor insertion is required. Considering that there can be a few little variances, this can be employed in situations where great accuracy is not necessary.Here, two thermistors are used to measure the temperature both inside and outside the package.A straightforward propotional, integral controller for a first order system may be used to control this system.

1.1.2 Multipoint Temperature

The temperature inside an industry plant or system varies greatly with the change in the gradient.The multipoint temperature control include the measurement and monitoring of temperature at different points inside a system.Here, a number of thermisters are placed at various places along the package, and we are measuring the temperature at each one while also taking into account how the various spots interact with one another.

1.2 OBJECTIVES

The objectives of this study are:

- Single point temperature control using PI controller.
- Multipoint temperature control using MPC for different prediction horizons.

1.3 SCOPE

Compared with other controllers and algorithms, the MPC has remarkable comprehensive performance, exhibits superior robustness and anti-interference ability, and significant improvements in the trajectory tracking control accuracy and real-time performance. Development of autonomous cars is shaping the future of transportation. High performance motion controllers are necessary to deploy the technology under a wide range of driving conditions. This thesis addresses trajectory tracking for autonomous vehicles, with the goal of developing a racing controller. We factor the task into the sub-problems of vehicle dynamics modeling and model-based control design.

1.4 SCHEME OF PROJECT WORK

The thesis is organized in 5 chapters. Chapter 1 titled by Introduction includes general background, objective, scope and scheme of project work. Chapter 2 surveys the literature review done on the work. Chapter 3 titled by Design Concept includes the design modelling which contains the vehicle dynamic model and vehicle tire model. Chapter 4 includes the methodology used and Chapter 5 gives the conclusion.

Chapter 2

LITERATURE REVIEW

2.1 OVERVIEW

This chapter describes the outstanding research done for the analysis and control methods implemented for the control of temperature using MPC ie Model Predictive Controller.For that, we have to study varying temperature control systems in order, first and second, and we have to study how to implement various controllers in these systems.

2.2 STUDY OF TEMPERATURE CONTROL SYSTEMS

2.2.1 Temperature Control of First Order Systems

Displaying the temperature management system's mathematical modelling based on PID controllers. In this case, the plant is an electric oven or heater, and the temperature needs to be regulated in relation to the reference input and control. To fine-tune the PID controller in this instance, we are employing the Ziegler-Nicholas approach. A PID controller can be used to enhance the system's step response characteristics. work[1].

2.2.2 Temperature Measurement

Sometimes knowing variables in difficult-to-access areas is crucial for control operations. Soft sensors, sometimes known as "virtual sensors," could be quite useful in certain circumstances. In reality, they are effective tools for the indirect measurement of values that otherwise would not be measurable due to the placement of physical sensors that would disturb the system being tested's regular operating circumstances. The authors of this study outline a method for measuring temperature values in a brew group of a commercial coffee maker indirectly.A finite element (FE) model was created and verified through targeted experimental testing to simulate both the fluid dynamics and the thermal distribution on the group. A hardware sensor would otherwise compromise the proper coffee brewing process and the safety/quality of the brewed coffee. Instead, the FE model was used to feed an autoregressive exogenous model (ARX model) that links the temperature in the boiler (i.e., a quantity typically assessed in the coffee machine) and the one near the water output. The coffee maker's control unit architecture can be improved with the aid of the acquired data-driven soft sensor.[2]

2.3 Multipoint Temperature

2.3.1 Multipoint Temperature Measurement in Reactor Tank

Maintaining a certain temperature control curve produces the required outcomes. Because the fermentation of beer is a complicated, non-linear process, it is possible to shorten the fermentation period while maintaining key fermentation quality criteria. A dynamic beer batch fermentation optimization approach is described. An ant colony system that is based on the MAX-MIN ant system is used to search for a temperature optimization profile. To collect more temperature data from the tank, a multi-point temperature examine instrument was created. A fermentation setup designed for a lab was constructed. The sensor contributes to increased control accuracy. Based on this optimization technique, it was possible to generate a smooth temperature profile that is simple to depict as a few linear segments.[3].

2.3.2 Multipoint Temperature Measurement in RLG

This work proposes a multiple-point temperature gradient approach for RLG bias correction in order to further enhance ring laser gyroscope (RLG) bias stability. Using the multiple-point temperature monitoring technique, the RLG block's whole thermo-image is created.

developed. The particle swarm optimization approach is employed to fine-tune the support vector machine (SVM) parameters in conjunction with the multiple-point temperature gradients between various sites of the RLG block, and an optimum design for choosing the thermometer positions is also addressed. The experimental outcomes support the suggested method's superiority and improve the RLG bias compensation model's accuracy and generalizability.[4]

2.3.3 Multipoint Temperature Measurement using Data driven MPC

Considering the growing global population, achieving food security is a top priority for many nations.Reductions in agricultural land due to urbanisation and soil degradation have a direct impact on the food production rate. Closed, controlled greenhouses are a vital source for year-round crop production given the rising global demand for food.Improving crop quality and yield depends on keeping the greenhouse at its ideal temperature throughout the year.However, compared to other agricultural practises, greenhouses consumes more energy. In order to control temperature and lower energy consumption, a data-driven model predictive control approach for a semi-closed greenhouse is suggested in this study. This approach consists of a multilayer perceptron model of the greenhouse system coupled with an optimization algorithm and an objective function.The multilayer perceptron model is trained using historical greenhouse data, and the input parameters used to predict temperature such as solar radiation, outside temperature, humidity difference, fan speed, and HVAC control. The performance of the greenhouse model is evaluated under various conditions, including varying the training data set's sample size and increasing the prediction time step.With an RMSE value of 0.33 °C and 0.36 °C, respectively, the results showed that the MPC approach had a better temperature control than the greenhouse adaptive control system for winter and summer.Similarly, model predictive control led to energy reductions of 7.70 percentage in the winter and 16.57 percentage in the summer.By fine-tuning the model using the fresh set of data, the proposed model predictive control framework is adaptable and can be used with other greenhouse systems. [5]

2.3.4 Multipoint Temperature Measurement of Greenhouse using Adaptive MPC

A model predictive control utilised to assess in a real field test for the simplest scenario with a single point measurement and a single heater under operational constraint on heater. The findings showed that the control was successful even if the brute-force approach was mostly used to find the best answer. The same method cannot be extended to get the best answer when dealing with multipoint heaters and multipoint temperature data in a real-time operation.He used a genetic algorithm as a method to control the temperature of the greenhouse for the aforementioned issue. The accuracy of the mathematical model of greenhouse temperature dynamics had a significant impact on the efficiency of model predictive control, therefore a recursive least square identification technique was also developed to update predictor parameters in real time. The proposed approach functioned effectively, according to the control findings in a laboratory demonstration greenhouse, and there was an average reduction of 20–35% in temperature inaccuracy. Additionally, the temperature differential shrunk by an average of 36% as well.[6].

2.3.5 Model Predictive Controller

Model predictive Controller (MPC), a crucial advanced control method for challenging multivariable control issues. The standard MPC,the idea may be summed up as follows. Consider the case where we want to manage a multi-input, multi-output process while adhering to inequality restrictions on the input and output variables. Future values of the outputs can be predicted using the model and current data if an adequately accurate dynamic model of the process is provided.[7]Then, using both forecasts and measurements, it will be possible to determine the proper changes in the input variables. In essence, after taking into account the input-output linkages represented by the process model, changes in the individual input variables are coordinated. The input variables are also known as manipulated variables (MVs) in MPC applications, whilst the output variables are also known as controlled variables (CVs). The term "DVs" or "feedforward variables" refers to measured disturbance variables.

2.4 SUMMARY

This chapter discussed previous works related to temperature control, which consist of various methods of temperature control, different controllers used for temperature control, multipoint temperature control in various systems, and the comparison between different controllers.

Chapter 3

DESIGN CONCEPT

3.1 SYSTEM DESIGN

3.1.1 System Description And Data Collection

Single point Temperature

The thermal system is a coriolis ring laser gyroscope (sensor) package, and its temperature has to be controlled. To measure temperature, thermistors are placed inside and outside of the temperature package, i.e., a control sensor and a monitor sensor. The heat energy is provided by powering the two heaters placed on the package. The thermal system is a coriolis ring laser gyroscope (sensor) package whose temperature is to be controlled. The experiment is conducted in normal atmospheric conditions.

Being a passive device, the thermistor is linked to a 0.5 DC source. The thermistor is a resistor whose value fluctuates in response to temperature. The resistance of thermistors changes as the temperature does. At first, the heater is not turned on, and a reading of the temperature across the thermistor is made. The heater's output is reduced to 2W after an hour. It is noticed that this causes a shift in voltage across the thermistor.at last a increase in power isgiven to heaters to find the thermal gain Using a look-up table and interpolation, this voltage is transformed to resistance, which is then turned to temperature.Since we are employing a thermometer with a negative temperature coefficient, the resistance decreases as the temperature rises. To determine the system's transfer function, this data is used.From this temperature step response data, thermal constant, delay time, and thermal gain are found. Type zero first order system with delay is

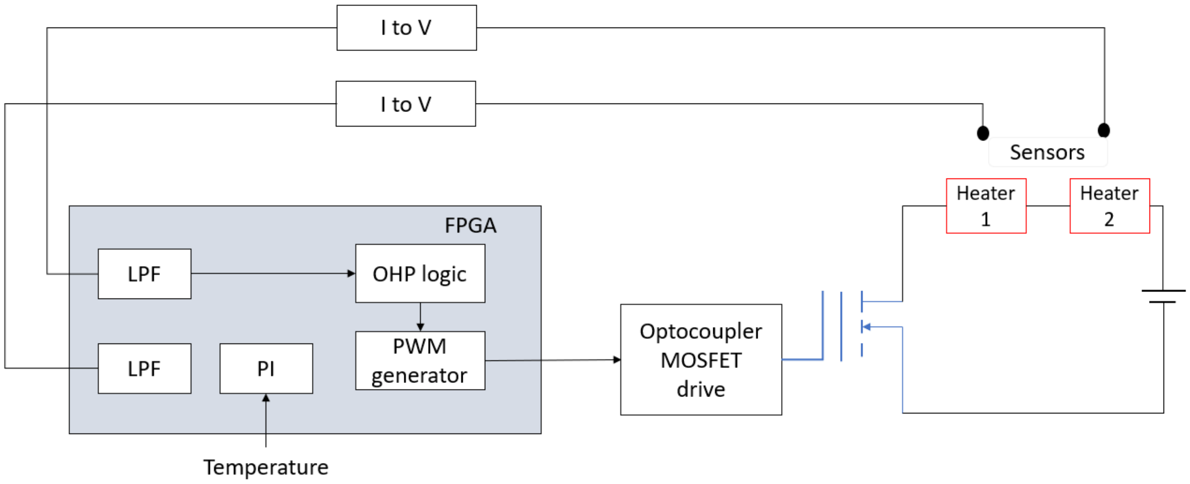

Figure 3.1: Functional diagram of thermal system for single point

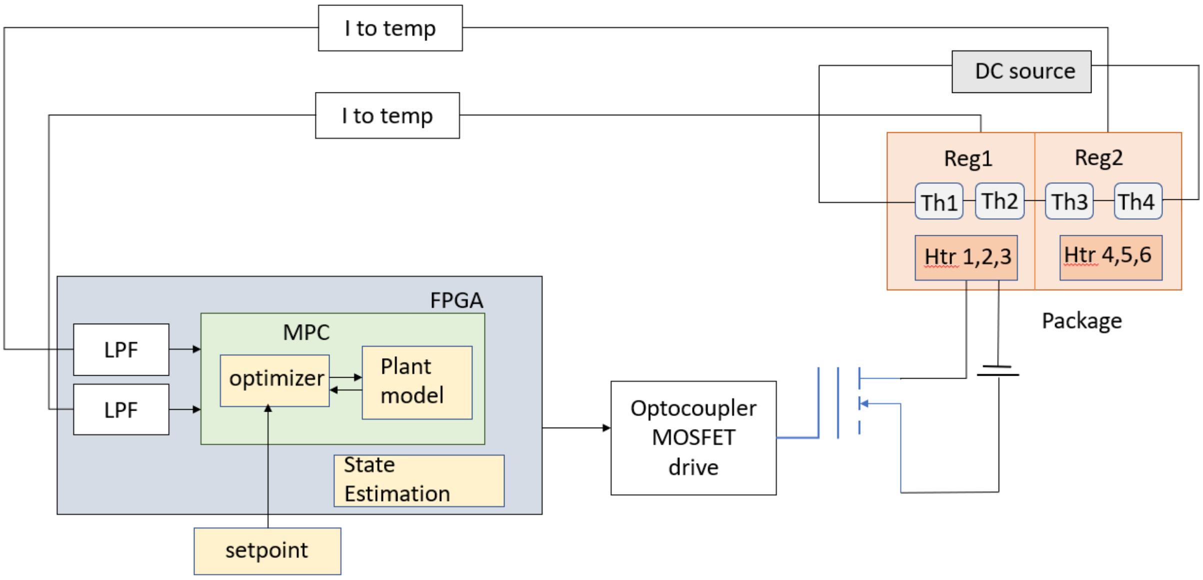

Figure 3.2: Functional diagram of multipoint temperature

formed;

$$G(s) = \frac{\theta(s)}{P(s)} = \frac{K_t e^{-sL}}{1+sT} = \frac{13.75e^{-5s}}{860s+1} \tag{3.1}$$

θ is the output temperature in degree celsius.P is the heater power input.Kt is thermal gain which the increase in temperature for a unit increase in the power.T is the time constant and L is the delay time.

Multi point Temperature

The thermal system is a Coriolis ring laser gyroscope (sensor) package, and its temperature has to be controlled. For measuring temperature at various points caused by heat from various

Temp(°C)	Resistance(K ohms)
25	10.00
30	8.194
35	6.752
40	5.592
45	4.655
50	3.893
55	3.270
60	2.760
65	2.339
70	1.990
75	1.700
80	1.458
85	1.255
90	1.084

Table 3.1: Resistance verses Temperature sample lookup table

heaters, we use a series of thermistors. The system is made up of two regions, Reg1 and Reg2. There are two thermistors and three heaters in each zone. Reg1 includes heaters H1, H2, and H3, as well as the thermistors Th1 and Th2. Reg2 includes heaters H4, H5, and H6 as well as the thermistors Th3 and Th4.Each heater having a resistance of 100.44ohms which are connected in series gives an output of 33.48Ω for Reg1 and 33.2Ω for the Reg2.Four thermistors are wired in series and coupled to a DC supply of 0.5 mA for the multipoint. First, Reg1 is powered, which means that H1, H2, and H3 are each given 32.526W of power, and the associated voltage across each thermistor is noted.

The thermal gain of a system refers to the amount of heat energy that is added to the system. It can be expressed in terms of power (energy per unit time) or total energy. The thermal gain of a system depends on various factors such as external heat sources, internal heat generation, and heat transfer processes.

