Design and Performance Evaluation of Tuning Methods of PID Controller

SANJAY KUMAR SINGH
(ID. No. (2010REC206))

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CERTIFICATE

This is to certify that the thesis entitled "**Design and Performance Evaluation of Tuning Methods of PID Controller**" being submitted by **Mr. Sanjay Kumar Singh (2010REC206)** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of Doctor of Philosophy in the Department of Electronics & Communication Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

(Dr. S.G. Modani)
Co-Supervisor
Former Professor
Department of Electronics &
Communication Engineering
MNIT, Jaipur (Rajasthan), India

Place: Jaipur
Date:

(Dr. D. Boolchandani)
Supervisor
Professor
Department of Electronics &
Communication Engineering
MNIT, Jaipur (Rajasthan), India

Place: Jaipur
Date:

DECLARATION

I, **Sanjay Kumar Singh**, declare that this thesis titled, **" Design and Performance Evaluation of Tuning Methods of PID Controller"** and the work presented in it, are my own. I confirm that:

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Date: **Sanjay Kumar Singh**

(2010REC206)

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Date:
Place: JAIPUR

Sanjay Kumar Singh
(2010REC206)
Department of ECE, MNIT, Jaipur

ABSTRACT

PID controllers have innumerable areas of applications and are widely used in industries because they are easy to implement in a DCS or PLC. It can be a prodigious tool for cultivating production, quality, and process productivity and due to their simplicity and efficiency, find wide use and acceptability in every process plant. It estimated that a large number of control loops commissioned in an ordinary plant, and only about 5-10% of control loops are non-PIDs. This wide range of application requires reliable tuning methods. Though many tuning techniques are available; however, none of them offers a best comprehensive solution to the performance. Different methods have been proposed to investigate and evaluate more precise & accurate modeling, system identification for analysis, controller design and higher performance requirements. There are some critical issues in the tuning of the controller for optimal process performance, an area that needs attention.

The conventional PID tuning is proved to be less efficient and results in abnormalities in the system of the plant with output having an entirely high overshoot and settling time. So our objective is to improve performance by different techniques. Soft computing techniques have applied to systems to optimize the PID controller parameters and to improve the overall performance of the system via Genetic algorithm, Particle swarm optimization (PSO), Bat algorithm (BA), Flower pollination algorithm and Multi-objective genetic algorithm (MOGA) and Multi-objective particle swarm optimization (MOPSO). Thus the new approach reveals the better ability to tune and provides an optimal output by probing for the best set of parameters with enhanced static & dynamic performance in time and frequency response.

Conventional methods seldom identify the several real process abnormalities such as a plant model mismatch, saturation, valve stiction, unmeasured noise, and disturbances into account. So these issues need to be taken into account to ensure robustness. Thus a robust design controller has proposed against the problem of PID tuning with real process abnormalities in the process industry. Various well known PID techniques are evaluated and compared on a benchmark of First Order Plus Time Delay processes.

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Common Control Abbreviations

SISO	Single-input, single-output
TITO	Two-input, two-output
MIMO	Multi-Input, Multi-Output
FOPDT	First-order plus dead time
SOPDT	Second-order plus dead time
IMC	Internal model control
SNR	Signal-to-Noise Ratio
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
BA	Bat Algorithm
FPA	Flower Pollination Algorithm
MOGA	Multi-Objective Genetic Algorithm
MOPSO	Multi-Objective Particle Swarm Optimization
AOF	Aggregate of Function
GFCL	Generate First Choose Later

Nomenclature

A: Oscillation Amplitude
G_c : Controller
G_p : Process/ Plant
D : Disturbance
G_n : Nominal Process
GM: Gain Margin
IAE: Integral of Absolute Error
IE: Integral of Error
ISE: Integral of Squared Error
ISTE: Integral of Squared Time& Error
ITAE: Integral of Time And Error
z: Robustness Factor
K_i: Integral Action
K_c: Gain (Controller)
K_p: Gain (Process)
K_u: Ultimate Gain
L: Loop
e: Error

M_s : Maximum Sensitivity
M_T : Maximum Complementary Sensitivity
MV : Manipulating Variable
N : Noise
Op : Controller Output
PM : Phase Margin
S: Sensitivity
S_D : Disturbance Sensitivity
S_U : Control Action Sensitivity
T: Complementary Sensitivity
T_M : Desired Time Constant (Vilanova)
T_S : Sampling Time
T_v: Total Variation
u : Controller Output
V : Valve
c : Output
r: Input or Setpoint

List of Symbols

ω_{pc} : phase crossover frequency

α : Dimensionless factor $\left(\frac{\theta}{\tau}\right)$

ξ : Damping factor

τ_d : Derivative time

ΔG: Modelling error

ω : Frequency

ω_{gc} : gain crossover frequency

P_u : ultimate period

τ : time constant

τ_c : desired closed loop time constant

τ_f : Derivative Filter Time constant

τ_i : integral time

θ_0 : original Dead-time

θ : Dead-time

PREFACE

Background of the Problem

Proportional Integral Derivative (PID) controllers are regarded as one of the most preferred choices that can be found in the applications of industrial control. Owing to their user-friendliness, robustness & victorious practical applications, these controllers are gaining widespread attention. Moreover these controls are easier to be comprehended by the control engineer as compared to any other advanced techniques. The PID controller is known to give an efficient performance in a wide array of practical aspects.

Since the original work did by John G. Ziegler and Natheniel B. Nichols in1942, significant research has been done to distinguish PID controller parameters. Because manual tuning is a difficult work and need, minute attention to process control engineer, exclusive focus is put on auto-tuning methods, which are dependent upon the application of individual input to the process. After calculating the process response, the parameters of PID controller can be established. Some of the methods employ information about the step response curve and significant research has been done to distinguish PID controller parameters. Some of the methods employ information about the step response curve such as (Ziegler and Nichols, 1942) (Cohen and Coon, 1953) (Hang et al., 1991) and (Astrom and Hagglund, 1995) etc. A good review of approaches has been done from literatures (S. Skogestad, 2001) (Astrom and Hagglund, 2004) (Johnson and Moradi, 2005) (Visioli, 2006) (Vilanova, 2008) and (O’Dwyer, 2009) etc.

Motivation

There are plenty of tuning techniques available in the literature, but none of them offer a perfect comprehensive solution to PID performance. The designed controller is expected to give maximum control results without depending upon constraints.

A motivation for this study was to find a reliable and straightforward tuning method which could be used for regulatory control as industry practitioners need practical guidelines that are easy to implement for tuning PID controllers in process plants.

An additional motivation for this study was the comments and feedback from industry practitioners who were interested in exploring alternative tuning rules for disturbance rejection in the process plant.

Irrespective of the reputation of PID controllers as the predominant controller for industrial applications. O'Dwyer (2009) states the proposed tuning approaches in literature are not having a remarkable impact in the industrial practices. These are having destructive problems with the tuning operators where the tuning rules are not well-suited in industry. Therefore this research proposed work will provide a better approach for performance and robustness with fewer regulations.

Research Objectives

The objective of this work is to investigate the suitable method of PID controller tuning using different algorithm implementation for enhancing the dynamic performance of the temperature control system of the centrifugal machine in the sugar industry through overcoming the effects of the constraints.

The objectives of the present study as mentioned below:

1. To study the mathematical model of the temperature control system of the centrifugal machine in the sugar industry.
2. To estimate the system identification parameters are using MATLAB parameter estimation toolbox.
3. To design a PID controller by tuning its gains, and to estimate its performance parameters.
4. To improve the system dynamic performance by applying the proposed Multi-objective genetic algorithm optimization techniques and to compare it with genetic algorithm, bat algorithm, particle swarm optimization, flower pollination algorithm and multi-objective PSO.
5. To improve the system dynamic performance by applying the proposed AMIGO Robust PID controller and evaluate its performance against situations where process abnormalities are encountered.

Organization of the Thesis

This thesis organized into six chapters. The chapters outlined as follows:

Chapter 1 “Introduction” includes an introduction to various PID controller tuning techniques in both time and frequency domains and some relevant fundamentals theory needed for this thesis covered. Both conventional and alternative approaches covered in this chapter.

Chapter 2 “Literature Review” includes a brief introduction about PID control tuning methods for different application to enhance the performance and robustness. Also the literature review on the previous works related to the topic of our study presented. It also includes the problem statement of this research.

Chapter 3 “Modelling and Identification” contains basic information about the process of centrifugal machine temperature system and evaluate the transfer function by reaction curve and strejc method. This chapter also covers the system identification approach for estimation & validation plant model to accomplish the design requirements for the controller. The results and discussion of the simulation work with comparison have been carried out.

Chapter 4 “Design of controllers using soft computing” contains necessary information about the different meta-heuristic algorithm used in work. This chapter covers the analysis of the proposed soft computing algorithm methodology and performance. The proposed methodology is to study and analyze the time and frequency domain performance indices being used to evaluate their capability in handling single-objective optimization technique, where the performance indices are simple and straightforward. Then aggregate of function (AOF) multi-objective optimization techniques to overcome the difficulty in single-objective optimization technique and discusses the merits and demerits of the existing performance indices. A novel and effective visualization Generate First Choose Later (GFCL) technique is being proposed, in an attempt to help users in taking a decision or selection in a multi-dimensional case, whereby the performance indices fail. This chapter concludes by performing empirical studies on multi-objective GA and PSO algorithms and discusses the results using performance indices and the proposed multi-objective GA visualization technique. The results and discussion of the simulation work with comparison have discussed in this chapter.