In an open system, where there is a continuous exchange of heat with the surroundings, the thermal gain can be calculated by considering the heat transfer into the system from external

Table 3.2: Transfer function of MIMO system

Thermister	**Time constsnt(T)**	**Thermal Gain(K)**	**Delay Time(L)**
Reg1 Th1	4453.8	1.6	3
Reg1 Th2	4277.22	2	1
Reg2 Th3	6526.6	1.4	70
Reg2 Th4	7460.8	1.3	57
Reg1 Th1	6827.1	2	70
Reg1 Th2	6759	1.67	57
Reg2 Th3	3760.655	1.2	1
Reg2 Th4	3835.05	1.3	3

sources. This can include sources such as sunlight, heating elements, or other heat-generating components.

In a closed system, where there is no exchange of heat with the surroundings, the thermal gain can be determined by considering the internal heat generation within the system. This can include processes such as chemical reactions, electrical resistance heating, or other forms of energy conversion that generate heat within the system.

The calculation of thermal gain can be complex and may involve considerations of heat transfer mechanisms, material properties, and system-specific characteristics. It often requires knowledge of the specific system being analyzed, such as its geometry, composition, and operating conditions. The time constant of a system refers to the time it takes for a system's output to reach a certain percentage(usually 63.2% of its final or steady-state value in response to a step input. It is a measure of the system's speed of response and provides insight into its dynamics.

The time constant is typically denoted by the symbol "τ" and is derived from the dominant pole of the system's transfer function. The dominant pole is the pole with the slowest response, which governs the overall behaviour of the system. The delay time or dead time of a system refers to the time it takes for the system's output to respond after a change in the input has occurred. It represents the time delay between a stimulus or input signal and the corresponding response in the system's output.

In many systems, particularly those involving physical processes or communication networks, there can be a noticeable delay before the system begins to respond to a change in input.

This delay is often caused by factors such as transportation time, signal propagation time, processing time, or other inherent system characteristics.

The delay time is typically denoted by the symbol "L" and is measured in units of time (e.g., seconds). It is an important parameter to consider when analysing the stability and performance of a system, as it can impact the system's behaviour, stability margins, and control design.

3.2 DATA ANALYSIS

When powering the first set of heaters 1, 2, and 3 on region 1, the figure 3.3–3.6 shows the voltage across the thermistors, which is measured and stored using a recorder. This figure shows that the voltage is directly proportional to the change in temperature inside the thermistor, i.e., negative temperature coefficient thermistors are used. The first straight region is the voltage when the heaters are not powered. The figures 3.7 to 3.10 show the resistance change of the thermistor, which is obtained by dividing the voltage across the thermistor by 0.5 mA (DC source). The resistance is also inherently sensitive to temperature. The figures 2.11 to 2.14 show the temperature of the thermistors when resistance is changing, which is found out using a lookup table (table 3.1) using the method of interpolation. The figures 2.15 to 2.18 show the filtered temperature.The system parameters are given in the table 3.2.

3.3 SUMMARY

This chapter described about the design concept which includes the system description, data collection of single point and multipoint thermal systems those temperaeratureis to be controlled.