In chapter 5 “Robust PID Controller Tuning”, contains necessary information about the well-known robust tuning methods based on time and frequency domain performance indices. This chapter covers the selection of these controllers in the presence of process abnormalities like model mismatch, valve stiction, saturation, sensor noise and disturbance with the results and discussion of the simulation work and comparison.

Chapter 6 “Conclusions and Future Work” contains a list of conclusion summary, and future scope of this research.

CHAPTER-1

INTRODUCTION

In this introductory chapter, some background of control systems theory is exposed. Also, the main problem to be considered throughout this work is introduced and motivated.

1.1 PROCESS CONTROL

In chemical processes, process control is very important due to the nature of the processes which include time delays, large time constants, uncertainties and nonlinearities [1]. In the 21st century, the structure of chemical processes has become increasingly complex to meet the demand of the ever competing world. The performance requirement for process plants have become correspondingly more difficult to satisfy and therefore the need for a properly tuned controller are also essential generally, the aims of a process control are:

To ensure a safe process
To ensure stability of a process
To meet product specification
To satisfy operational limits
To abide by environmental regulations
To reduce energy consumption and waste material
To operate a process in the most profitable manner

In a different way, without a process control system, it is impossible to operate the most modern and complex processes safely and profitably while satisfying quality standards [1, 2].

1.2 DEVELOPMENT OF PROCESS CONTROL

The modern process plant has become more complex and challenging to operate. Consequently, much attention has given to process control itself. The process-control research focuses on the development of industrially relevant methods and tools. Since the 1980s, industrial process control has seen many changes [3]. A most manually controlled system has replaced by computerized control systems.

A controller used to be in the form of a box installed near the sensor and valve, but now, it is in the form of a computer code that runs on a processor, in a centralized control room.

Process control was based on the pneumatic controller, by early 1960s. It is during 1960s-1970s where tremendous changes have seen in process control. In the 1970s, digital computers used as part of the control system. In the 80s, it is used with the computerized system to act as an advanced supervisory system, with automation control. The use of digital systems and computers has contributed to the development of process control [1].

In controlling a process, the control system must ensure the stability of the process and at the same time, optimize the performance of the process with minimum cost & maximum profit, and ensure that the product meets specification. There are two types of conventional control approach – feed-forward and feedback control, although the latter controller most widely used. In feedback control system, the process variables to be controlled measured, and the measurements are used to adjust the manipulated variables. An excellent example of a feedback controller is the PID controller. It consists of integral, derivative and proportional actions. It has used since the classical feedback control introduced. However, current research area has broadened and include model-based predictive control, fuzzy logic control and nonlinear control by neural networks, plant-wide distributed control and on-line process monitoring through advanced state and parameter estimation [1, 2, 4, 5].

Despite the development of more advanced types of controllers, the PID still receives much attention and is the most popular type of controller in the industry.

1.3 General Description of a Controlled System

The system structure defined as closed-loop control and feedback control. In closed-loop control, the desired value of the plant compared with the set- point or reference signal with the use of a feedback signal. An alternative structure is the open loop control which does not utilize feedback signal. An alternative structure is the open loop control which does not utilize feedback signal. A certain amount of disturbance is present in every control system; feedback implementation is to suppress load disturbance.

A controlled system is composed of several components in the basic control loop which are a Preamplifier, controller, plant, and transducers which are actuators and sensors.
The basic control loop structure shown in Figure 1.1.

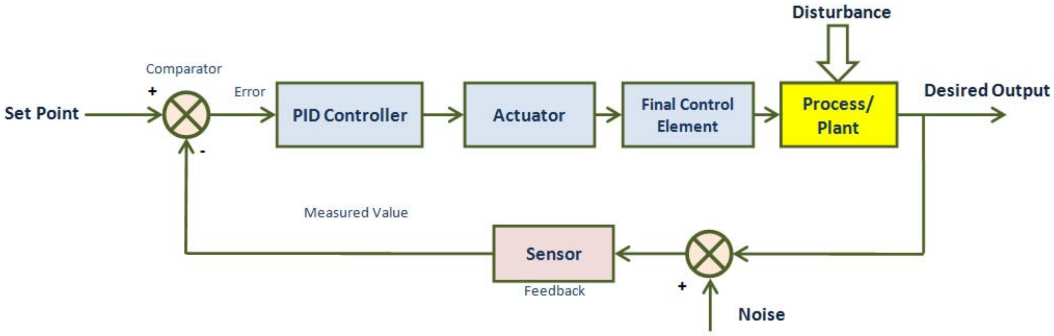


Figure 1.1: Basic Control Loop Structure [6]

In the control loop, the process is the real system for which some several physical variables to control. Its example is kiln, boiler, and centrifugal machine. The actuator is part of the process that supplies material through the control signal to the plant. It can be considered to act as an amplifier. Controller (compensator) is an additional component that when inserted into the control system compensates a deficient performance like dynamic, stability and static performance. The controller input is usually an error signal which is apparently the difference between a required set- point and the original output. A transducer is that device which is used to convert one form of energy into another form of energy. There are two kinds of the transducer, actuators, and sensors. An actuator is a particular transduction that transforms a signal from a controller to provide the required control action to the plant and sensor that convert a physical measurement of a plant variable into an analogous electrical signal. Pre-filter is using the input reference signal before to the calculation of the error signal.

Control loop system usually has spatially distributed hardwired processes with the different control loop, and communication components will be required. The basic concept of control is to maintain process variable (output) as close as possible to the setpoint or the reference input. To show this, consider the following single-input-single-output (SISO) feedback loop which used throughout this thesis both for analysis and the design of PID controllers.

The choices to let the load disturbances act on the process inputs are carried by, e.g. [6], which affirms that this is the usual industrial control case in the process.

For a linear system, which is the case in this study, the dynamics could show as transfer functions using the Laplace transform and the Laplace variable s. The symbols in the figure correspond to:

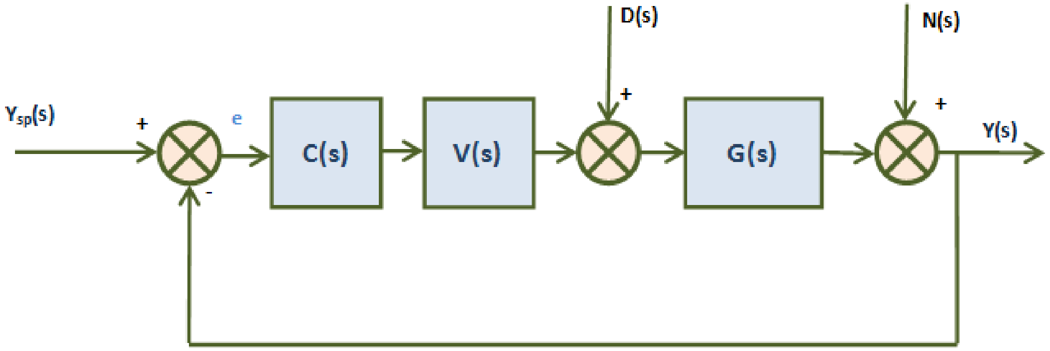


Figure 1.2: single input - single output (SISO) loop with unity feedback [6]

The dynamics from different inputs to the process output are given by the following equations:

$$\frac{Y(s)}{Ysp(s)} = \frac{C(s)V(s)G(s)}{1+C(s)V(s)G(s)H(s)} \tag{1.1}$$

$$\frac{Y(s)}{D_i(s)} = \frac{G(s)}{1+C(s)V(s)G(s)H(s)} \tag{1.2}$$

$$\frac{Y(s)}{N(s)} = \frac{-C(s)V(s)G(s)H(s)}{1+C(s)V(s)G(s)H(s)} \tag{1.3}$$

1.4 THE PID CONTROLLER

1.4.1 HISTORY AND DEVELOPMENT

The PID controller has served in the industry for more than six decades. Despite the fact, that it is a 'Classic Controller,' and was developed in 1920 [7]. It still used extensively. More than 90% of industrial control loops still rely on various forms of PID. It caused by particular characteristics of the PID itself. It is a simple controller, and easy to understand, especially for the control operators or plant operators, who usually opt for a straightforward solution that will give satisfactory results. It has been proven sufficient for processes with first order or second order dynamics and for operations that do not require tight control [8].

Since the initial development of PID controllers, it has generated much interest. Increased attention has been given towards PID control in recent years [8]. The widespread use of microprocessors in control system and the development of autotuning are the factors that contributed to the heightened interest in PID controller.

Although the PID has used for quite some time, it is for & on being obsolete. On the contrary, interest in PID has never diminished. It can use in a wide range of problems in all areas of engineering - process control, automotive, flight control, and motor valve, just to name a few, hence making it the most popular type of controller [7].