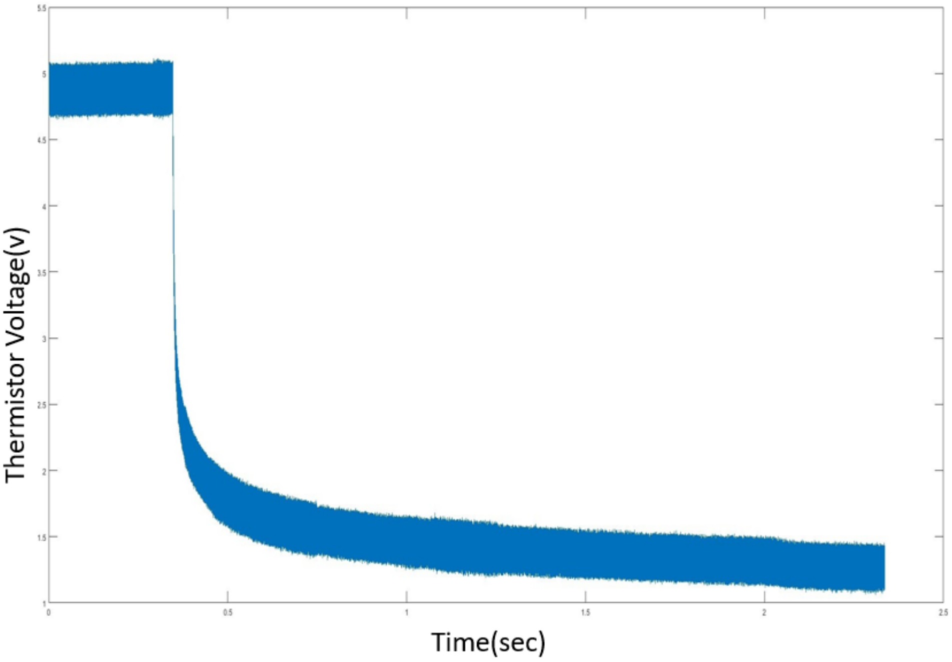

Figure 3.3: Voltage of Reg1 Th1 when powering H1,H2,H3

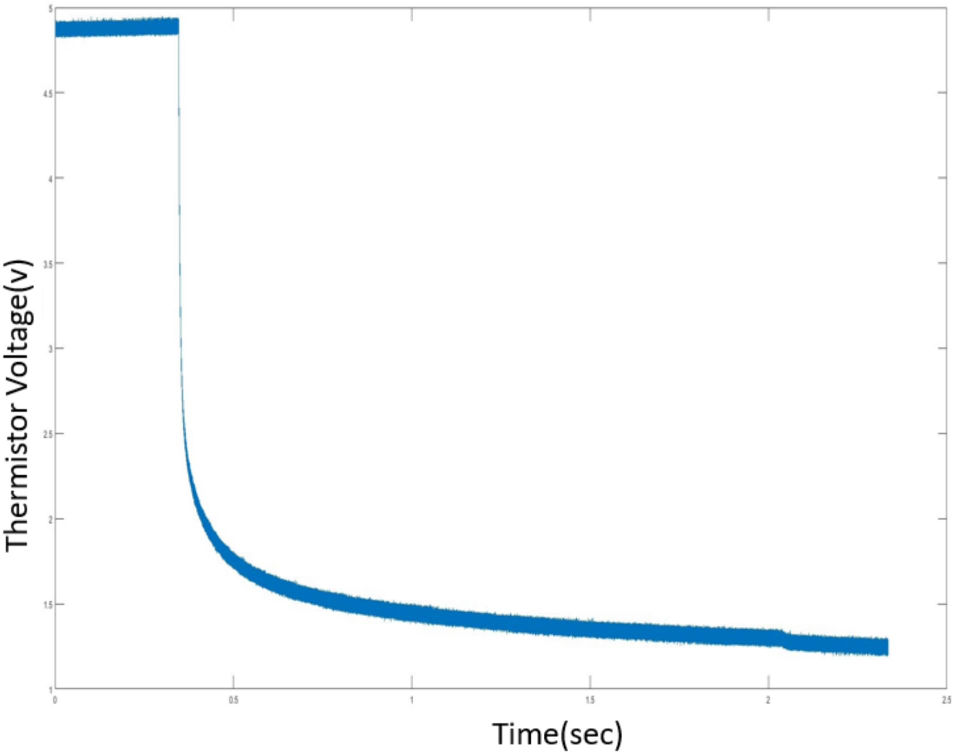

Figure 3.4: Voltage of Reg1 Th2 when powering H1,H2,H3

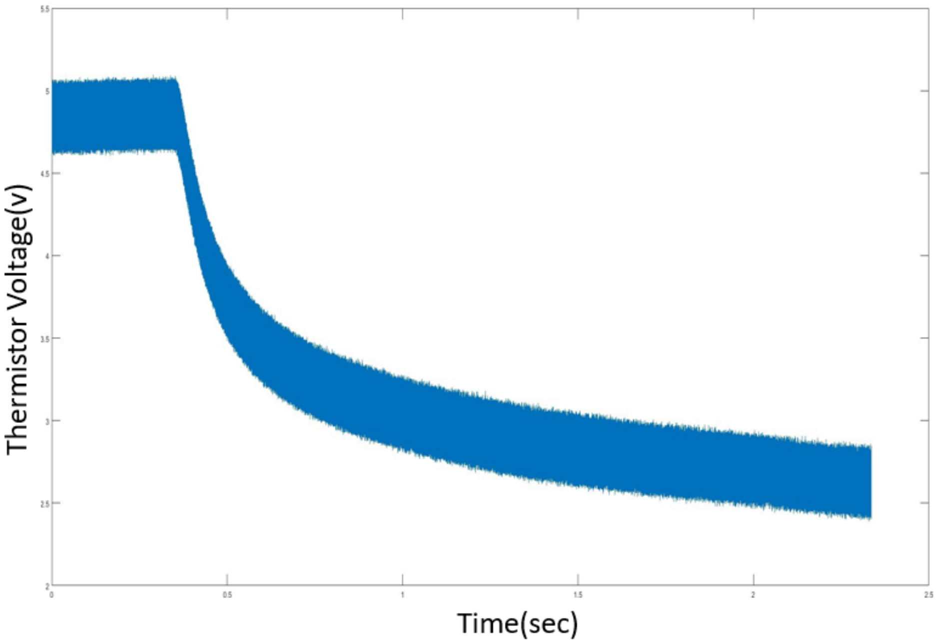

Figure 3.5: Voltage of Reg2 Th3 when powering H1,H2,H3

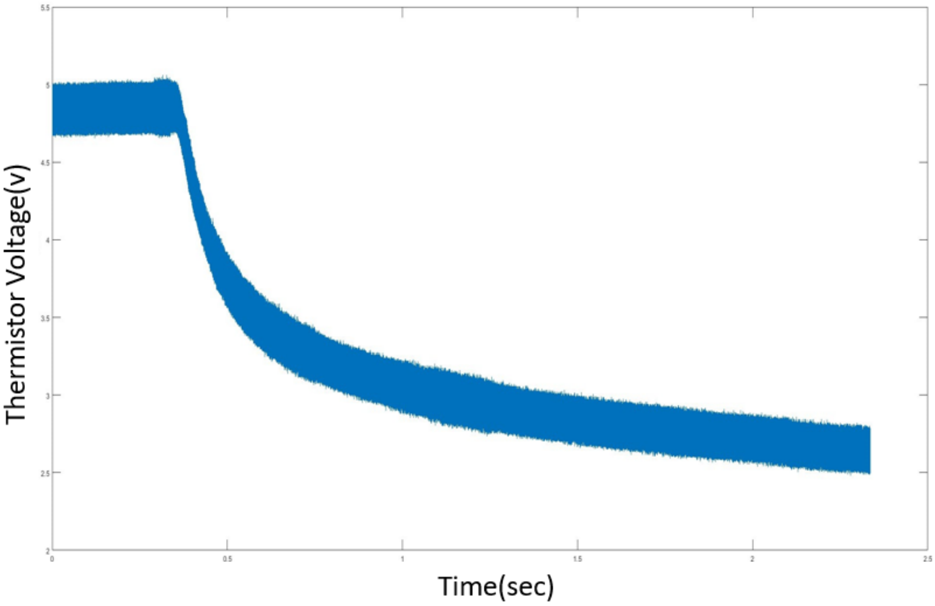

Figure 3.6: Voltage of Reg2 Th4 when powering H1,H2,H3

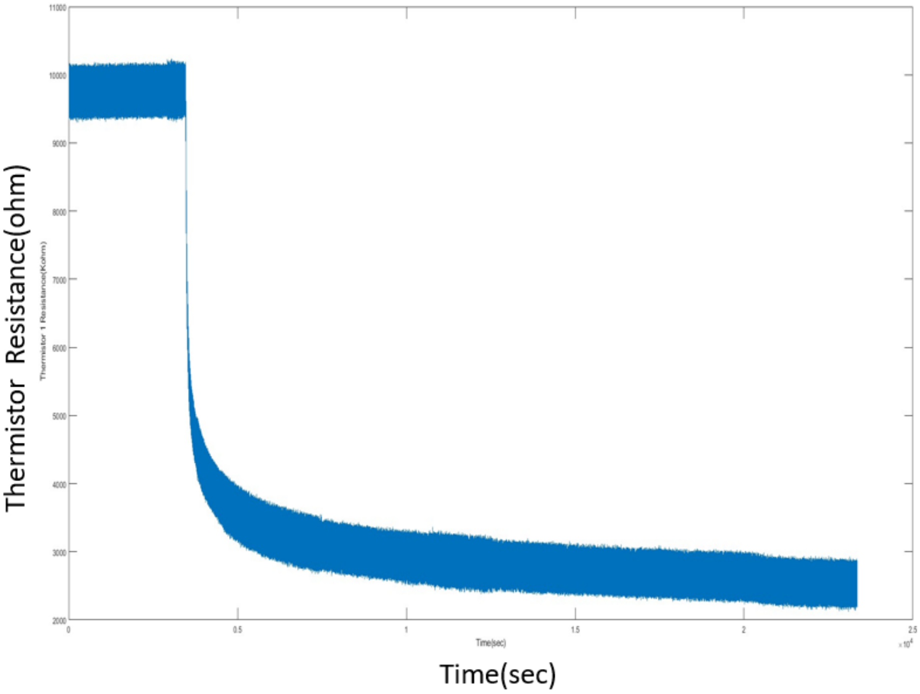

Figure 3.7: Resistance of Reg1 Th1 when powering H1,H2,H3

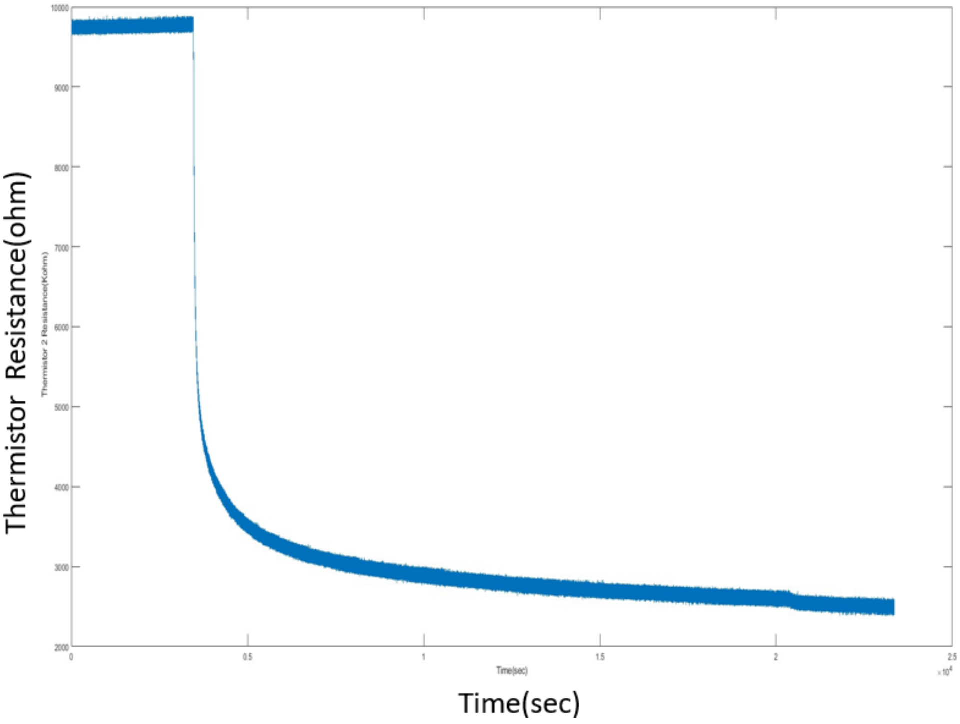

Figure 3.8: Resistance of Reg1 Th2 when powering H1,H2,H3

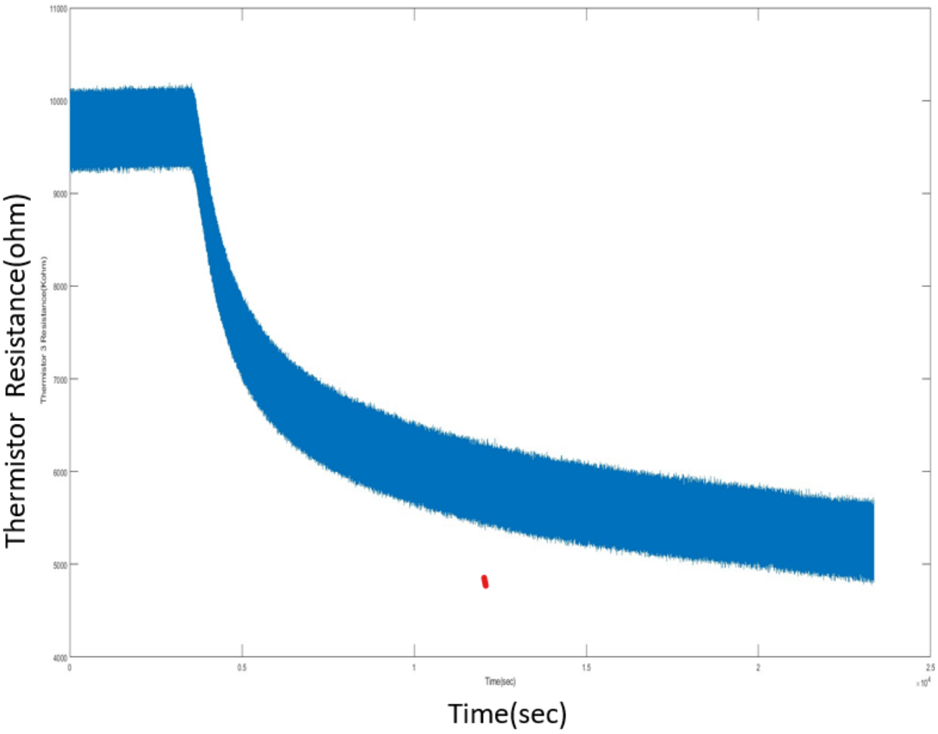

Figure 3.9: Resistance of Reg2 Th3 when powering H1,H2,H3

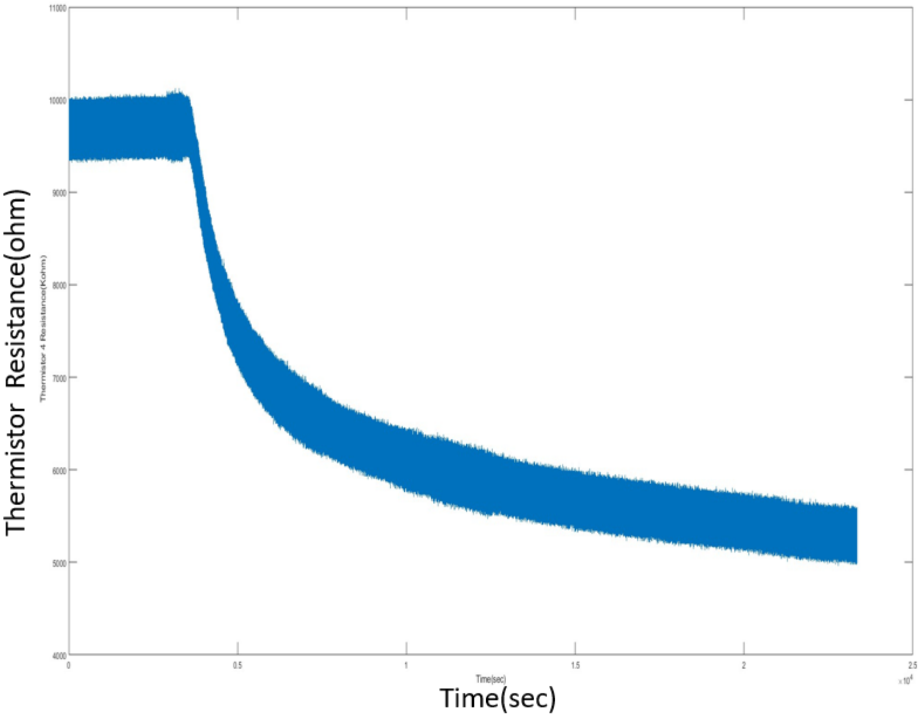

Figure 3.10: Resistance of Reg2 Th4 when powering H1,H2,H3

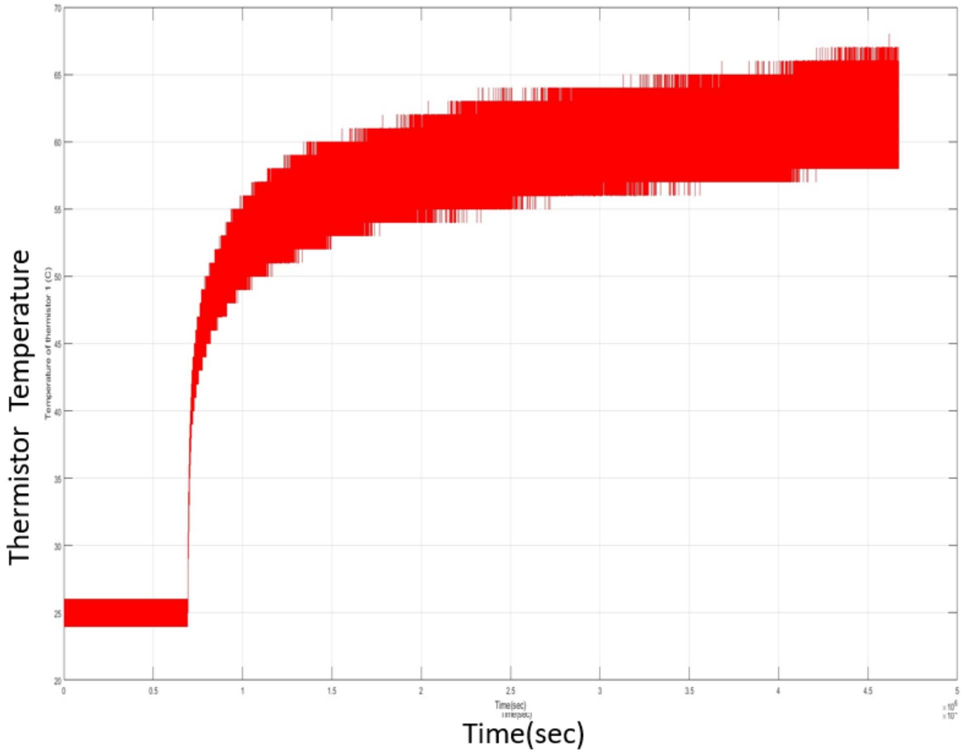

Figure 3.11: Temperature of Reg1 Th1 when powering H1,H2,H3

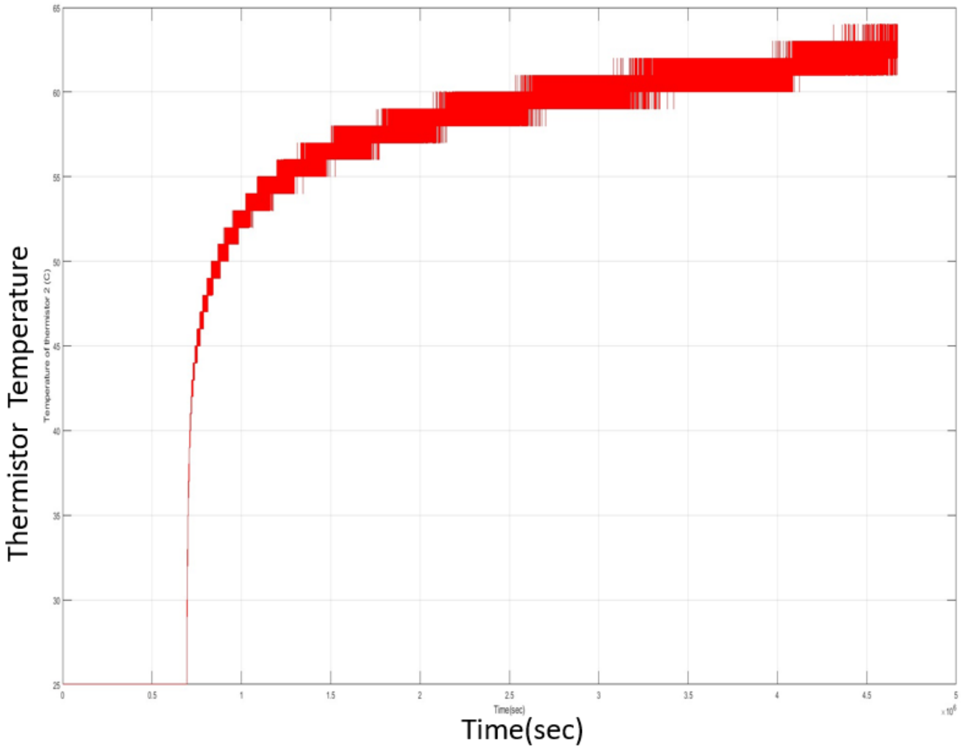

Figure 3.12: Temperature of Reg1 Th2 when powering H1,H2,H3

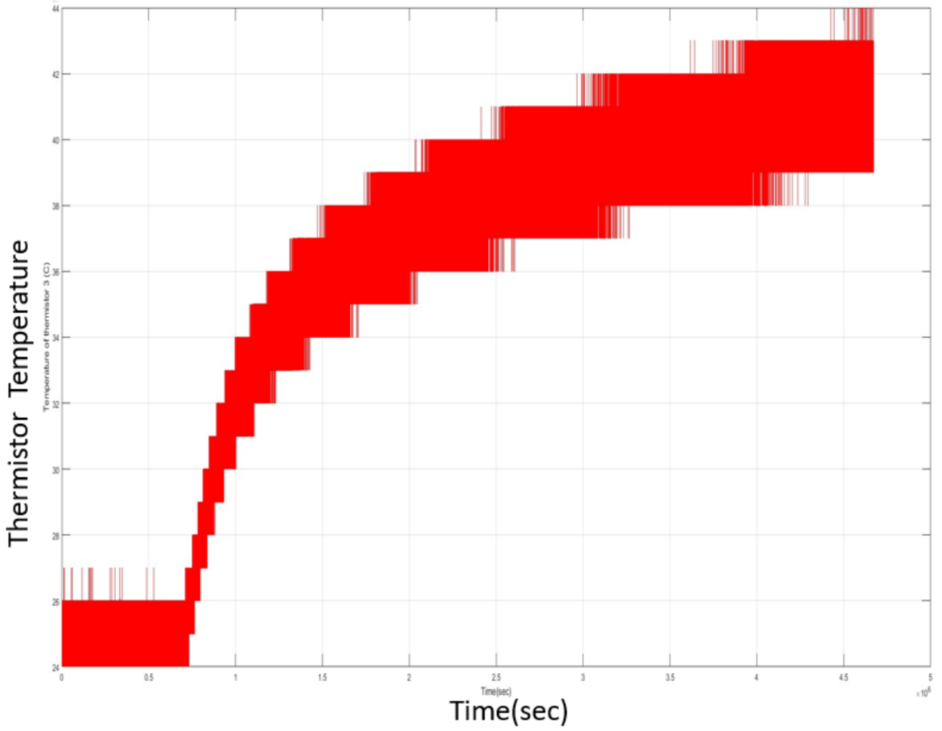

Figure 3.13: Temperature of Reg2 Th3 when powering H1,H2,H3

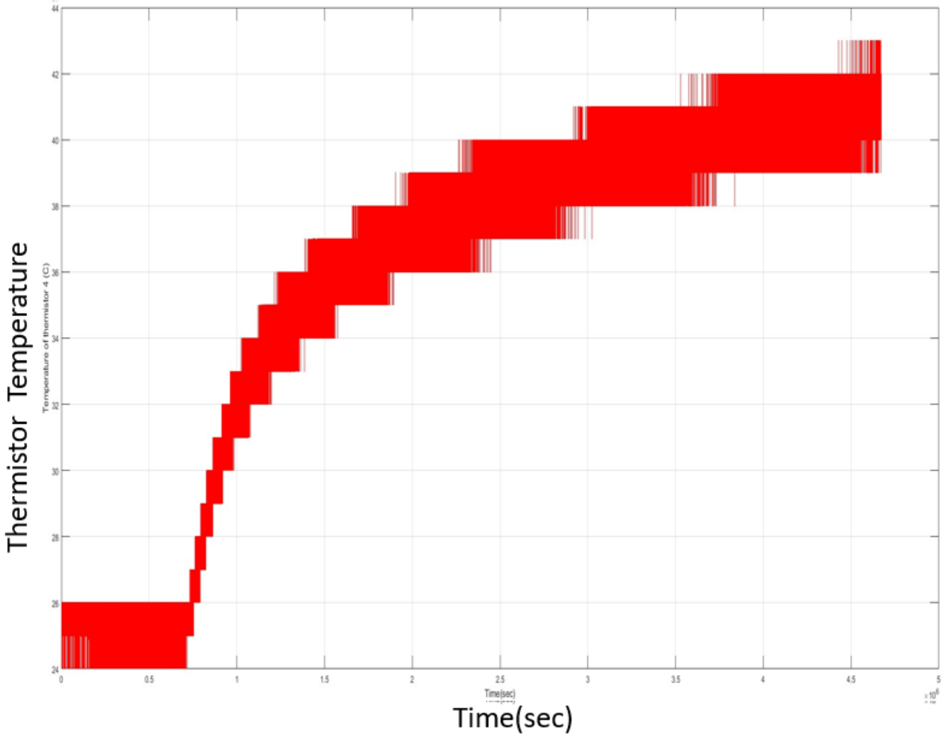

Figure 3.14: Temperature of Reg2 Th4 when powering H1,H2,H3

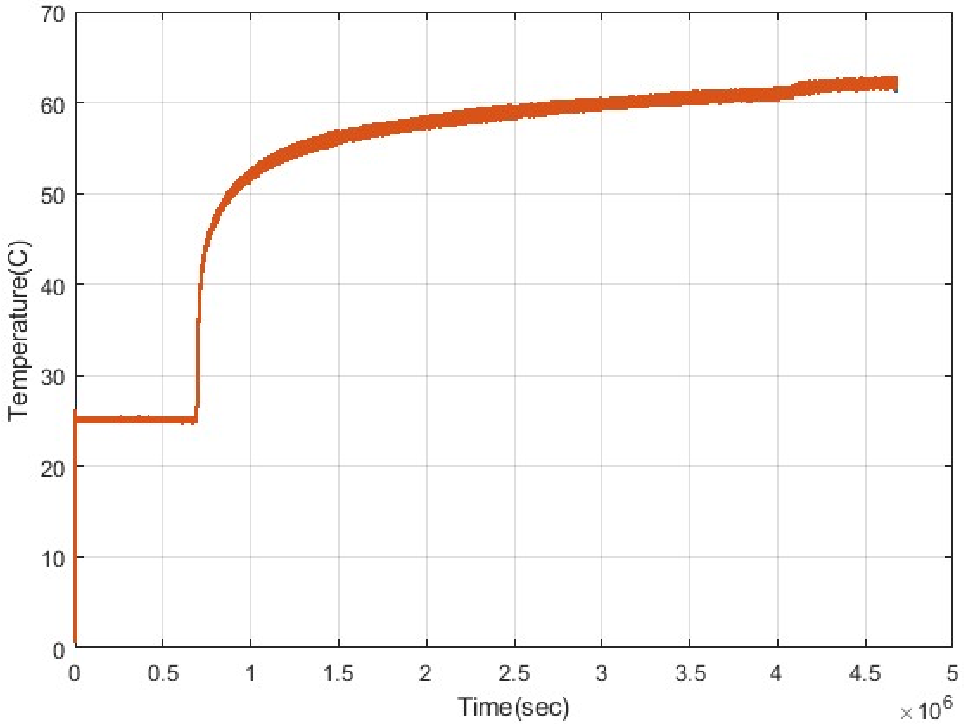

Figure 3.15: Filtered Temperature of Reg1 Th1 when powering H1,H2,H3

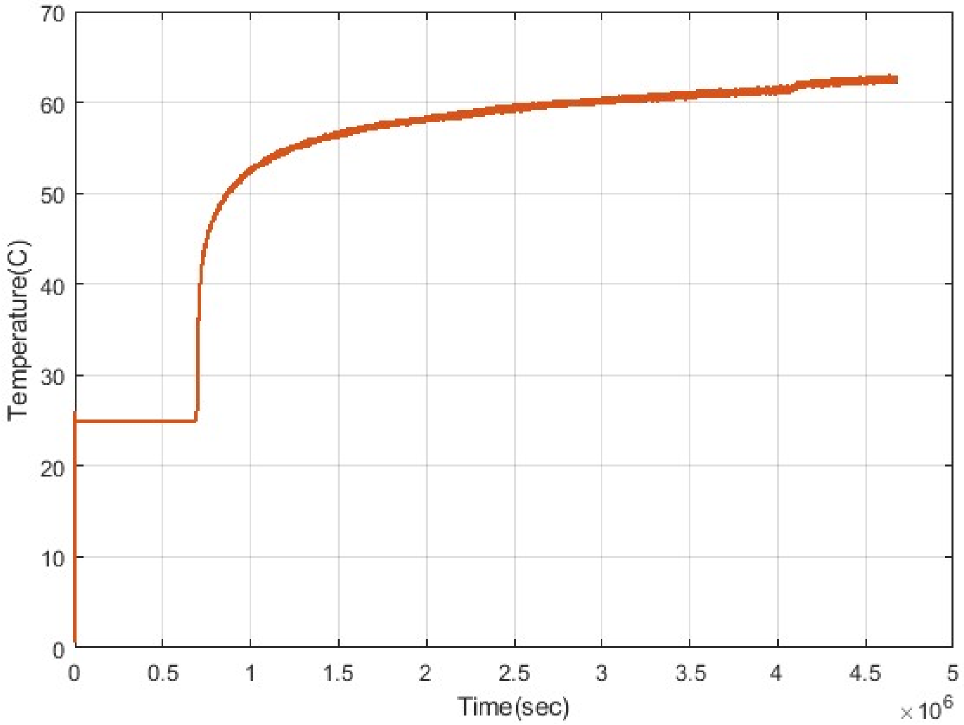

Figure 3.16: Filtered Temperature of Reg1 Th2 when powering H1,H2,H3

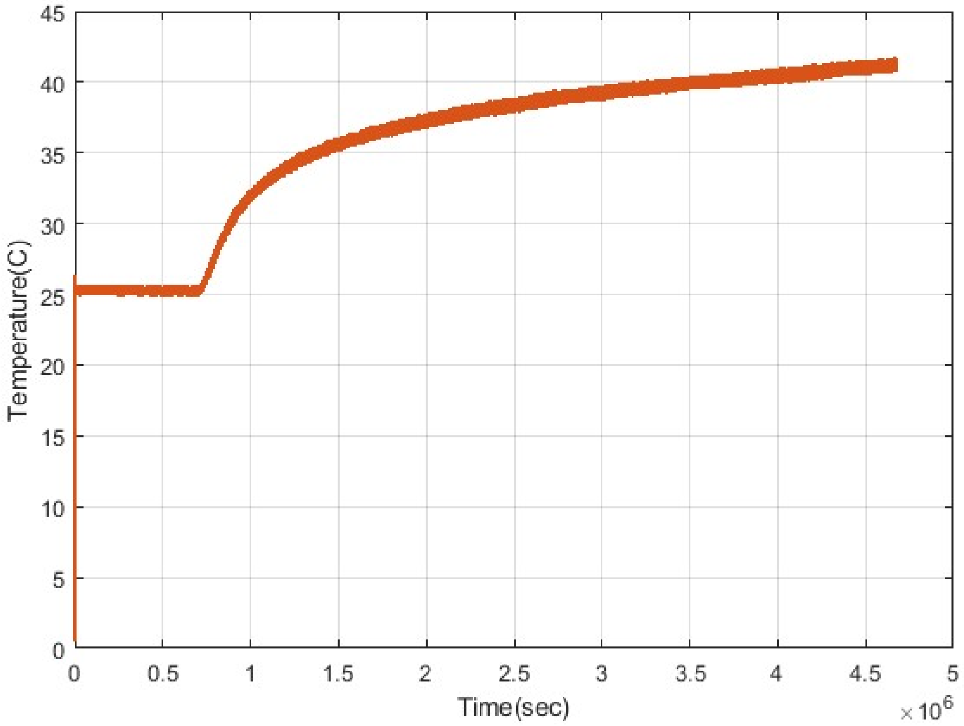

Figure 3.17: Filtered Temperature of Reg2 Th3 when powering H1,H2,H3

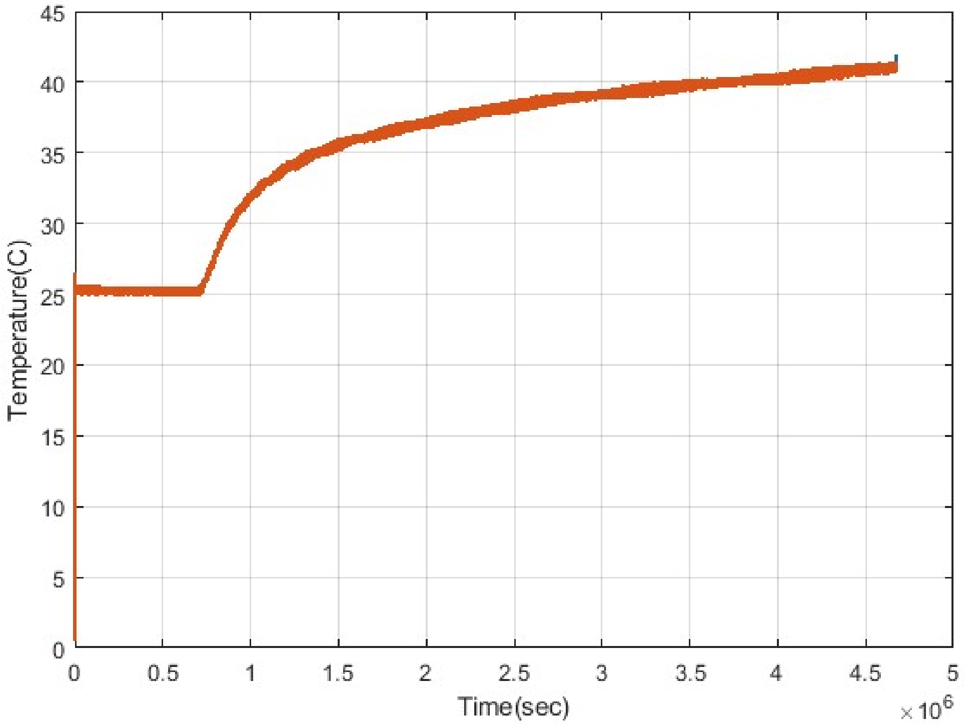

Figure 3.18: Filtered Temperature of Reg2 Th4 when powering H1,H2,H3

Chapter 4

METHODOLOGY

4.1 OVERVIEW

Heat is transferred from the heater to the system which is measured using thermister and heat is also lost to the atmosphere ,if it is not properly closed.

The transfer function of the Type Zero First Order with Time Delay system is given by:

$$G(s) = \frac{\theta(s)}{P(s)} = \frac{K_t e^{-sL}}{1 + sT}$$

where:

- Kt is the thermal gain of system
- Lis the time delay of the system, and
- T is the time constant

4.1.1 PID Controller for Single Point

The most popular controller in the sector is the PID controller. Three parameters make up a PID controller: the proportional constant "KP," the integral constant "KI," and the derivative constant "KD." These three factors are designed to handle mistakes from the past, present, and future.Gc' is the transfer function of the PID controller and is given by equation (3.7)

$$\begin{aligned} G_c &= K_P + \frac{K_I}{s} + K_D s \\ G_c &= K_P \left(1 + \frac{1}{T_i s} + T_d s\right) \end{aligned} \tag{4.2}$$

Proportional action is meant to minimize the instantaneous errors. However, by itself it cannot make the error zero and provides a limited performance. The integral action forces the steady state error to zero, but has two disadvantages: due to the presence of a pole at the origin, it may result in system instability and the integral action may create an undesirable effect known as wind-up in the presence of actuator saturation. error and it may result in large control signals when the error.The derivative action acts on the rate of change of signal is of high frequency.