As industrial processes become more complex with the need for higher efficiency, and at the same time better product quality, the conventional controller has been developed to a more advanced controller. PID has evolved from analog to digital. The digital controller based on the basic P, I and D actions, but also include other algorithms for the betterment of PID controller performance. The use of artificial intelligent concepts like neural network and fuzzy control has incorporated in PID. An extensive literature has published in this area. [9,10,11]. Thus, history has shown that despite being developed more than 50 years ago, the PID controller still received much attention. It explained by the basic structure of PID controller itself, which is an advantage, and will be discussed further in the next section.

1.4.2 CONTROLLER ACTION

The primary objectives of this thesis are to recommend methods for both design and analysis of the PID controller. The three PID controller parts will be explained in this section, together with some possible PID controller forms and measurement filters.

Proportional Action

The proportional action (P) of the control signal is proportional to the control error,

$$u_p(t) = k_p e(t) + u_0 \, , e(t) = br(t) - y(t) \tag{1.4}$$

such that it responds to present variations from the set-point. The proportional gain k_p is the parameter normally related with the P action, but it is sometimes change by a parameter called the proportional band (PB) [6]. A P controller separately cannot assurance zero static control errors, because the control signal becomes zero for proportional mode $e(t)$=0. The bias term u_0 is used to diminish this effect in controllers that are short of an integral part. The magnitude of the static error depends on k_p . The speed and noise sensitivity of the closed-loop system will normally increase with an increasing k_p at the same time as the robustness decreases. The P action is susceptible to noise since k_p is multiplied directly with the measurements, y(t), unless filtered first. Sudden changes in the set-point can be smoothed out in the control signal by choosing a set-point weight 0 ≤ b < 1.

Integral Action

The integral action (I) integrates past values of the control error,

$$u_i(t) = \frac{K_c}{\tau_i}\int_0^t e(t)dt = k_i \int_0^t e(t)dt, \; e(t) = r(t) - y(t) \tag{1.5}$$

and will thus eliminate static control errors due to set-point and load disturbances changes. It introduces the integral time τ_i , but also depends on the proportional gain K except the portion $\frac{K_c}{\tau_i}$ is replaced by a self-regulating parameter, k_i called the integral gain. Reducing τ_i normally leads to a faster, even though less robust, closed-loop system. The summation of past control errors makes the I-part not sensitive to noise. A shortcoming of the I-action is that the controller performance needs to handle so-called integrator wind-up [8].

Derivative action

The derivative action (D) of the PID controller,

$$u_d(t) = K_c\tau_d \frac{de_d(t)}{dt} = k_d \frac{de_d(t)}{dt}, e_d(t) = cr(t) - y(t) \tag{1.6}$$

Forecast future behavior of the controlled variable. It introduces the derivative time τ_d, but also depends on K unless $K_c\tau_d$ is substitute by the derivative gain k_d. Closed-loop robustness will normally increase with an increasing τ_d at the same time as the performance decreases. This is a outcome of the damping properties of the D-action. The system as a entire can still obtain better performance, since the proportional and integral gains can be increased to balance robustness. A major disadvantage of the D-action is that the differentiation of the control error makes it very noise susceptible. It is so important to use a low-pass filter together with the D-action. The set-point weight c is usually kept zero to avoid large transient responses in control signals.

1.4.3 Controller forms and measurement filters

There are a number of possible controller combinations that can be formed with the three parts .The most common ones are P, I, PI, PD and PID control. PID, PI and I controllers will be considered in this thesis, since the majority of process applications of industrial control benefit from the I-part.

The **'I'** controller has only one parameter k_i.

$$C_I(s) = \frac{k_i}{s}, \tag{1.7}$$

The PI controller is given by

$$C_{PI}(s) = K_c(1 + \frac{1}{s\tau_i}) \tag{1.8}$$

For PID control there are two common forms: the parallel form,

$$C_{PID}(s) = K_c(1 + \frac{1}{s\tau_i} + s\tau_d) \tag{1.9}$$

This adds the PI controller to the D-part, and the series form that is suitable for Designing based on lead-lag compensation [12].

$$C'_{PID}(s) = K_c' \frac{(1 + s\tau_i')(1 + s\tau_d')}{s\tau_i'} \tag{1.10}$$

For $\tau_i \geq 4\,\tau_d$, the parallel and series forms are equivalent. The parallel form is, however, more common because it can have complex zeroes [13]. For this reason, the parallel form will be the main focus in this thesis, while the series form will only be used for comparison of different PID tuning methods.

The low-pass filter is an indispensable part of the controller in which the derivative part is very noise vulnerable. There are a number of technique in which filtering can be applied collectively with a PID controller.

$$C_{PIDF}(s) = K_c(1 + \frac{1}{s\tau_i} + \frac{s\tau_d}{s\left(\frac{\tau_d}{N}\right) + 1}) \tag{1.11}$$

Where N is usually a number between 5 and 10, or on the entire measurement signal,

$$F(s) = \frac{1}{s\tau_f + 1} \tag{1.12}$$

Some other research has also revise these filter forms [14-17]. A benefit with the filter is that we can design a controller with a filter. This is the approach used in this thesis, but a second-order filter has been used to approve the amplitude roll-off for high frequencies in PID control.

$$F_{PID}(s) = \frac{1}{\left(s\tau_f\right)^2 / 2 + s\tau_f + 1} \tag{1.13}$$

Some other studies have also investigated low-pass filters of higher-order for the PID control [18-21]. A first order filter will be used here for PI control, also for roll-off high-frequency

$$F_{PI}(s) = \frac{1}{s\tau_f + 1} \tag{1.14}$$

The filter time constant is the one and only parameter which requires being set in both PI and PID filter. They should be more general with many (two or more) parameters, but these forms were selected to keep the amount of parameters of the controller low.

Figure 1.3 showed that the filters of PI and PID are suited very well for a closed-loop system, In that lower order and higher order filters are not give any advantages in the noise sensitivity performance [18].

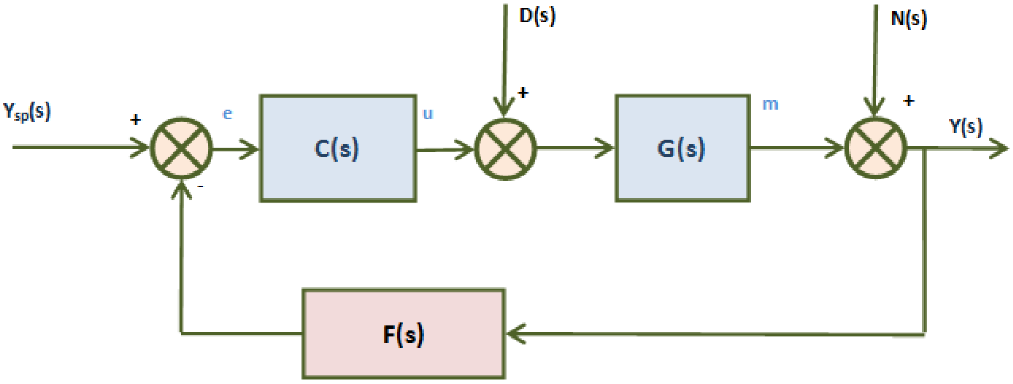


Figure 1.3: Closed Loop System [18]

In Figure d denotes load disturbance, n measurement noise, $Y_{sp}(s)$ set-point, G(s) plant, C(s) controller and, F(s)measurement filter controlled variable m,

Assuming regulatory control around a constant set-point, $r = 0$, the closed-loop system can be depicted by three equations

$$M(s) = \frac{G(s)}{1 + G(s)C(s)F(s)} D(s) - \frac{G(s)C(s)F(s)}{1 + G(s)C(s)F(s)} N(s) \tag{1.15}$$

$$Y(s) = \frac{G(s)}{1+G(s)C(s)F(s)} D(s) + \frac{1}{1+G(s)C(s)F(s)} N(s) \tag{1.16}$$

$$U(s) = -\frac{G(s)C(s)F(s)}{1+G(s)C(s)F(s)} D(s) - \frac{C(s)F(s)}{1+G(s)C(s)F(s)} N(s) \tag{1.17}$$

In frequency domain system, Sensitivity functions are important variables in linear time invariant (LTI) systems. They are closely related to system's dynamic equation, which describe the feedback behavior.

By definition [20]

Nominal complementary sensitivity $\frac{Y(s)}{Y_{sp}(s)} = T(s) = \frac{C(s)G(s)}{1+C(s)G(s)}$ (1.18)

Nominal sensitivity $\frac{Y(s)}{N(s)} = S(s) = \frac{1}{1+C(s)G(s)}$ (1.19)

Nominal input-disturbance sensitivity $\frac{Y(s)}{D_i(s)} = S_D(s) = \frac{G(s)}{1+C(s)G(s)}$ (1.20)

Nominal control sensitivity $\frac{Y(s)}{U(s)} = S_U(s) = \frac{C(s)}{1+C(s)G(s)}$ (1.21)

In fact, the nominal sensitivity is the transfer function from the disturbance to the process variable, and the complementary sensitivity shows the dynamics from the set-point to the process variable. Sensitivity functions are essential factors in representing the trade-off between various control objectives and impose important constraints on the system's robustness. While the sensitivity function(S) is a measure of how the system rejects disturbances, it is also a measure of the degree of robustness as it will be discussed in a later section.

Note that the summation of the sensitivity and complementary sensitivity functions is always equal to unity.

$$S(s)+T(s)=1 \tag{1.22}$$

1.4.4 PID CONTROL STRUCTURE

Controller manufacturers classify the proportional, integral and Derivative control actions into three various controller topologies. These are called series, ideal, and parallel algorithms tuning of controller depends on structure and units which are used in a process [22].

It was an arduous task to construct a parallel structure with the aid of pneumatic components as the first controllers were of said nature. Still, a wide range of controller used in serial structure; however, it is easy to recognize controller structure using electronics. The presence of parallel structure is robust even where the usage is not prevalent.

Two topologies are used
Serial (interactive)
Parallel (non-interactive)

Series Algorithm

Derivative action manipulates the proportional and integral actions in serial interacting structure. This algorithm generally uses in classic pneumatic and electronic controllers.

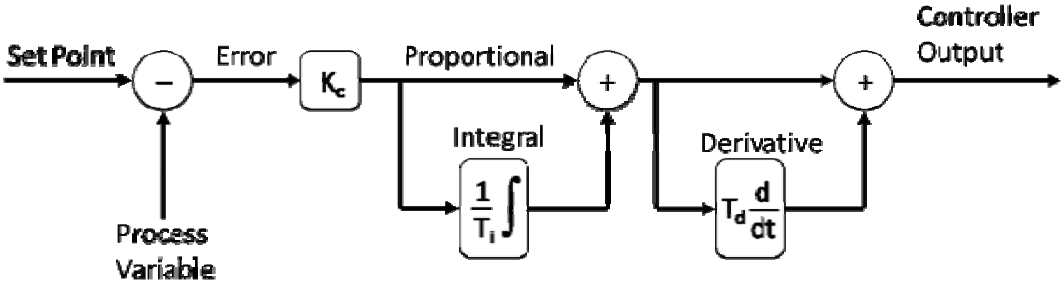


Figure 1.4: Series Controller Algorithm [32]

$$u(t) = K_c\left(e(t) + \frac{1}{\tau_i}\int e(t).dt\right)\times\left(1+\tau_d\frac{de(t)}{dt}\right) \tag{1.23}$$

Parallel Algorithm

Parallel structure is mostly called "ideal" Due to the fact that proportional, integral and derivative modes are self-directed; these structures are known as non-interactive structures.

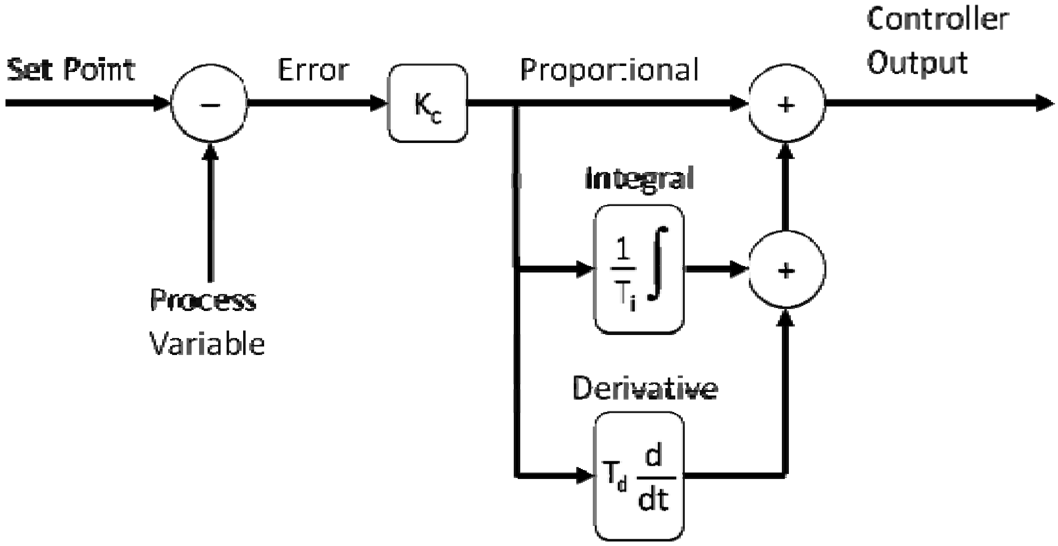


Figure 1.5: Ideal Controller Algorithm [32]

Ideal Controller Algorithm

$$u(t) = K_c\left(e(t) + \frac{1}{\tau_i}.\int e(t)dt + \tau_d.\frac{de(t)}{dt}\right) \tag{1.24}$$

The ideal algorithm is known as Standard, ISA/ Non-interactive algorithm. Some of the examples include Cohen-Coon & Lambda PID tuning rules.

A parallel form of PID controller algorithm is easy, comprehensible but not spontaneous to tuning, that is due to the nonexistence of controller gain (K_c). Changing the proportional gain (k_p) should be accessed by changing the integral and derivative setting simultaneously.

Parallel Controller Algorithm Structure shown in Figure 1.6

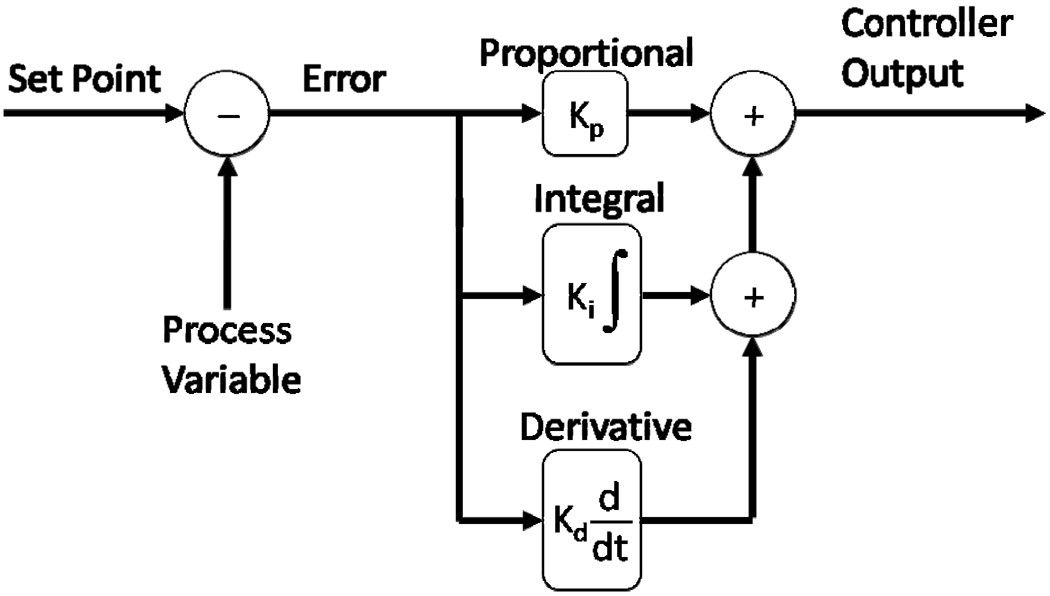


Figure 1.6: Parallel Controller Algorithm [32]

PID controller algorithm expression is given by:

$$u(t) = K_c\left(e(t) + \frac{1}{\tau_i}.\int e(t)dt + \tau_d.\frac{de(t)}{dt}\right) \tag{1.25}$$

or

$$u(t) = k_p.e(t) + k_i.\int_0^t e(t)\,dt + k_d.\frac{de(t)}{dt} \tag{1.26}$$

In parallel or non-interacting structure, proportional, integral and derivative actions do not influence each other. In the absence of derivative mode, the interactive and non-interactive controller algorithms are identical. Every serial structure representation has an equivalent Parallel structure representation, but not vice versa. For this reason generally, the Parallel structure form is considered more in the controller [23].

1.4.5 Industrial Process Environment

This section will provide some situation of the process industrial control condition and show how the PID controller fits so well into its structure. The main objectives of process control are to make certain a safe and stable process just about the set-point and to minimize the deviation of the control error. This has to be capable in spite of changing environment, equipment, and raw materials. Disturbances are usually not accessible before they have already influenced the process under control [24, 25].

Large process industries typically have large number control loops. The PID control algorithm is used to control almost 90–97% control loops. This majority is due to the following PID controller properties:
Easy understandable
Widely used in the process
Pre-programmed in all control systems
Easy tunable
Tradition

More frequent use of advanced process control, require of qualified personnel. Several investigations of the current process control status point out that only 20–30% of all controllers operate acceptably. In addition, 30% of the loops run in manual mode, while another 30% of the loops increase unpredictability over manual control [21, 24].
There are numerous reasons to not perform control loops satisfactorily.
Lack of tuning time of controller
Little control knowledge in industry
Equipment problems, like control valve stiction

Manual model-free tuning of controllers is still the most commonly used PID-design method in the industry. More skilled control engineers tend to use simple modeling methods relatively. Internal Model Control (IMC) and lambda are the most tuning method which is used in the process industry [27]. Some types of features behind the success of these methods are that they are simple, fast and intuitive.
Almost all PID controllers in the process industry have the D-action turned off so that they are in fact PI controllers [24].
Whereas, the experts of process control agree that considerable value in many control applications could be added to the derivative part. [6, 21, 26]

The D-action is still rarely used due to several reasons:
PI control is often sufficient.
There are numerous ways to execute the PID controllers to match the design parameter.
The D-action can lead to high noise sensitivity
Better models than PI control are required for high performing PID control.