Controller tuning is the process of choosing the controller settings to satisfy stated performance requirements. Ziegler and Nicholas [2] proposed tuning guidelines.PID controllers (i.e., values Kp, Ti, and Td are selected based on experimental step responses or on the value of Kp that yields marginal stability when only proportional control action is utilised) are used to control systems. When mathematical models of plants are unknown, Ziegler-Nichols rules, which are briefly provided below, might be helpful.There are two methods called Ziegler–Nicholas tuning rules: the first method and the second method.

Ziegler–Nicholas first method

This method applies if the response to a step input exhibits an S-shaped curve. Such step-response curves may be generated experimentally or from a dynamic simulation of the plant. The S-shaped curve may be characterized by two constants, delay time L and time constant T. The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersections of the tangent line with the time axis and line c(t)=K, as shown in Fig. 2. The parameters of the PID are taken as:

$$\begin{aligned} K_p &= 1.2(T/L) \\ T_i &= 2L \\ T_d &= 0.5L \end{aligned} \tag{4.3}$$

Ziegler–Nicholas second method

In the second method, we first set Ti = and Td = 0. Using the proportional control action only (see Fig. 3.), we increase Kp from 0 to a critical value Kcr at which the output exhibits sustained oscillations. Thus, the critical gain Kcr and the corresponding period Pcr are experimentally determined. Ziegler and Nicholas suggested that we set the values of the parameters Kp, Ti , and Td according to the formula shown below:

$$\begin{aligned} K_p &= 0.6K_{cr} \\ T_i &= 0.5P_{cr} \\ T_d &= 0.125P_{cr} \end{aligned} \tag{4.4}$$

The open loop response of the temperature control system is shown in Fig. 4. The response is a S-shaped curve and so we use Ziegler-Nicolas tuning method-1, to find the parameters of the PID controller. From the open loop step response curve the values of L and T are found to be 3 and 24 respectively. Hence, the parameters of the PID are:

$$\begin{aligned} K_p &= 1.2(T/L) \\ T_i &= 2L \\ T_d &= 0.5L \end{aligned} \tag{4.5}$$

4.1.2 Model Predictive Controller for Multi Point

a. Model Predictive Controller

MPC which stands for Model Predictive Controller is a feedback algorithm that predicts the future of the process.It is advanced method of process control that is used to control a process while satisfying a set of constraints.MPC relays on dynamic models of the process most of linear emphirical models, transfer function models obtained by system identification. Think about how we may manage a multiple-input, multiple-output process while adhering to inequality limits on the variables for both input and output. Future values of the outputs can be predicted using the model and current measurements if a dynamic model of the process is provided and is suitably accurate. On the basis of both predictions and measurements, the necessary modifications in the input variables may then be computed.In essence, the changes in the individual input variables are coordinated after considering the input-output relationships represented by the process model. In MPC applications, the input variables are also known as manipulated variables (MVs) and the output variables are also known as controlled variables (CVs). The term "DVs" or "feedforward variables" refers to measured disturbance variables.the main objectives of the MPC is that :

- MPC can handle MIMO systems.

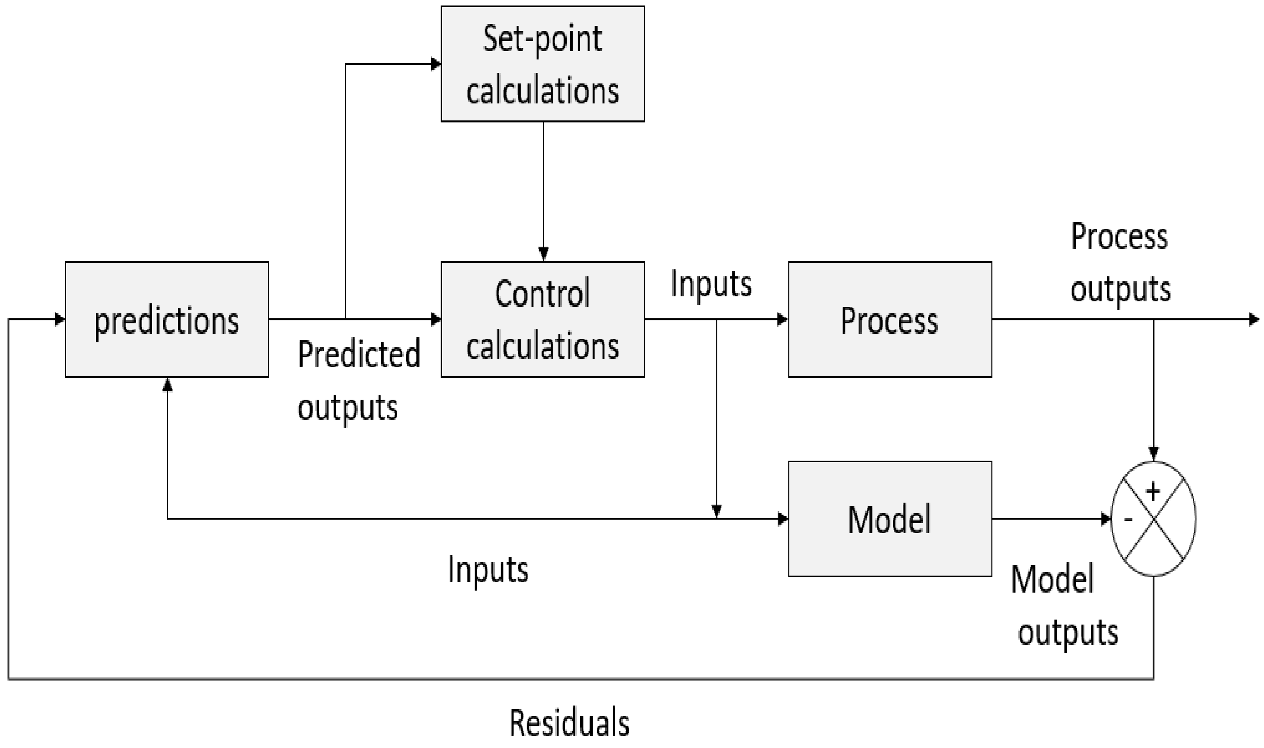

Figure 4.1: Closed loop frequency response

- MPC can handle constraints.
- MPC has preview capability.
- Solves an online optimization problem at each step so it requires a powerful fast processor with large memory.

The present values of the output variables are predicted using a process model. A Prediction block receives input from the residuals, or the disparities between the actual and anticipated outputs. Both the set-point calculations and the control calculations, which are carried out by the MPC at each sampling moment, make use of the predictions. Either form of calculation can take inequality restrictions, such as upper and lower limits, into account for the input and output variables. The residual functions as a feedback signal, and the model runs concurrently with the process. The synchronisation of the control and set-point computations, however, distinguishes MPC from other systems. Additionally, because MPC is better suited for restricted MIMO control issues than IMC or Smith predictor, it has a far higher influence on industry practise.

Set points, also known as goals, are derived from an economic optimisation based on a steady-state model of the process, which is often a linear model. The goals of optimisation fre-

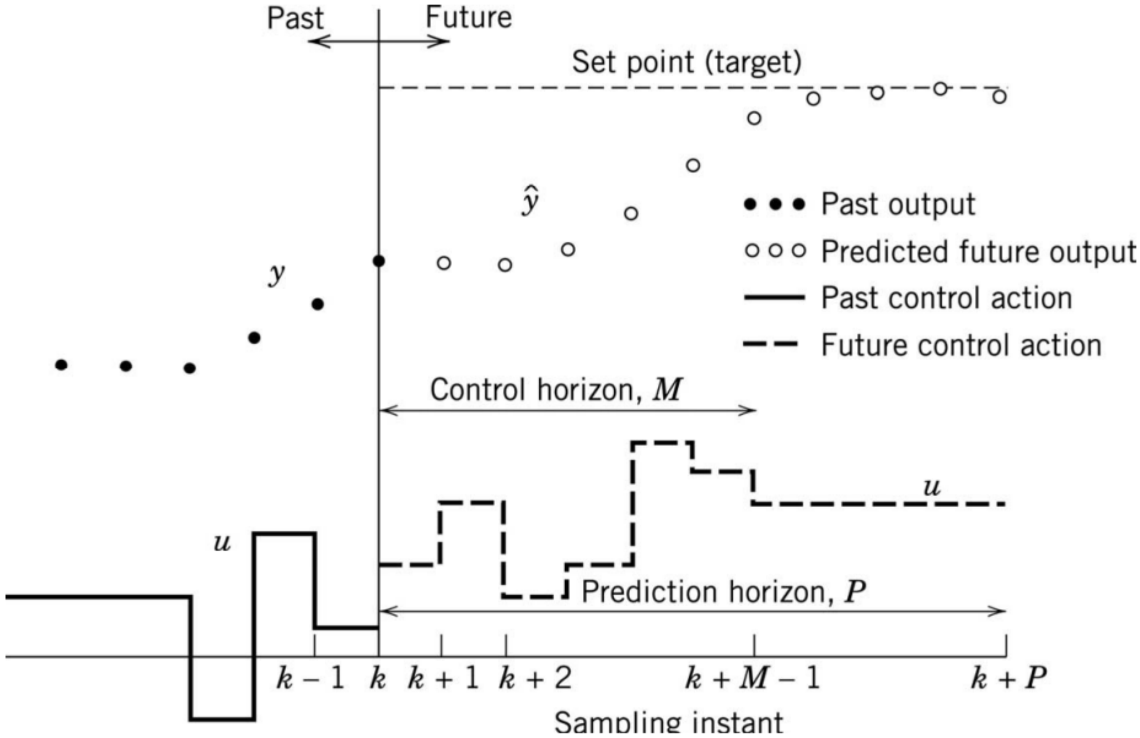

Figure 4.2: Basic concept of MPC

quently include maximising a profit function, minimising a cost function, or increasing output. Due to changing process circumstances, particularly adjustments to the inequality restrictions, the optimal set point values change often. Variations in the equipment, instrumentation, and process conditions as well as economic information like pricing and expenses are what cause the constraint changes.The MPC computations are based on the most recent measurements and forecasts of the outputs' future values. The goal of the MPC control computations is to select the best possible order of control moves (i.e., controlled input changes) to move the expected response to the set point. Figure 3.2 displays the actual output y, predicted output $\hat{y}$, and altered input u for the SISO control.
MPC design parameter:

- Sample time(Ts): By choosing the sample time we determine the rate at which the controller executes the control algorithm.When Ts is too large then the controller cannot react to he disturbance in the plant fast enough.When Ts is too small then the controller can teact much faster disturbances and set point changes but this cause excess of computational alternative.

- Prediction horizon and Control horizon: Lengthof time to reach the future value prediction horizon shifts forward by one time step. MPC need to tracks the best path to reach the refernce point that is the optimised path, solving an optimized problem.At k-th sampling instant, the values of the manipulated variables, u, at the next M sampling instants, u(k), u(k+1), . . . ,u(k+M -1) are calculated. Set of M "control moves" is calculated so as to minimize the predicted deviations from the reference trajectory over the next P sampling instants while satisfying the constraints.were M is control horizon and P is the prediction horizon
- Constraints:Constraints refer to limitations or restrictions that affect what is possible or permissible in a given situation. Constraints are important because violating them can cause to undesired consequences. there are of two types soft constraints and hard constraints, soft constraints can be violated but hard constraints can't be violated.
- Cost function: Minimizing the cost function the mpc also ensures the model is optimized.
- Receding Horizon approach:At each sampling instant, a series of M control moves is computed, but only the first move is actually carried out. Once additional measurements are available, a new sequence is computed at the following sampling instant, this time implementing only the initial input move. At each sample moment, this process is repeated.

b. MPC Control Algorithm

1. **Single Predictions for SISO Models:** Then, we show how step-response models may be applied to forecast future results. Other varieties of linear models, such as transfer function or state-space models, can be used to provide comparable predictions.A steady, single-input, single-output process' step-response model may be expressed as;

   $$y(k+1) = y_0 + \sum_{i=1}^{N-1} S_i \Delta u(k-i+1) + S_N u(k-N+1) \tag{4.6}$$

   Where $\Delta u(k-i+1)$ signifies the change in the altered input from one sample moment to the next,$\Delta u(k-i+1) = u(k-i+1) - u(k-i)$, and y(k+1) is the output variable at the (k+1)- sampling instant. They are both deviation variables: y and u. The N step-response coefficients, S1 to SN, are the model's inputs. N is often chosen so that 30$\leq$ N $\leq$120. y0 stands for y(0), the starting point. To keep things simple, we'll suppose that $y_0 = 0$.

Predictions of future outputs over a prediction horizon, P, are the foundation of model predictive control. Now let's think about how these forecasts were calculated. Assume that k represents the current sampling moment and that $\hat{y}(k+1)$represents the forecast made at time k. If y0=0, then Eq.3.6 may be used to get this one-step-ahead forecast by substituting y(k+1) for $\hat{y}(k+1)$:

$$\hat{y}(k+1)=\sum_{i=1}^{N-1} S_i \Delta u(k-i+1)+S_N u(k-N+1) \tag{4.7}$$

$$\hat{y}(k+1)=S_1 \Delta u(k)+\sum_{i=2}^{N-1} S_i \Delta u(k-i+1)+S_N u(k-N+1) \tag{4.8}$$

Due to $\Delta u(k)$= u(k)-u(k-1), the first term on the right shows the impact of the present manipulated input u(k). The second component u(i),i,k denotes the results of earlier inputs. In a similar way, a comparable equation for a two-step-ahead forecast may be obtained.

$$\hat{y}\left(k^{\prime}+2\right)=\sum_{i=1}^{N-1} S_i \Delta u\left(k^{\prime}-i+2\right)+S_N u\left(k^{\prime}-N+2\right) \tag{4.9}$$

We may substitute k with k' and then extend the right-hand side to identify the contributions in relation to the current sample moment, k, since Eq. 3.9 is true for all positive values of k' without losing generality.

The j ahead prediction can be derived as:

$$\hat{y}(k+j)=\sum_{i=1}^{j} S_i \Delta u(k+j-i) \quad+\sum_{i=i+1}^{N-1} S_i \Delta u(k+j-i)+S_N u(k+j-N) \tag{4.10}$$

The second and third elements in Eq. 20-10's right-hand side denote the expected behaviour in the absence of any current or foreseeable control actions, or, more precisely, the expected behaviour when u(k+i)=u(k-1) for i>0 or, alternatively, u(k+i) =0 for i>0. This concept is referred to as the expected unforced reaction and is represented by the symbol y (k+j) since it takes prior control actions into account. Therefore, y(k+j) is defined as:

$$\hat{y}^o(k+j) \triangleq \sum_{i=i+1}^{N-1} S_i \Delta u(k+j-i)+S_N u(k+j-N) \tag{4.11}$$

$$\hat{y}(k+j)=\sum_{i=1}^{j} S_i \Delta u(k+j-i)+\hat{y}^o(k+j) \tag{4.12}$$

eq.3.12 can be reduced to

$$\hat{y}(k+J) = S_J \Delta u(k) + \hat{y}^o(k+J) \tag{4.13}$$

Setting $\hat{y}(k+J) = y_{sp}$ and rearranging gives the desired predictive controller:

$$\Delta u(k) = \frac{y_{sp} - \hat{y}^o(k+J)}{S_J} \tag{4.14}$$

2. **Multiple Predictions for SISO systems:** Considering a typical situation of multiple prediction rather than one single prediction.Vector notations can be used.For next P samples the vector predicted response can be notated as:

$$\hat{\boldsymbol{Y}}(k+1) \triangleq \text{col}[\hat{y}(k+1), \hat{y}(k+2), \ldots, \hat{y}(k+P)] \tag{4.15}$$

And the vector predicted unforced response can be defined as:

$$\hat{\boldsymbol{Y}}^o(k+1) \triangleq \text{col}\left[\hat{y}^o(k+1), \hat{y}^o(k+2), \ldots, \hat{y}^o(k+P)\right] \tag{4.16}$$

Define $\Delta U(k)$ to be a vector of control actions for the next M sampling instants:

$$\Delta \boldsymbol{U}(k) \triangleq \text{col}[\Delta u(k), \Delta u(k+1), \ldots, \Delta u(k+M-1)] \tag{4.17}$$

The control horizon M and prediction horizon P are important design factors. Generally speaking, $P \leq N + MandM \leq P$. The anticipated outputs must shift ideally to the new set points for the MPC control computations to be successful. The model predictions in Eq.3.12 are readily expressed in vector-matrix notation for the control computations as:

$$\hat{\boldsymbol{Y}}(k+1) = S \Delta \boldsymbol{U}(k) + \hat{\boldsymbol{Y}}^o(k+1) \tag{4.18}$$

Where S is an P*M matrix,

$$S \triangleq \begin{bmatrix} S_1 & 0 & \cdots & 0 \\ S_2 & S_1 & 0 & \vdots \\ \vdots & \vdots & \ddots & 0 \\ S_M & S_{M-1} & \cdots & S_1 \\ S_{M+1} & S_M & \cdots & S_2 \\ \vdots & \vdots & \ddots & \vdots \\ S_P & S_{P-1} & \cdots & S_{P-M+1} \end{bmatrix} \tag{4.19}$$

3. **Multiple Prediction for MIMO systems:** The Principle of Superposition may be used to extend the preceding study for SISO systems to MIMO systems. To keep things simple, we'll start with a process control issue that has two outputs, y1 and y2, and two inputs, u1 and u2. Four separate step-response models, one for each input-output combination, are included in the prediction model, which consists of two equations:

$$\begin{aligned}\hat{y}_1(k+1) &= \sum_{i=1}^{N-1} S_{11,i}\Delta u_1(k-i+1) + S_{11,N}u_1(k-N+1)\\ &+ \sum_{i=1}^{N-1} S_{12,i}\Delta u_2(k-i+1) + S_{12,N}u_2(k-N+1)\end{aligned} \tag{4.20}$$

It is practical to represent the MIMO step response model using vector matrices.

$$\tilde{\boldsymbol{Y}}(\boldsymbol{k}+\boldsymbol{1}) = \boldsymbol{S}\Delta\boldsymbol{U}(k) + \hat{\boldsymbol{Y}}^{\boldsymbol{o}}(k+1) + [y(k) - \hat{y}(k)] \tag{4.21}$$

$\tilde{\boldsymbol{Y}}(\boldsymbol{k}+\boldsymbol{1})$is the mP dimensional vector of corrected prediction over the prediction Horizon P,

$$\tilde{\boldsymbol{y}}(k+1) \triangleq \text{col}[\tilde{\boldsymbol{y}}(k+1), \tilde{\boldsymbol{y}}(k+2), \ldots, \tilde{\boldsymbol{y}}(k+P)] \tag{4.22}$$

$\hat{\boldsymbol{Y}}^{\boldsymbol{o}}(k+1)$ is the mP dimensional vectorof predicted unforced responses.

$$\hat{\boldsymbol{Y}}^{\boldsymbol{o}}(k+1) \triangleq \text{col}\,[\hat{\boldsymbol{y}}^{\boldsymbol{o}}(k+1), \hat{\boldsymbol{y}}^{\boldsymbol{o}}(k+2), \ldots, \hat{\boldsymbol{y}}^{\boldsymbol{o}}(k+P)] \tag{4.23}$$

$$\Delta\boldsymbol{U}(k) \triangleq \text{col}[\Delta\boldsymbol{u}(k), \Delta\boldsymbol{u}(k+1), \ldots, \Delta\boldsymbol{u}(k+M-1)] \tag{4.24}$$

4.2 SUMMARY

This Chapter discussed about the method for controlling first order temperature control system using PID controller which is tuned using first method of Ziegler Nicholas.And method of controlling system using model predictive controller for multiple input multiple output system.

Chapter 5

RESULTS AND DISCUSSION

5.1 RESULT FOR SINGLE POINT TEMPERATURE CONTROL

The temperature-controlled system employing a Pi controller that has been fine-tuned via the Ziegler-Nicolas approach is seen in Figure 5.1.PI controller was used to convert the system from type 0 to type 1 in order to achieve zero steady state error and excellent disturbance rejection.Design the PI zero to have a sufficient stability margin.