In conclusion, the D-action is not used more often. On the other hand, almost all academic research in the field of PID tuning includes the D-action and this thesis is no exception. For academic work to be accepted in the process industry, it is thus important to consider all above- mentioned reasons for preferring PI control over PID. There are still many occasion and cause for improving the performance of PID control loops. The most frequently used PID tuning rules are mainly decided on the robustness of the closed-loop system. [14, 21]

In this thesis, we have given emphasis on performance evaluation. So now to discuss about performance evaluation.

1.4.6 Performance Evaluation

Performance evaluation is playing the vital role in the design of PID control. The Figure depicts the different type of performance evaluation method.

Tuning of PID controllers for the process industry is rarely done in a single loop due to limited effort. Generally requirements comprise different process abnormalities like set-point tracking, load disturbance rejection, robustness due to process uncertainty; noise sensitivity is a prime concern in process control where stability, steady-state regulation is a key issue [47].

When performance is well thought-out, it is essential to keep in mind that no one control loops requires optimal performance. The purpose is to provide insight into the trade-offs between performance and robustness explicitly.

A practical method to design a controller is to get a process model and a collection of various requirements normally include different specifications. A primary concern of disturbance rejection is used steady-state regulation issue in process control, while set-point tracking is the main use in motion control [6].

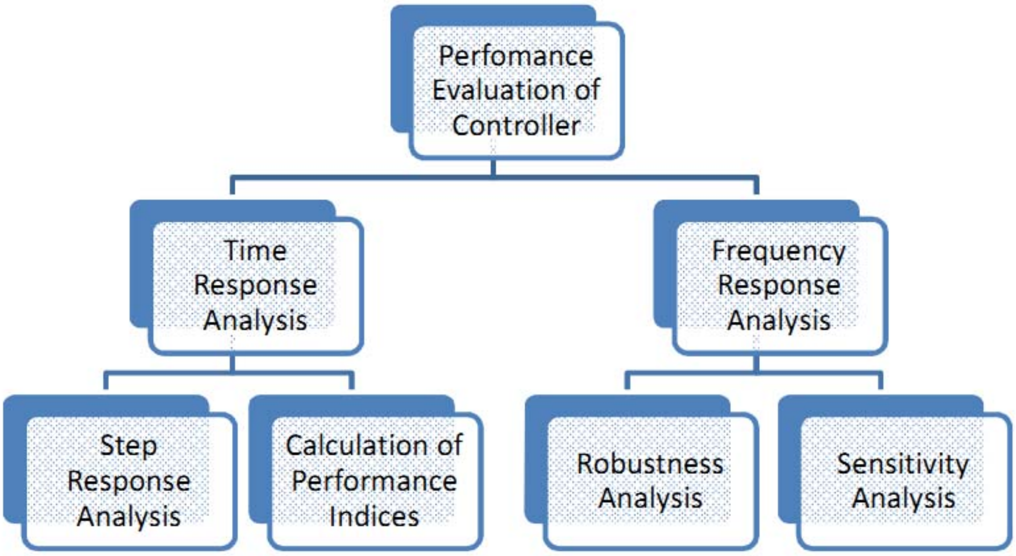


Figure 1.7: Performance evaluation technique for controller design

Performance

In the design of a control system, the performance specification to be satisfied may be given in transient responses specifications terms to a specific input or in terms of a performance index which is a number that indicate the “goodness” of the performance.

The performance indices which are generally used are

1. Integral square error $ISE = \int_0^\infty e^2(t)dt$ (1.27)
2. Integral of time multiplied square error $ITSE = \int_O^\infty te^2(t)dt$ (1.28)
3. Integral absolute error $IAE = \int_0^\infty |e(t)|dt$ (1.29)
4. Integral of time multiplied absolute error $ITAE = \int_O^\infty t|e(t)|dt$ (1.30)

A performance index must have the following properties

It must be a function of system parameters.

It must offer selectivity, that is, an optimal adjustment of parameters must clearly distinguish non-optimal adjustment of parameters.

It must exhibit an extremum that is, a maximum or a minimum.

It must be easily computed, analytically or experimentally.

Although ITAE offers the best selectivity, ISE is extensively used for both deterministic and statistical inputs because it is easy to compute the integrals both experimentally and analytically.

The main drawback of ISE is that a system who’s designing has been done by this criteria exhibits poor relative stability due to oscillatory and fast caused by a swift decrease in a large initial error. However, ISE is often of practical significance because its minimization results in the power consumption minimization for some systems like spacecraft.

The minimization of a selected performance index is the result of an optimal control system. Disturbance rejection will be characterized by the integrated absolute error (IAE) when performance is considered; all control loops not need optimal performance

Robustness

It is very important to ensure that all plant processes are safe and stable around the set-point. Therefore, the primary aim of many PID-design methods is to secure the robustness of the closed-loop system via to keep good margins to the point of instability.

The phase margin and the gain margin are classical robustness measures that are still used today. Robustness can be captured by the sensitivity function, S(s), and the complementary sensitivity function, T(s), The maximum values of these functions $|S(j\omega)| \leq M_s$, $|T(j\omega)| \leq M_T$ and $M_{sT} = \max\left(|S(j\omega)|, |T(j\omega)|\right)$ will also be used to quantify the robustness of the closed-loop system with controller C(s) [8, 21].

c. Noise sensitivity

A large amount of signal activity in control, produced by measurement noise could cause unwanted worsening of actuator. The impact of measurement noise to control action transfer function depends on controller parameters and the low-pass filter factor. Other option is total variation (TV), the total variation (TV) of the control signal [47].

$$\text{TV}= \sum_{0}^{\infty} |u_{i+1} - u_i| \tag{1.31}$$

Where $|u_{i+1} - u_i|$ denotes the control signal change between two successive samples [47]. TV value should be low as possible to offer the smoothness of the control signal.

d. Constrained optimization of PID controllers

Performance, robustness and noise sensitivity took into consideration to formulate the cost function in constrained optimization. Nevertheless, it difficult to solve the non-convexity of optimization problem directly.

1.5 Classification of PID Controller Tuning Algorithms

In the literature for PID controller tuning, the author sees a need for classification of existing methods to present the tuning rules in a systematic manner.

PID controller tuning methods can be divided into time domain and frequency domain methods. For each class, different types of algorithms have been proposed. Time domain methods can be further subdivided to continuous cycling methods, optimization methods, and reaction-curve methods. For the frequency domain methods we have pole placement methods and loop shaping methods. Figure 1.8 shows a tree diagram of these structures.

The classification is based on the approach that each tuning rule uses to calculate controller parameters. Nevertheless, overlapping between tuning categories does occur and the mentioned classes are not mutually exclusive. For example, the Ziegler Nichols technique belongs to both continuous cycling and reaction-curve method categories. The user can decide to choose any one based on the availability of data/model and ease of the use. In addition to the algorithms in the above table, there are also other non-conventional methods not reviewed here.