The 200 Hz frequency generated and pulse width controlled by a PI controller's duty cycle. PWM output should only be generated when the module is activated; else, output will be insufficient. The 200 Hz signal obtained from the clock divider module is connected to a loop of integers ranging from 0 to 1000. Up until the counter value meets the duty cycle value obtained from the PI controller, the PWM pulse output is maintained at a high level. Once the counter value reaches 1000 and the PWM pulse outside is kept at a low level, the action will be repeated. The duty cycle update that occurs after the PI controller has been executed is shown in Figure 5.2.

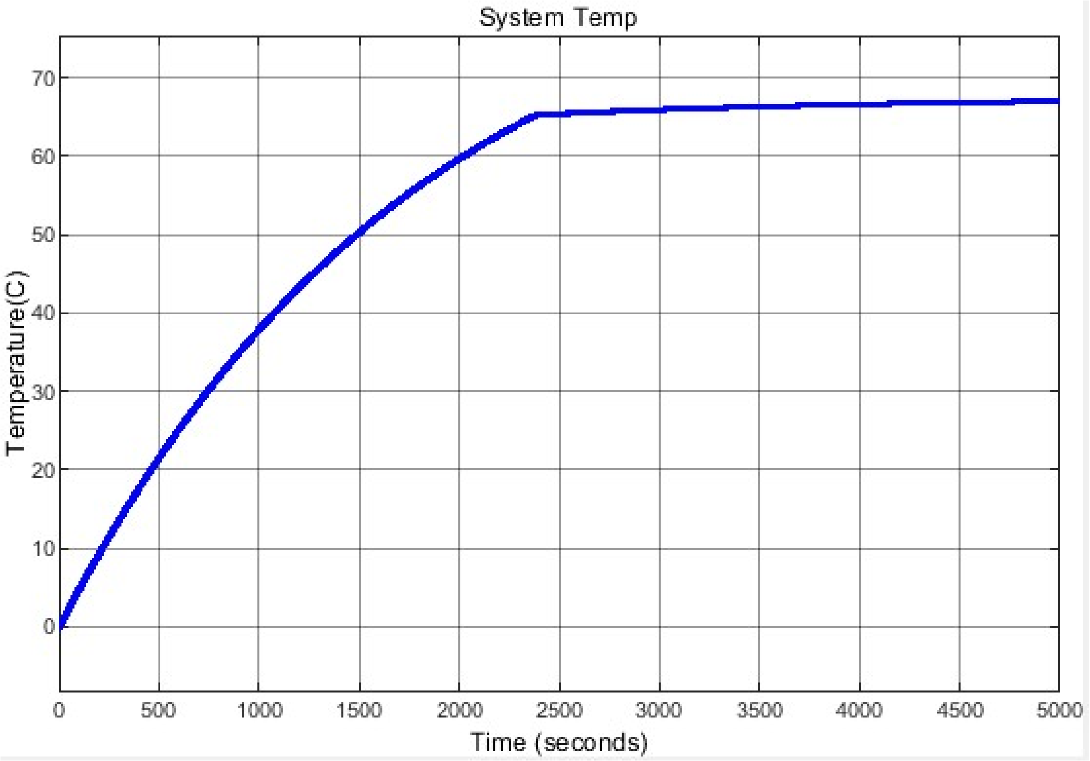

Figure 5.1: System temperature for SISO system controlled using PI

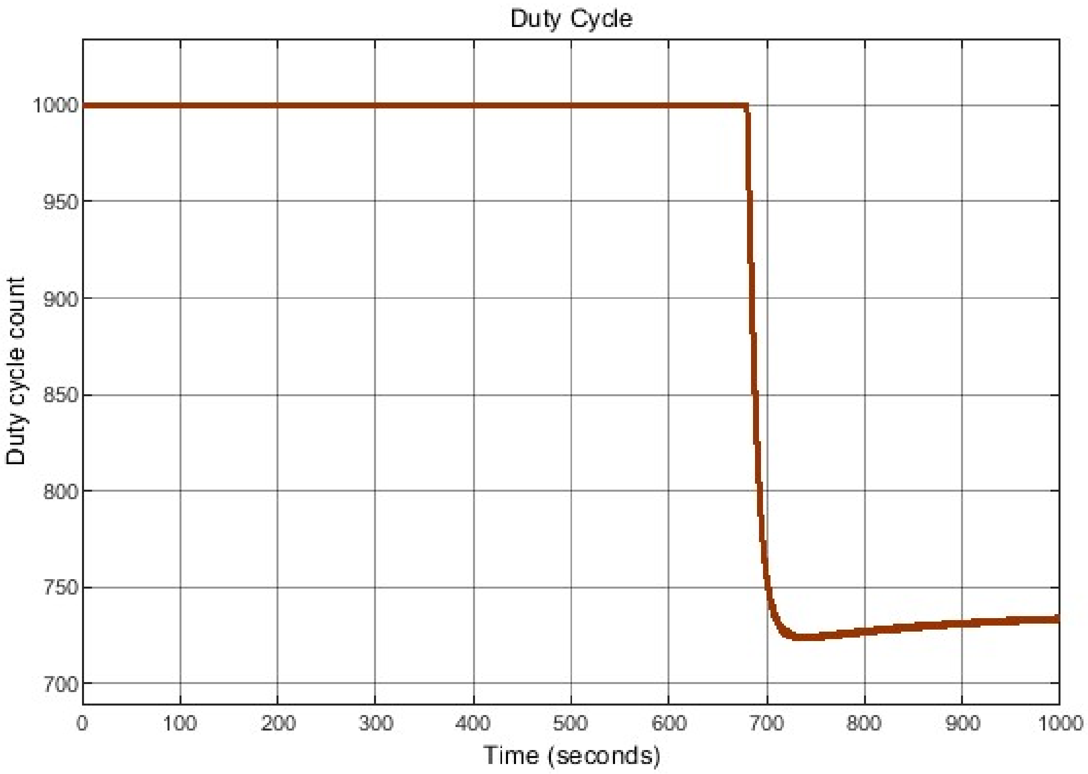

Figure 5.2: PWM output for the first order plus dead time system

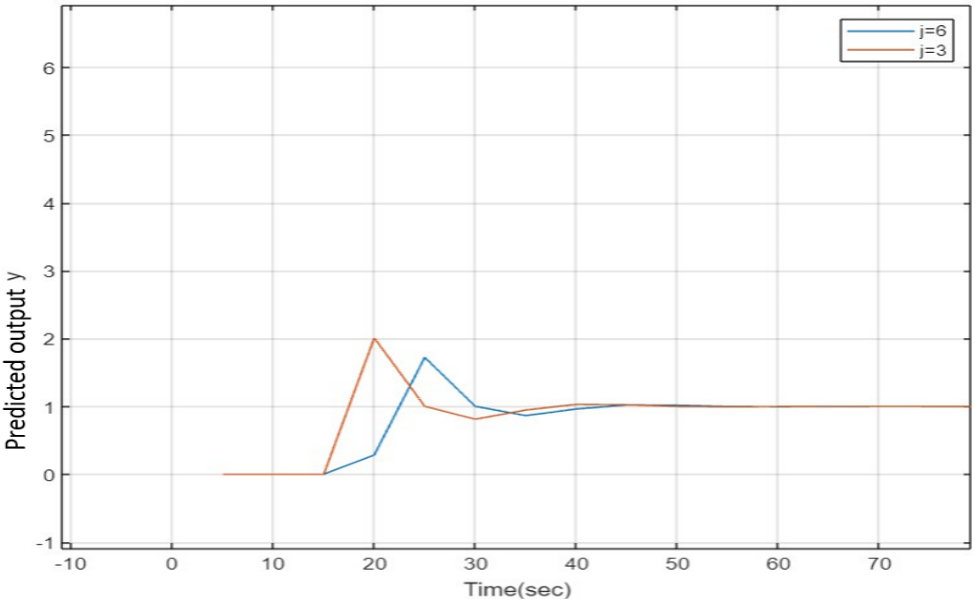

Figure 5.3: Predicted output for different j value on fifth order system.

5.2 RESULT FOR MULTIPOINT TEMPERATURE CONTROL

To a fifth-order system, Equation 5.1 applies the model predictive control law for various step-ahead prediction values (j). The predicted output is shown in Figure 5.3.According to the figure 5.3, when the value of j rises, the anticipated output will settle quickly and the overshoot will decrease and smooth out.The figure 5.4 shows the control input for the different j values which gives the idea about how the control input changes with change in j values.

$$\frac{Y(S)}{U(S)} = \frac{1}{(5s+1)^5} \tag{5.1}$$

For applying the predictive control law to a system, we first take the step response of the system for calculation of the step response coefficient. Figure 5.5 shows the step response of the system in equation 5.2.We are giving the setpoint as 5, and the predicted output for the system is given as 5.6, but the predicted output doesn't make use of the current output, so there may be a bias due to this, and the corrected predicted output is given in figure 5.7.And the control input for this step ahead prediction is given in figure 5.8.

$$\frac{Y(s)}{U(s)} = \frac{5e^{-2s}}{(15s+1)} \tag{5.2}$$

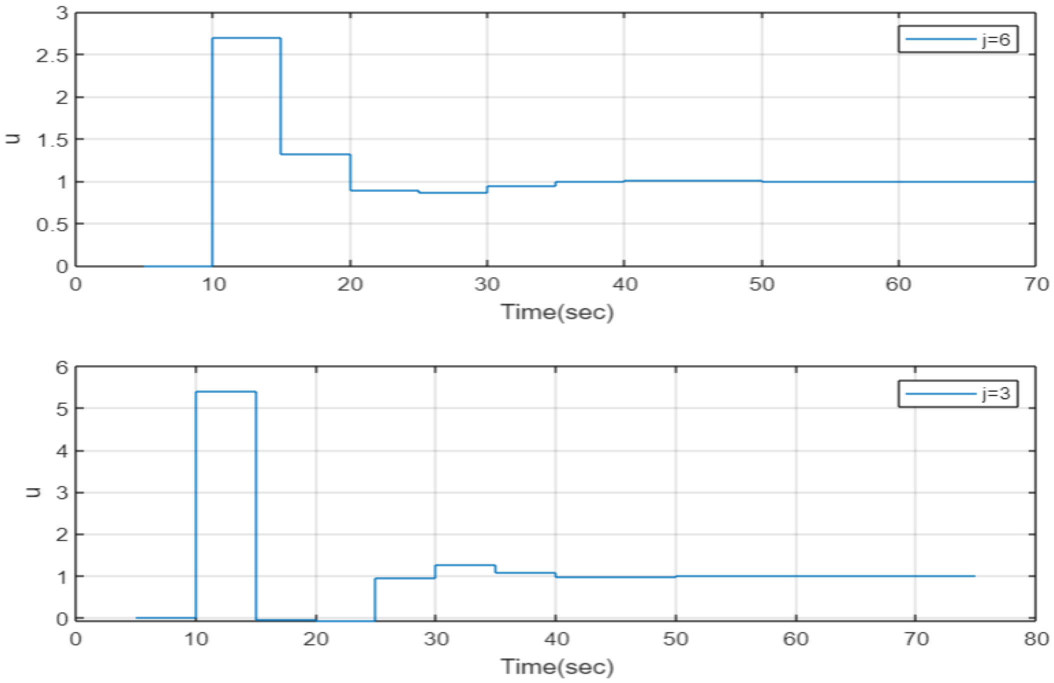

Figure 5.4: Control Input responses at different value of j

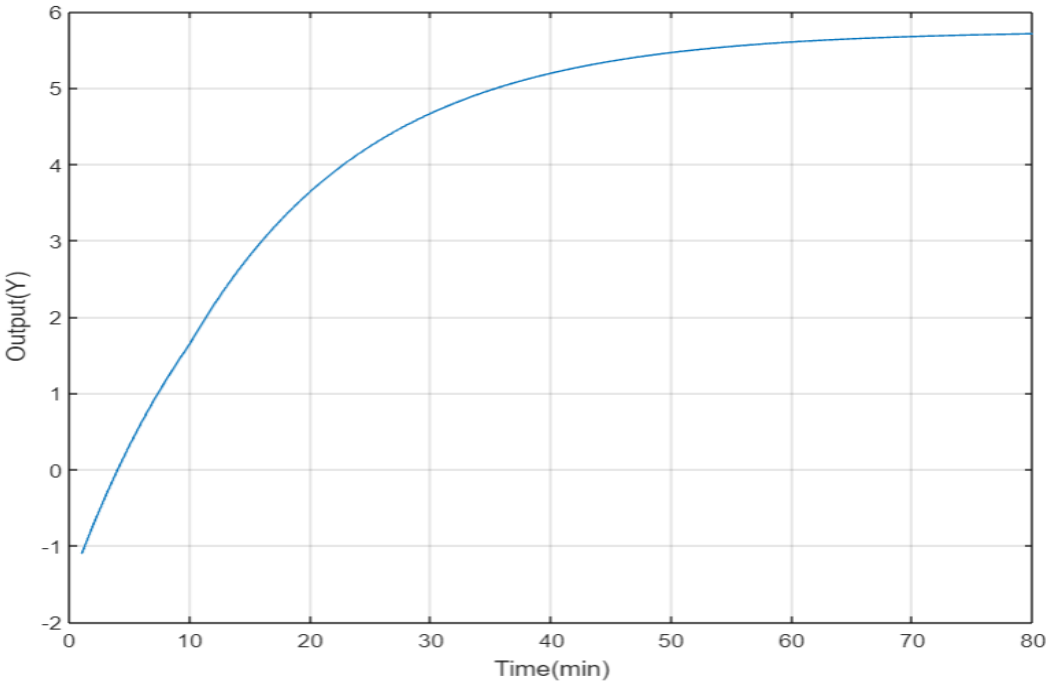

Figure 5.5: Step response of first order plus dead time process

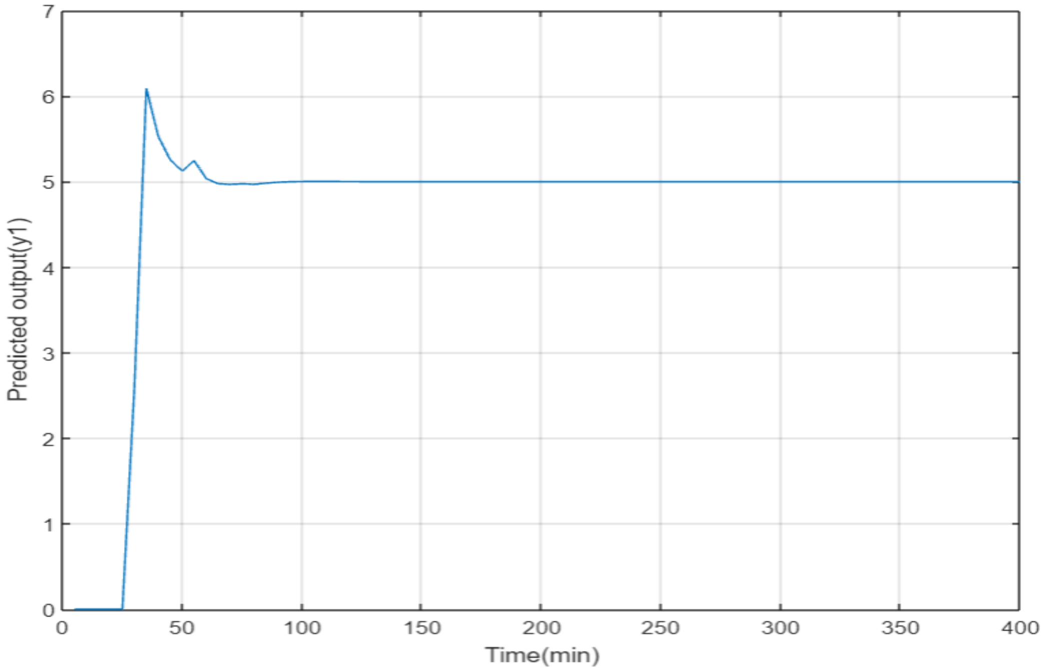

Figure 5.6: Predicted Output of first order plus dead time process

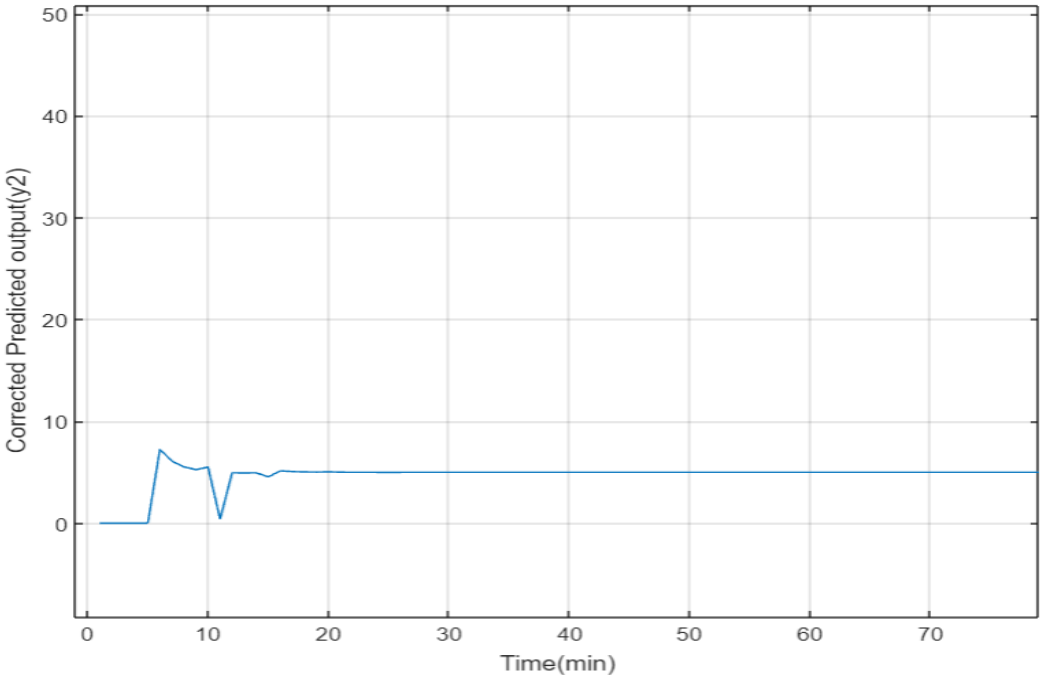

Figure 5.7: Corrected predicted Output of first order plus dead time process

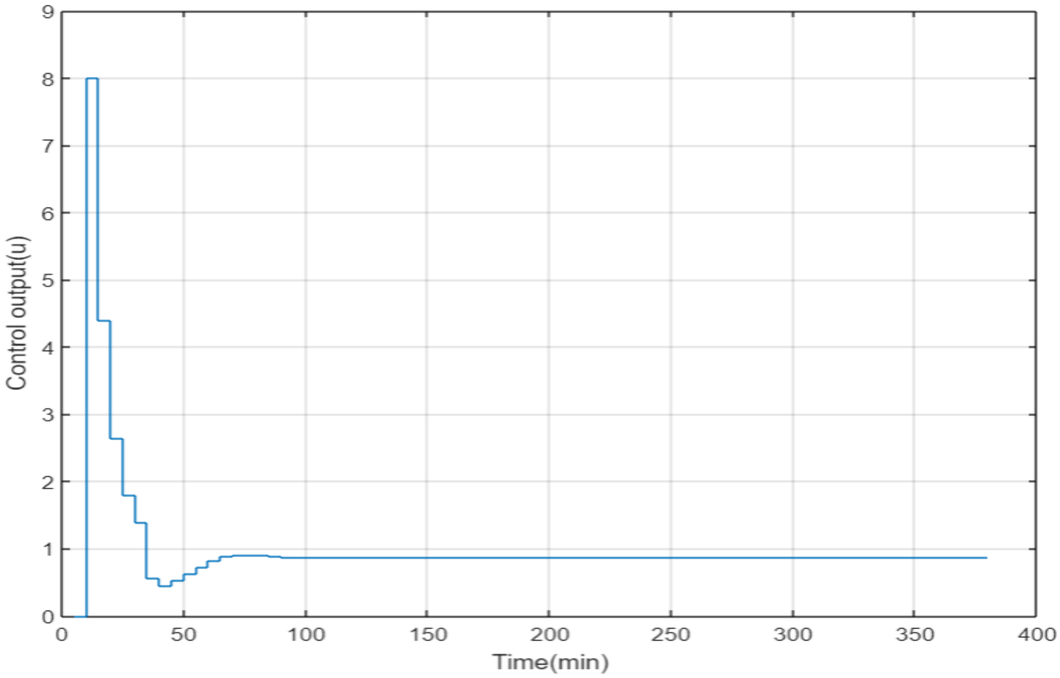

Figure 5.8: Control input of first order plus dead time process

The step response coefficients are obtained by evaluating the step response of the system (Figure 5.9) in equation 5.3. at the sampling instants t=iΔt .Applying the multiple prediction control law to the system for comparison of different prediction horizons and control horizons.The control input comparison for the different P and M values is given in Figure 2.10.When P=3 and M=1 then,

$$K_c1 = \begin{bmatrix} 0 & 7.79 & 28.3 \end{bmatrix}$$

When P=4 and M=2 then,

$$K_c2 = \begin{bmatrix} 0 & 33.1 & 48.3 & -13.4 \\ 0 & -71.4 & -97.4 & 57.3 \end{bmatrix}$$

The predicted output for multiple prediction is given in the figure 5.11 it shows as the values of prediction horizon and control horizon increases the curve will become more smoother ie the settling time will be less peak overshoot will be less.After correcting the bias the corrected predicted output is given in 5.12.

$$\frac{Y(s)}{U(s)} = \frac{e^{-s}}{(10s+1)(5s+1)} \tag{5.3}$$

We have four-step responses for each transfer function, and the firstThe step response of the MIMO system is given in figure 2.13. In this MIMO system, we have two inputs and two

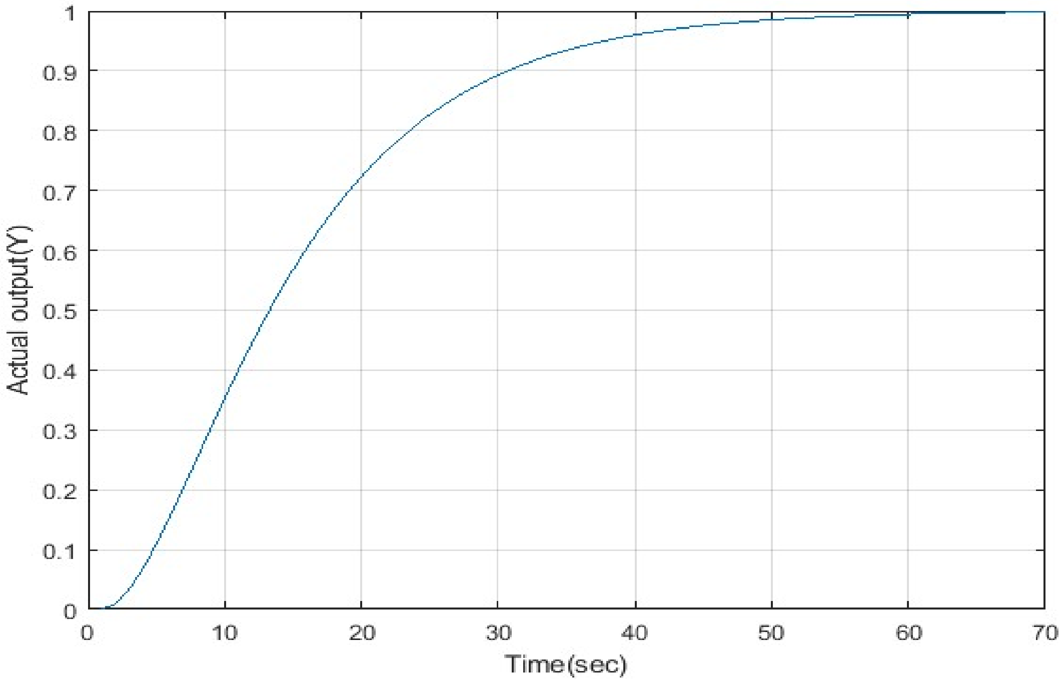

Figure 5.9: Step response of system.

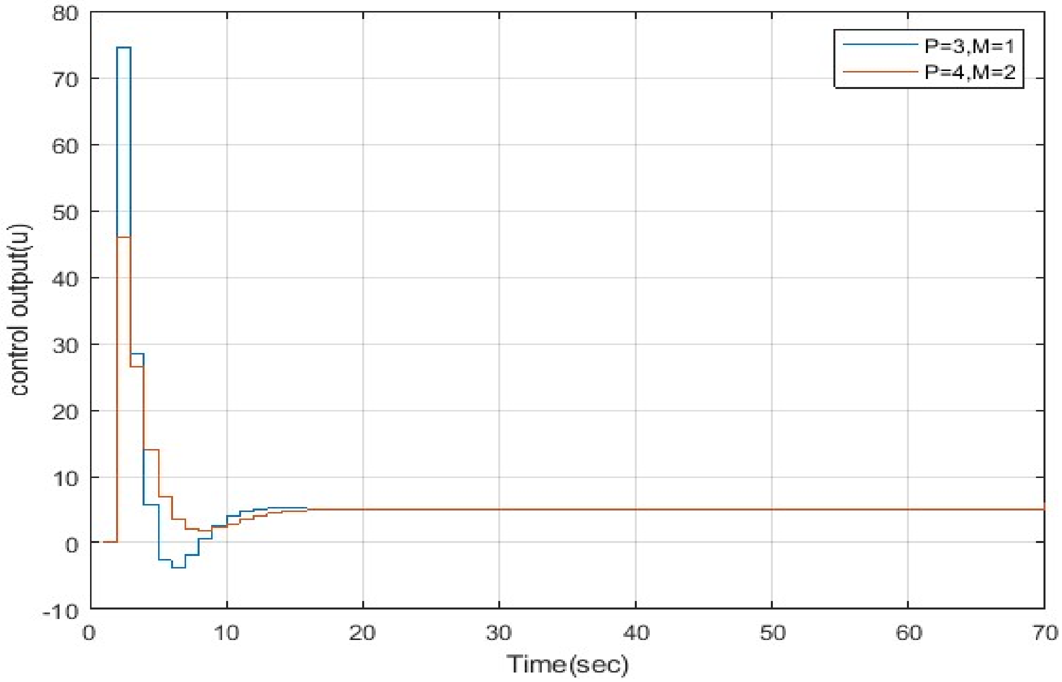

Figure 5.10: Control input for multiple prediction in system.

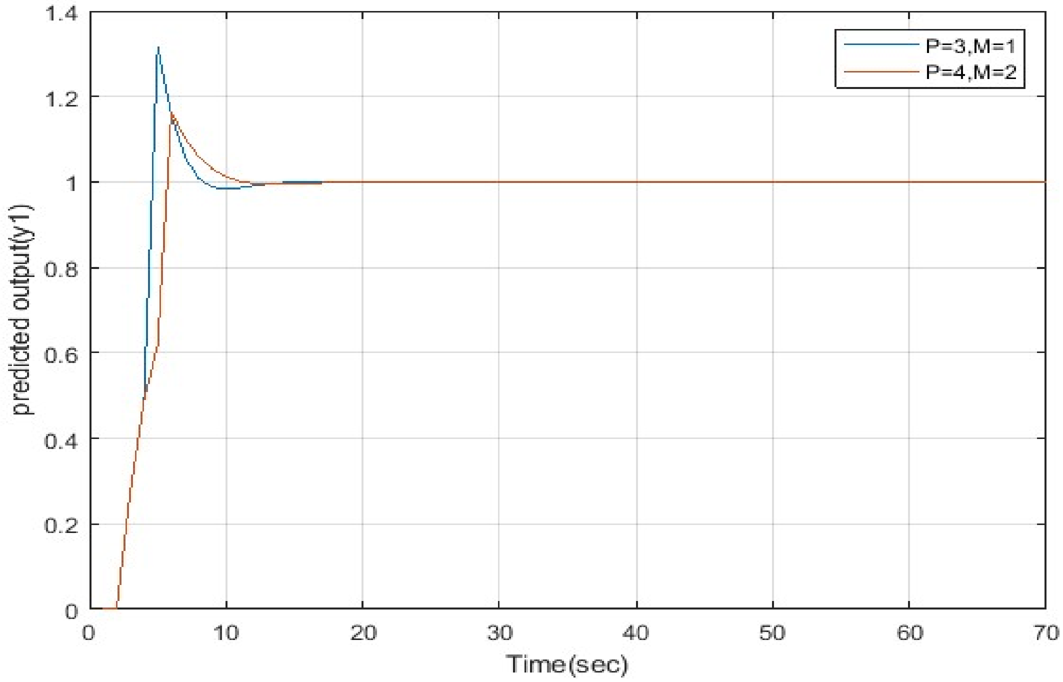

Figure 5.11: Predicted output for multiple prediction in system.

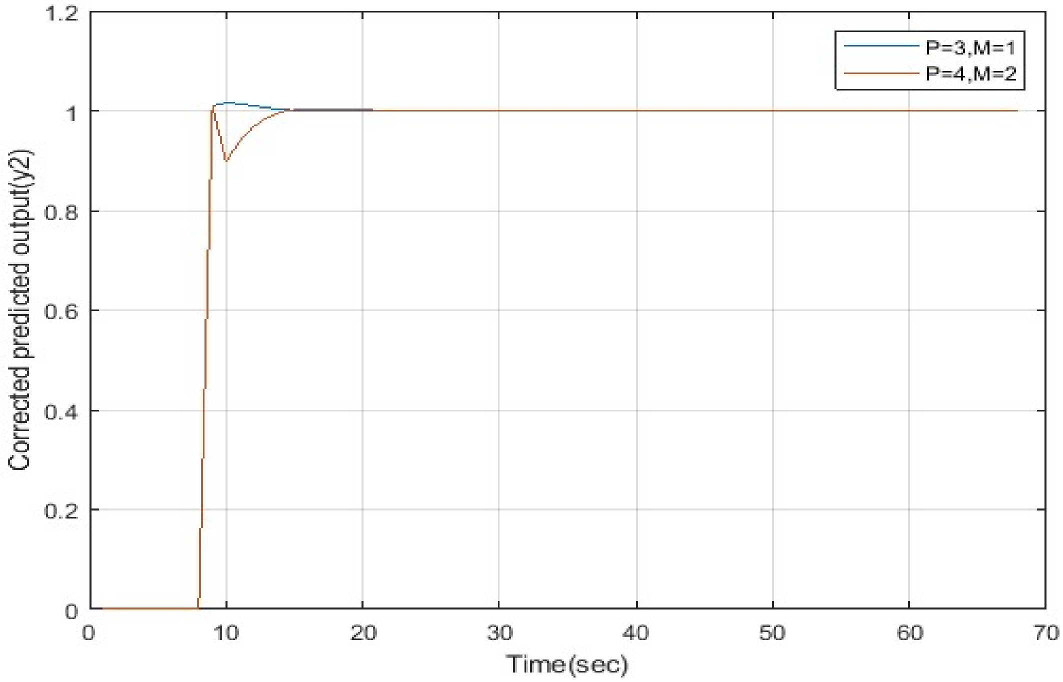

Figure 5.12: Corrected predicted output for multiple prediction in system.