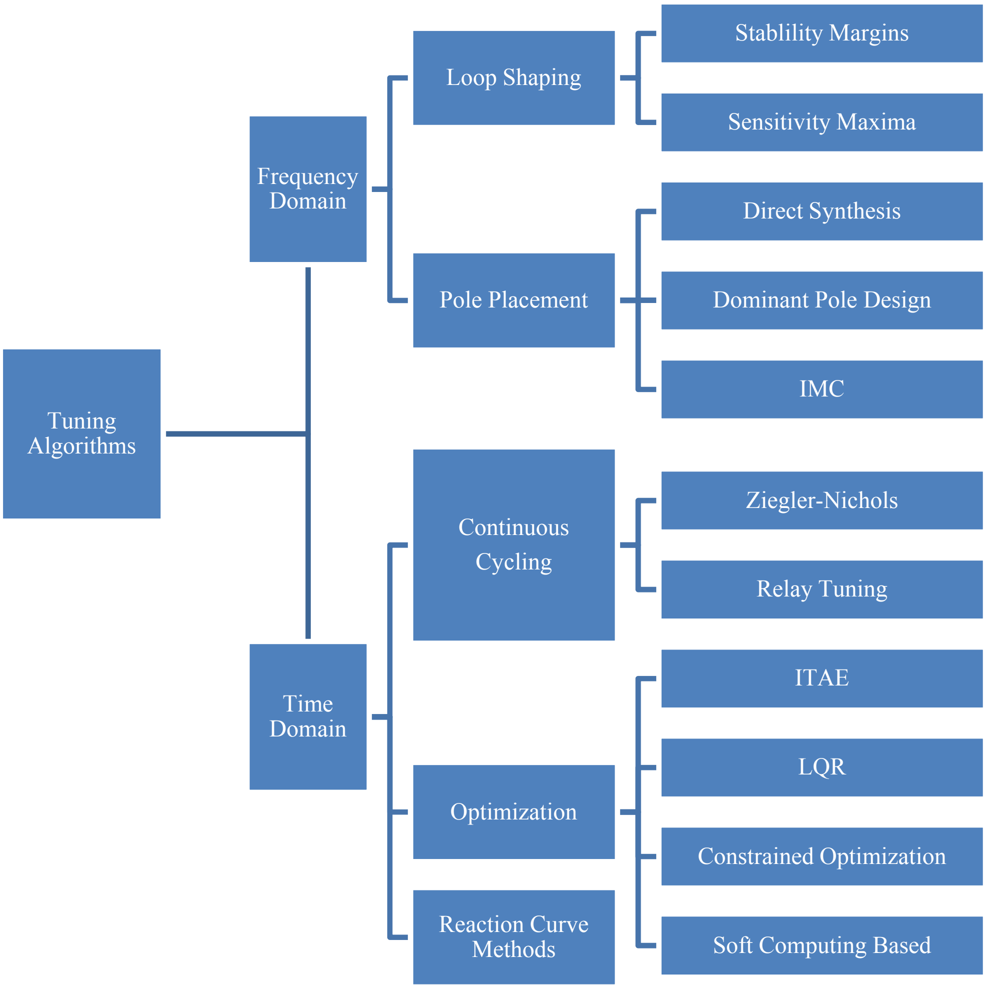


Figure 1.8: Organization of various PID controller tuning methods

Some old and new tuning techniques in each of the classes mentioned are described in the following sections.

1.5.1 TIME DOMAIN METHODS

a. Continuous Cycling Techniques

Continuous cycling technique consists of tuning rules which allow the process to reach to the verge of instability and by observing the output response it is possible to calculate tuning parameters.

The main advantage of this class is that they are model free and easy to perform. However, a number of disadvantages of such methods are listed below [1]:

- Instability needs to be observed by increasing the proportional gain
- Unique performance could not be achieved due to the empirical nature
- The trial and error nature of the method
- The need to upset the process variable during the test
- Confounding of limit cycle with instability bounds
- Doubt in safety and practicality of the algorithm

Modifications to the main theory have been proposed to use quarter decay ratio or a 135^0 phase lag instead of instability to mitigate some of the above concerns [96].

Ziegler–Nichols

In 1942, John G. Ziegler and Nathaniel B. Nichols [Z-N] gave the first ever method for PID tuning, which remains equally popular even today due to its simplicity and applicability to any system or process governed by a model.

Z-N Open-Loop PID tuning method

Z-N considered an open loop step response as shown in Figure 1.9

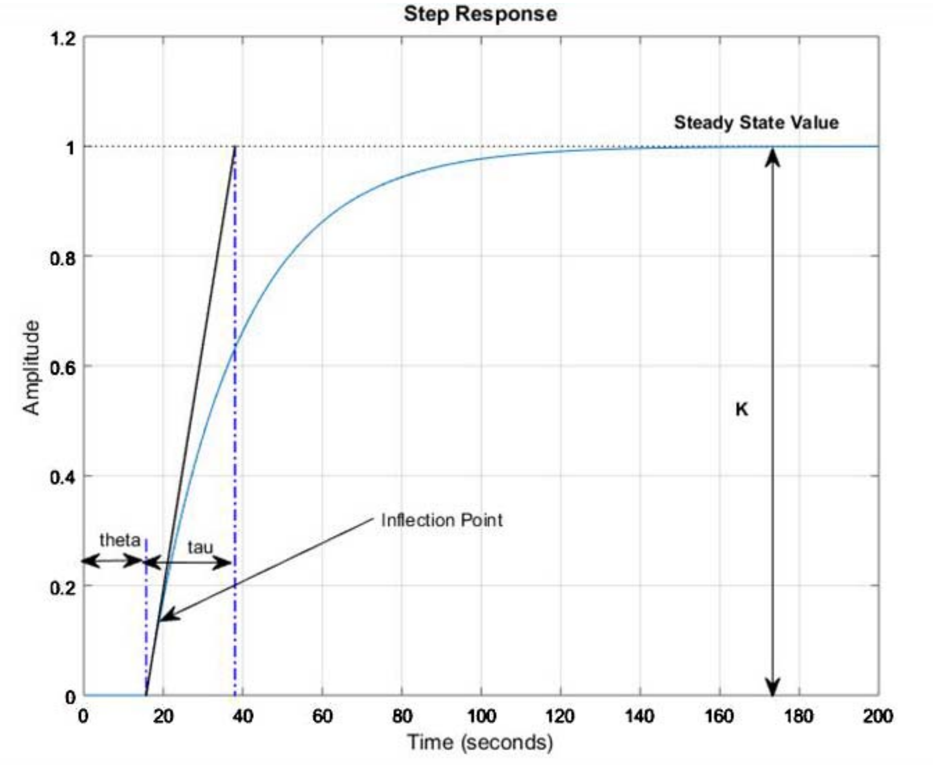


Figure 1.9: Zeigler-Nichole Reaction Curve [6]

Here K= Gain, T =Time Constant, θ = Dead Time

The above reaction curve has been obtained by keeping the control system in manual model viz. open loop.

The values of K, τ and θ were practically estimated. They concluded that

Gain can be approximated by the ratio of the net change of the output to the step change made at controller output.

Dead time estimated from the interval between the initiation of step change and beginning of tangent drawn to response/reaction curve at its steepest point.

The time constant can be estimated from the inverse slope of this tangent.

Hence, k_p, k_i and k_d was given as:

$$k_p = \frac{1.2\tau}{K\theta} \tag{1.32}$$

$$k_i = \frac{0.6\tau}{K\theta^2} = \frac{K_c}{\tau_i} \tag{1.33}$$

$$k_d = \frac{0.6\tau}{K} = K_c\tau_d \qquad (1.34)$$

Zeigler –Nichols open-loop tuning parameters which give roughly quarter wave damping are given in table 1.1.

Table 1.1: Zeigler–Nichols Open-Loop Tuning Parameters for Quarter Wave damping [6]

Type of controller	K_c	τ_I	τ_D
P	$\frac{\tau}{K\theta}$	-	-
PI	$\frac{0.9\tau}{K\theta}$	$3.3\,\theta$	-
PID	$\frac{1.2\tau}{K\theta}$	$2\,\theta$	$0.5\,\theta$

Ziegler-Nichols Closed Loop PID Tuning Method

Let the mathematical equation governing a PID controller may be as:

$$u(t) = k_p.e(t) + k_i.\int_0^t e(t)\,dt + k_d.\frac{de(t)}{dt} \qquad (1.35)$$

Before proceeding with a brief discussion of PID tuning methods, it is important to note that modified non-interacting PID controller function is

$$u(t) = K_c\left(e(t) + \frac{1}{\tau_i}.\int e(t)dt + \tau_d.\frac{de(t)}{dt}\right) \qquad (1.36)$$

Here $k_p = K_c$, $k_i = \frac{K_c}{\tau_i}$ and $k_d = K_c\tau_d$

Where K_c =proportional gain, τ_i = Integral time and τ_d = derivative time

The two steps involved are:

The magnitude of the proportional gain is increasing until the system response starts exhibiting sustained oscillations. Adjusting the gain until the closed-loop system is stable

The value of controller gain at which the response starts exhibiting sustained oscillations is known as critical gain. The time between sustaining peaks is known as the critical period.

A modification of Ziegler-Nichols tuning parameters was given by Tyreus and Luyben. It has been observed that the tuning parameters of this method result in fewer oscillations. The best choice of tuning parameters depends upon the dynamic behavior of the system, control objectives and operators understanding of the system.

Another type of self-tuning controllers is on the basis of mathematical model of the system. These are called model-based self-tuning controllers. In model based Self-tuning controllers, if the model is highly accurate, then the PID controller will also predict the future effects of its present efforts and tune it accordingly.

Table 1.2: Zeigler –Nichols Tuning Parameters [6]

Type of controller	K_c	τ_i	τ_d
P	$0.50K_u$	-	-
PI	$0.45K_u$	$\frac{P_u}{1.2}$	-
PID	$0.60K_u$	$\frac{P_u}{2.0}$	$\frac{P_u}{8.0}$

Table 1.3: Tyreus -Luyben Tuning Parameters [6]

Type of controller	K_c	τ_i	τ_d
PI	$\frac{K_u}{3.2}$	$2.2P_u$	-
PID	$\frac{K_u}{2.2}$	$2.2P_u$	$\frac{Pu}{6.3}$

Reaction-Curve Techniques

This class of tuning rules, sometimes called step response methods, represents the simplest form of calculating tuning parameters. The process is excited by a simple step test in open loop condition and some characteristic properties are then measured [1]. These methods are simple to carry out and were mostly proposed in the beginning period of the tuning era. However, they do not always provide accurate models due to disturbances in the process. A test with large step might be necessitated to attain the required Signal to Noise Ratio (SNR) [6].

This method offers a good approximation to FOPTD model by the curve. The PID controller tuning parameters can be easily obtained by three parameters. [1].

An example of this category is given by Zeigler-Nichol [28]. The Cohen and Coon tuning rule [29] was proposed in 1953 for rejecting process disturbances and was designed again based on the quarter amplitude ratio criterion and calculate the controller parameters given an open loop step response. The tuning rule has the disadvantage of poor (oscillatory) performance in some conditions.