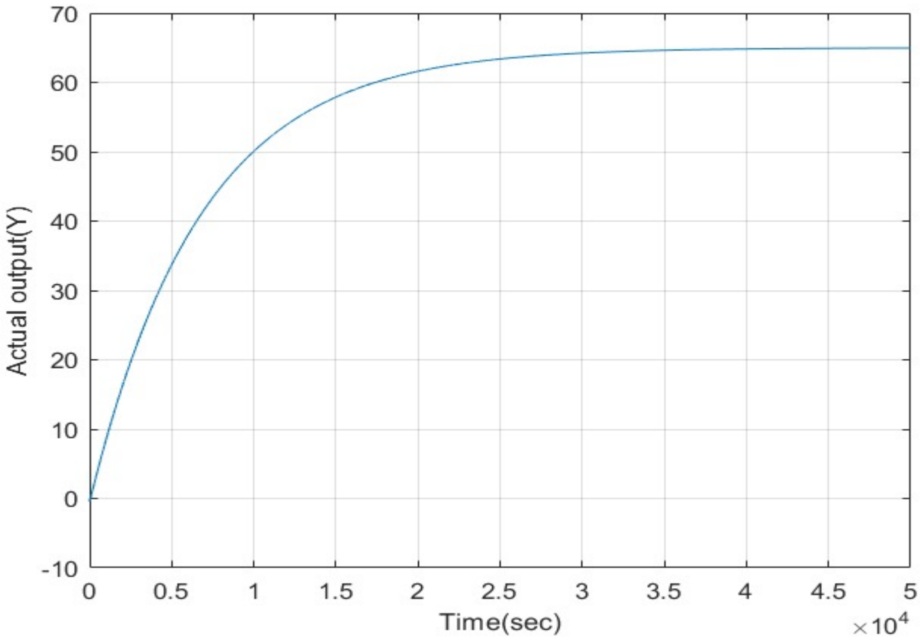

Figure 5.13: Step response of first transfer function of system

outputs. The first predicted output (y1)for the system is given in Figure 5.14 and the control input(u1) for this is given by 5.15. Figure 5.16 depicts the second output(y2), while Figure 5.17 depicts the control input(u2).

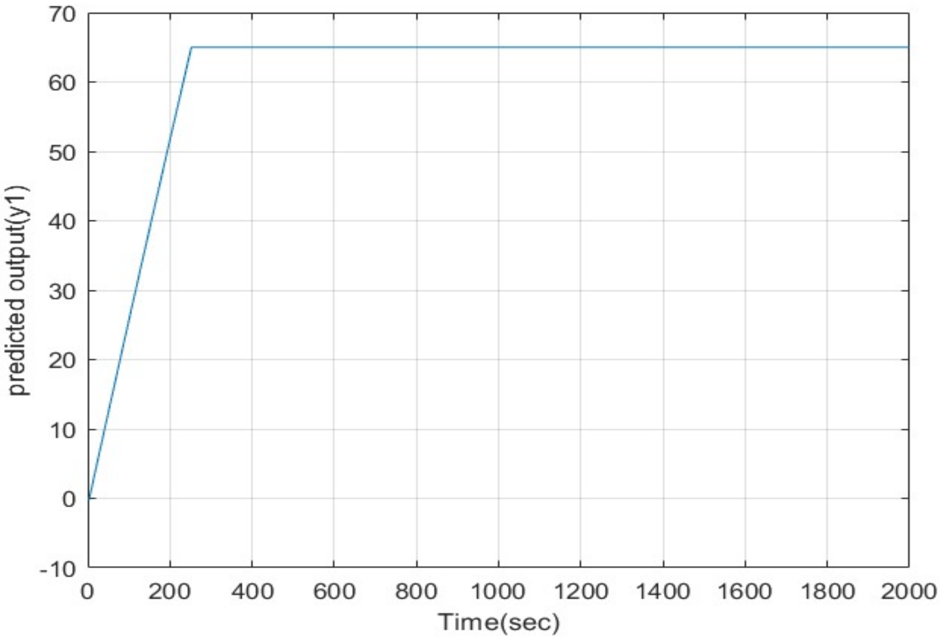

Figure 5.14: First output of (y1) our system

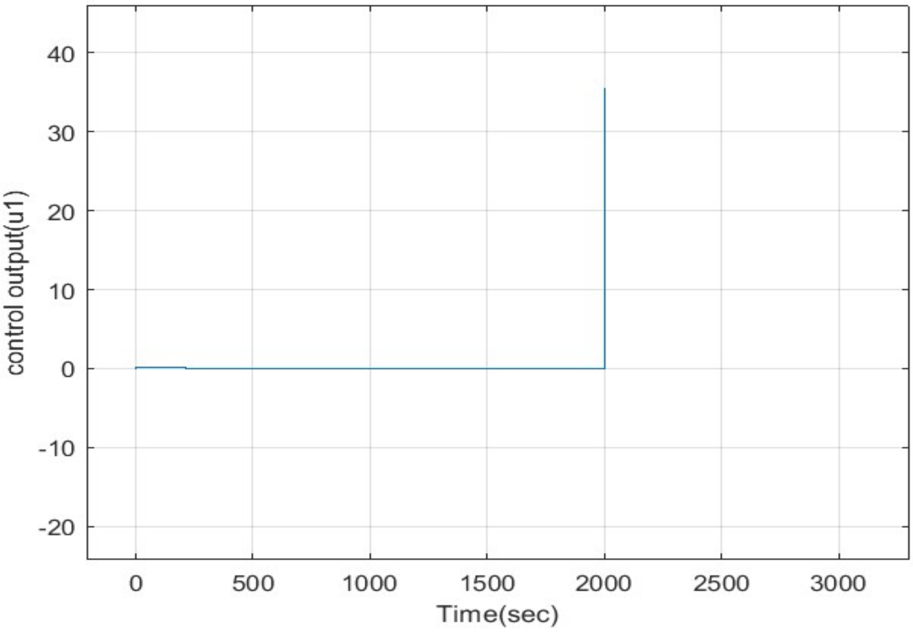

Figure 5.15: First control input(u1) of our system

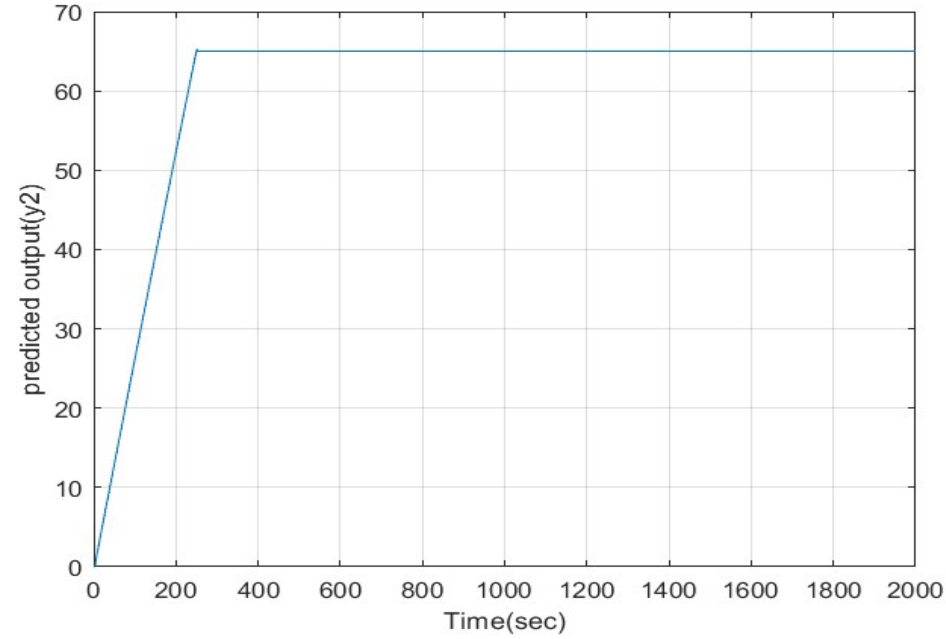

Figure 5.16: Second output of (y2) our system

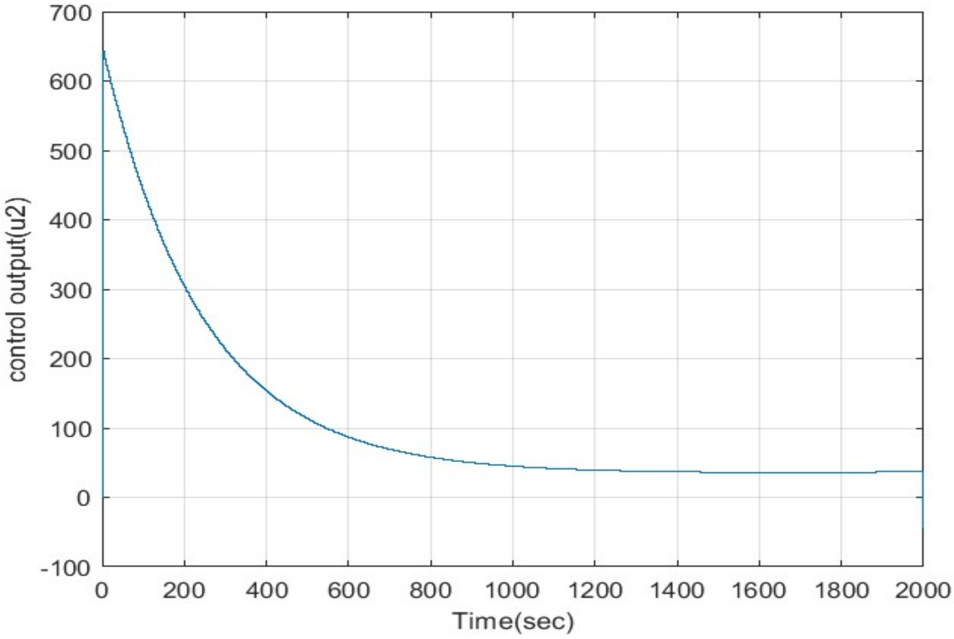

Figure 5.17: Second control input(u2) of our system

5.3 SUMMARY

The section gives the output we obatined for single point temperature control using PI controller and outputs for multipoint temperature using the predictive control law for different systems.

Chapter 6

CONCLUSION

6.1 CONCLUSION

6.1.1 Single Point Temperature Control

To regulate the single point temperature control for a first order plus dead time system in the first section, we are utilising a straightforward PI controller.Table 6.1 displays the single point temperature control's parameters.To adjust the PI controller's settings, the delay time, time constant, and thermal gain are determined using the ziegler-Nicolas technique.

Since we are taking into account the four distinct zones, we are unable to take into account the interactions for an ideal system, thus we must assign four separate controllers to handle the four transfer functions in order to regulate the multipoint temperature using a PID controller. The four separate zones should theoretically have the same delay, but in practise, this may change, thus we can't apply the same control rule to all four PID controllers. Therefore, we must create four unique PID controllers and perfect the system so that the zones do not interfere.

6.1.2 Multi-Point Temperature Control

For the multipoint temperature control we are developing the Model predictive controller from the step response model of the system .It is a MIMO system with two inputs and two outputs, and the transfer function was determined using actual results.A predictive control law is being used.

Table 6.1: Parameters of SISO System

Thermal Gain (Kt)	C/W	13.75
Delay time (L)	sec	5
Time Constant (T)	sec	860
Setpoint temperature	°C	65
Heater supply voltage	V	28V
Input power (starting)	W	15W
Heater resistance	Ω	158.8
Gain margin	dB	12
Phase margin	deg	45

heightSystem	Settling time
G11	125
G12	174.73
G21	150.37
G22	125.335
Y1	1.26
Y2	1.25

6.2 RECOMMENDATIONS

The study shows how the model predictive control system can keep the temperature at the setpoint.

6.3 SCOPE FOR FUTURE WORK

- We can design the MPC in such a way that the output has to track the set point by changing the control output in such a way that the output reaches the setpoint in an optimal manner.
- We can develop MPC so that, due to ambient temperature change, there will be a change in the output response, and we have to neglect the disturbance for the minimum time. For example, when the ambient temperature changes from 25 to 45, the initial temperature

changes, and as a result, the response also changes. And this has to be neglected in the shortest possible time.

REFERENCES

[1] Y. Singh, J. Kumar, K. Pandey, K. Rohit, and A. Bhargav, “Temperature control system and its control using pid controller,” *Int. J. Eng. Res. Technol*, vol. 4, no. 02, pp. 4–6, 2016.

[2] G. Cosoli, P. Chiariotti, M. Martarelli, S. Foglia, M. Parrini, and E. P. Tomasini, “Development of a soft sensor for indirect temperature measurement in a coffee machine,” *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 5, pp. 2164–2171, 2019.

[3] Q. Wang and Z. Xie, “Fermentation temperature control opitimisation in laboratory scale using max-min ant system and multi-point temperature instrument,” in *2010 The 2nd International Conference on Industrial Mechatronics and Automation*, vol. 1. IEEE, 2010, pp. 76–79.

[4] G. Li, P. Zhang, G. Wei, Y. Xie, X. Yu, and X. Long, “Multiple-point temperature gradient algorithm for ring laser gyroscope bias compensation,” *Sensors*, vol. 15, no. 12, pp. 29 910–29 922, 2015.

[5] F. Mahmood, R. Govindan, A. Bermak, D. Yang, C. Khadra, and T. Al-Ansari, “Energy utilization assessment of a semi-closed greenhouse using data-driven model predictive control,” *Journal of Cleaner Production*, vol. 324, p. 129172, 2021.

[6] K. Ito and Y. Hara, “Multipoint-measurement multipoint-heating greenhouse temperature control with wooden pellet fuel using an adaptive model predictive control approach with a genetic algorithm,” in *2017 25th Mediterranean Conference on Control and Automation (MED)*. IEEE, 2017, pp. 54–59.

[7] D. E. Seborg, T. F. Edgar, D. A. Mellichamp, and F. J. Doyle III, *Process dynamics and control*. John Wiley & Sons, 2016.