Optimization Techniques

The basic idea for this class of tuning rule is to minimize an objective function of closed loop error and time with determined orders. In this way, parameters can be calculated by using time domain and frequency domain performance indices for an optimal solution. These tuning rules are normally optimized to give good performance for set-point tracking or regulation in a system. The optimization methods are powerful; they can solve whatever criteria are specified by the designer [8]. Soft computing techniques have been applied to systems in order to optimize the parameters and improve the overall performance of a system. These methods are of high interest to researchers to tune response of PID controllers. Nevertheless, their drawback is that there can be many local minima for a system which could mask the optimal solution. Computational strength is another concern for this class of methods.

AMIGO Tuning Method

The AMIGO (Approximate M-constrained integral gain Optimization) method, Astrom and Hagglund (2004) [13], was obtained by applying constrained optimization to a large test batch of process models and then use parameter fitting to find the tuning rules. The parameters of an FOPTD model are determined by the 63%-rule.

The controller is tuned for a robustness of $M_S = M_T = 1.4$.

In Astrom and Hagglund [13] is proposed an Estimated Method that completes this objective in a simple way, which consist a set of equations to calculate the parameter of the controller in a same way to the method used in Ziegler-Nichols method.

Curve fitting was then employed to find rules for PI and PID control tuning with respect to FOPTD parameters which are derived from the 63%-rule. Suggested AMIGO Tuning Rule for PI Controller is

$$K_c = \frac{0.15}{k_p} + (0.35 - \frac{\theta\tau}{(\theta+\tau)^2})\frac{\tau}{k_p\theta}, \tag{1.37}$$

$$\tau_i = 0.35\theta + \frac{13\theta\tau^2}{\tau^2 + 12\theta\tau + 7\theta^2} \tag{1.38}$$

And the PID rule for the parallel form is

$$K_c = \frac{1}{k_p}\left(0.2 + 0.45\frac{\tau}{\theta}\right) \tag{1.39}$$

$$\tau_i = \frac{0.4\theta + 0.8\tau}{\theta + 0.1\tau}\theta \tag{1.40}$$

$$\tau_d = \frac{0.5\theta\tau}{0.3\theta + \tau} \tag{1.41}$$

Tuning Method for Minimum Error Integral Criteria

It is observed that for a quarter decay ratio frequently shows to oscillatory responses. The alternative technique is based on an overall performance index for controller design tuning. Some of the performance indices are IAE, ISE, ITE, and ITSE which discussed already in this chapter. In simulation work, FOPTD, SOPTD systems have been considered.

$$\text{FOPTD}\, G_P(s) = \frac{K}{\tau s+1} e^{-\theta s} \tag{1.42}$$

$$\text{SOPTD}\, G_P(s) = \frac{K}{\tau^2 s^2 + 2\xi\tau s + 1} e^{-\theta s} \tag{1.43}$$

FOPTD and SOPTD, which is an under a damped system. Both system simulations are carried out by using MATLAB.

This method having two cases, which are set-point tracking and disturbance rejection, exists with the unit step input.

It is observed at that for IMC technique do not have a mathematical relation for second and third order systems with delay time so before anything we estimate our system with the FOPTD transfer function the usage of the same technique used for Cohen-Coon and minimum error tuning methods and its settings given Table (1.4).

Lopez et al. [36] built-up tuning formulas which are based on a FOPTD transfer function using minimum error criteria. Tuning relation for disturbance inputs which given in Table (1.5). Those methods show the identical trends as the quarter decay ratio formulas different from the integral time, which depends on more effective on process time constant and less in the process dead time.

This approach evolved through Rovira et al. [36], considered that the minimum ISE criterion was unacceptable because of its exceedingly oscillatory nature.

The tuning relations for set-point tracking and disturbance rejection for FOPTD are specified in Table 1.4, 1.5.

Table 1.4: Minimum ISE criterion for disturbance inputs [36]

Error Signal	ISE		IAE ITAE	
$K_c = \frac{a_1}{K}(\frac{\theta}{\tau})^{b_1}$	a_1	1.495	1.435	1.357
	b_1	-0.945	-0.921	-0.947
$\tau_i = \frac{\tau}{a_2}(\frac{\theta}{\tau})^{b_2}$	a_2	1.101	0.878	0.842
	b_1	0.771	0.749	0.738
$\tau_d = a_3\tau(\frac{\theta}{\tau})^{b_3}$	a_3	0.560	0.482	0.381
	b_3	1.006	1.137	0.995

Table 1.5: Minimum ISE criterion for set-point changes [36]

Error Signal	IAE		ITAE
$K_c = \frac{a_1}{K}(\frac{\theta}{\tau})^{b_1}$	a_1	1.086	0,965
	b_1	-0.869	-0,855
$\tau_i = \frac{\tau}{a_2 + b_2(\frac{\theta}{\tau})}$	a_2	0.740	0.796
	b_1	-0.130	-0.147
$\tau_d = a_3\tau(\frac{\theta}{\tau})^{b_3}$	a_3	0.348	0.308
	b_3	0.914	0.9292

1.5.2 Frequency Domain Methods

Pole Placement Techniques

Direct Pole Placement

Pole placement method closed loop poles are tantamount to place at desired locations. This need to inclusive knowledge of the transfer function is critical to calculate the fitting controller settings. The controller parameter is analytically calculated by pole movement as per specified desired closed loop pole. The numeral of closed-loop poles that can be placed equals the number of controller parameters.

For 1^{st} and 2^{nd} order processes, it is possible to place all closed loop poles with a PID controller. This method is not used for higher order process. So it is necessary to make an approx. first or second order model [31].

Direct Synthesis

Direct synthesis consent to an engineer to design the analytical solution for a closed-loop dynamic of a given process. Homogeneously, all of the zeros and poles of a system would be placed by using such techniques. It is easy to see that for FOPTD and SOPTD models, PI and PID controllers can help accomplish the desired performance. The number of poles that can be placed is equivalent to the number of controller parameters. If a PID controller is selected, these techniques can be used for process models with the maximum order of 2 [31].

Dominant Pole Design

Divergent to the direct synthesis method, it is not always possible to assign all of the poles and zeros of a system using a PID controller, this case mostly occurs in more complex processes with higher orders. For such cases, the design would mainly focus on placing the slowest or dominant pole of a system.

Astrom and Hagglund [22] the proposed design for controller tuning which based on placing a dominant pole for the closed loop. It assumed that for controller tuning, the performance of any closed loop systems decided by two dominant poles.

The parameters of the controller can be computed analytically, if the transfer function of the process is known. In this method design parameters are damping factor and natural frequency and applicable to higher-order processes.

Shen [23] proposed a refined dominant pole design method by GA optimization techniques, and Branica [35] developed a method to calculate PID tuning parameters for FOLPD model parameter. In this method proposed a least-squares fitting method.

Internal Model Control

Internal Model Control (IMC) design technique is one of the popular methods used in control theory. It has some attractive features which distinguish it from others as a powerful and robust design tool. This approach is developed by Morari and Zafiraon [32].

Consider the following IMC schematic

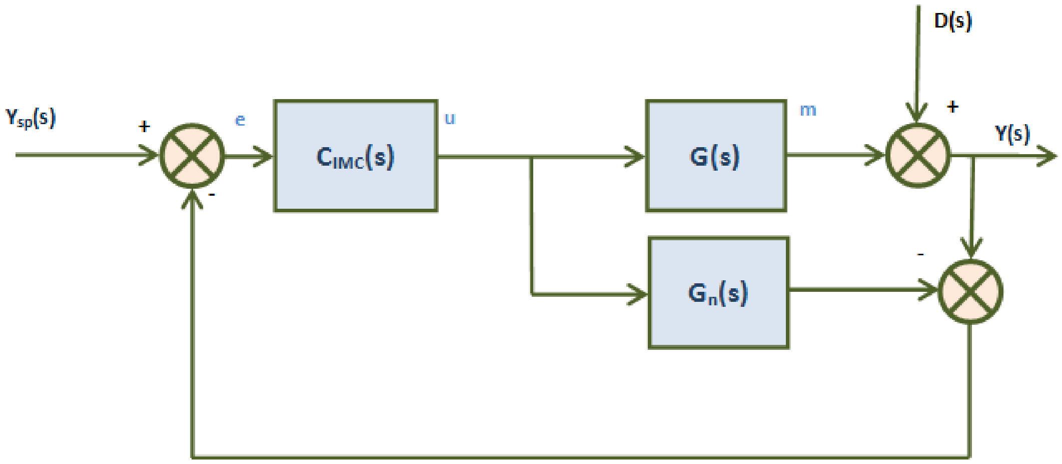


Figure 1.10: Original IMC structure

In this block diagram, CIMC(s) represents the IMC controller while G(s) and $G_n(s)$ represent the actual and nominal models of the process, respectively. Interestingly, the above diagram can be rearranged and redrawn as a conventional feedback loop as shown in Figure 2.

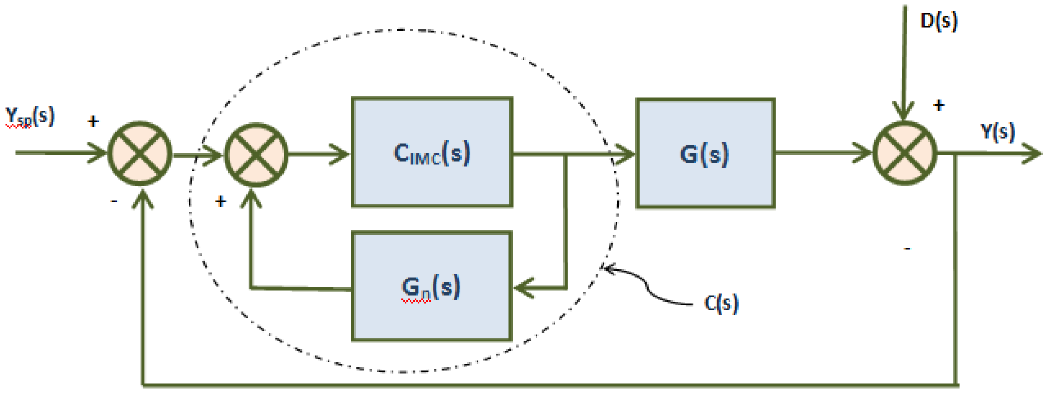


Figure 1.11: Re-arranged IMC structure

In this figure, the IMC controller and the conventional controller one can be converted to each other by the following equations:

$$C(s) = \frac{C_{IMC}(s)}{1 - C_{IMC}G_n(s)} \tag{1.44}$$

$$C_{IMC} = \frac{C(s)}{G_n(s)\left[1 + C(s)\right]} \tag{1.45}$$

One of the excellent features of IMC formulation is that it can take into account the uncertainties inside the process model and hence it is worthy of attention in robustness analysis.

Using the above configuration, the dynamics from the set-point variable (SP) and disturbance variable (DV) to the process variable (PV) can be explained via:

$$Y(s) = \frac{C_{IMC}(s)G(s)}{1+C_{IMC}(s)\Delta G(s)} Y_{sp}(s) + \frac{1-C_{IMC}(s)G_n(s)}{1+C_{IMC}(s)\Delta G(s)} D(s) \tag{1.46}$$

Let $\Delta G(s)$ denote an additive model plant mismatch (i.e. $G(s)-G_n(s)$). From the set- point tracking criterion $\frac{Y(s)}{Y_{sp}(s)}=1$ and the disturbance rejection criterion $\frac{Y(s)}{D(s)}=0$ we can deduce that the following relation should be hold $C_{IMC}(s)=G_n(s)^{-1}$.

The IMC controller acts as exact inverse of the nominal process. IMC based real PID parameters are given in Table (1.6).

Table 1.6: IMC based real PID parameters [32]

Controller form	$K.K_c$	τ_i	τ_d	τ_f	Recommended $\frac{\lambda}{\theta}$ ($\lambda > 0.2\tau$ always)
PID	$\frac{2\lambda+\theta}{2(\lambda+\theta)}$	$\tau+\frac{\theta}{2}$	$\frac{\lambda\theta}{2\lambda+\theta}$	$\frac{\lambda\theta}{2(\lambda+\theta)}$	>0.25
PI	$\frac{\tau}{\lambda}$	τ	-------	------	>1.7
Improved PI	$\frac{2\lambda+\theta}{2\lambda}$	$\tau+\frac{\theta}{2}$	--------	-----	>1.7

The best ratio choice of the $\frac{\theta}{\lambda}$ is based on performance and robustness considerations. This type of controller cancels the process poles and zeros for a high order. Parameter λ represents the trade - off between robustness and performance.

IMC can also provide good step tracking responses and worst disturbance rejection response due to sluggish poles which are canceled.

Several modifications of the IMC method are available in literature, including time delay using a MacLaurin approximation [16, 17]. Skogestad [33] is also done an interesting modification, who presents simple IMC based tuning rules.

Ziegler Nichols Internal Model Control (ZNIMC)

ZNIMC tuning rule gives a compromise solution that performs well as the Ziegler-Nichols rule and-and robust as the IMC technique. IMC structure is to make sure the desired robustness and substitutes the integral time formulation with the Ziegler-Nichols tuning rule.

It gives reliable tuning technique when the desired closed loop time constant was selected properly. An important advantage of the ZNIMC rule is that it has the conventional user defined desired closed loop time constant in the same way as IMC does. The tuning algorithm has a simple solution for lag-dominant processes [4]. The guideline for robust PID tuning design same way as set-point tracking.

Lag Dominant if 0:2 <α< 0:5 $\alpha = \frac{\theta}{\tau}$

Ziegler-Nichols is a more aggressive tuning method than IMC rule. In practice, low robustness and the oscillatory responses are observed.

Mathematically ZNIMC rule is given by

$$K_c k_p = \frac{\tau + \frac{\theta}{2}}{\tau_c + \frac{\theta}{2}} \; \tau_i = \frac{P_u}{2} \; \tau_d = \frac{\theta\tau}{2\tau + \theta} \tag{1.47}$$

where P_u is the ultimate period in the critically stable condition.

The ZNIMC tuning technique is a confinement version of the Ziegler-Nichols to increase the robustness.

Vilanova Tuning Method

Vilanova [34] proposed a robust IMC based ISA tuning rule for set-point tracking, In this rule two user defined parameters are incorporated, one is desired closed loop time constant, which is to manipulate the speed of response and the other one is z-factor for direct tuning of robustness. The main advantage of the tuning rule is an increased degree of freedom for the design, but a disadvantage is that there are no clear guidelines for specifying these parameters which may be sometimes confusing.

Vilanova suggest tuning relation that is directly expressed the process model in term of K, θ , τ .

$$K_c = \frac{\tau_i}{K(\rho + \tau_m)} \tag{1.48}$$

$$\tau_i = \tau + \lambda_1 - \tau_m \frac{(\rho + z)}{(\rho + \tau_m)} \tag{1.49}$$

$$\frac{\tau_d}{N} = \tau_m \frac{(\rho + z)}{(\rho + \tau_m)} \tag{1.50}$$

$$N + 1 = \frac{\tau}{\tau_i} \frac{\rho}{\theta} \frac{(\rho + \tau_m)}{(\rho + z)} \tag{1.51}$$

1.6 SUMMARY

This chapter provides an overview of the PID Structure & Tuning methods found in the literature. It is challenging to include all of them; various techniques were supplied primarily based on the work with the aid of Ziegler-Nichols, and use quite easy process models to derive tuning recommendations. The benefit is that the strategies are simple, easy to use and do not require a deep understanding of the system. Nevertheless, this leads additionally to unidentified stability; robustness and gives no value over the ensuing performance. The applicability of these methods is usually constrained to the process industry. Using more sophisticated model-based tuning methods, such as loop shaping, or IMC permits a better definition of desired closed-loop behavior and robustness. A disadvantage is that first, an accurate model needs to be obtained, which is time-demanding and often tricky. An exciting field is the auto-tuning of PID-controllers. Advantages are that they are easy to use, and can cope with disturbances and process changes. This area is subject to research.

CHAPTER - 2

LITERATURE REVIEW

This section discusses the literature survey of performance evaluation of tuning via analytical, experimental and soft computing techniques for different applications. It aims to identify the trend and direction of practical PID development.

2.1 Overview

PID control has been the most widely used form of feedback in the industry for the last six decades. It is quite old, but earlier in the 1930s; the development was motivated by instrument companies, plant designers and operators [37]. Today the vast interest along with academics and still increasing. The historical development of PID controller, the fundamentals of PID theory and the basics of control strategies introduced in the previous chapter for better understanding and design of the PID controllers. This section covers the comprehensive, general and specific literature survey on Modeling, different tuning methods with performance evaluation and various applications of PID controllers for process parameters in a control system. A lot of literature is existing related to this topic. Here is the literature review that is significant to the work carried out for the thesis work.

In this part of the literature review, work related to the performance augmentation for different types of PID tuning methods familiarized. The literature used in this region is posted in these sections bestowing on the modeling and identification of plant & tuning methods type.

2.2 Literature Review

The literature survey is a platform regarding current status, methodologies, which are adopted due to their advantages and disadvantages and have to be analyzed. Based on this context, a problem suitable for the research work has to developed. This chapter deals with the focus on the literature review for those various aspects of PID controller and their tuning. The various journals and books that have some relevance to this research work are used as a reference to guide for completing the research work. Some literature and their brief description presented.

The kinds of literature review can organize as follows:

2.2.1 Review of Work based on Soft Computing based

D. Kumanan et al. [38] proposed a PID controller parameter tuning firefly algorithm (FA) method for flow control loop and compared it with conventional Ziegler - Nichols method. Proposed FA based controller method gives better performance than Z-N regarding set-point tracking, Steady state error response and performance indices.

Nagaraj B et al. [39] proposed a PID controller tuning method which based on soft computing techniques like using GA, EP, PSO, and BFO for real-time control of a blend chest consistency system in papermaking. It gives betters the performance indices of the process using tracking set-point and time domain specifications. This controller tracks the set- point much faster and also maintains a steady state error. The performance of Soft Computing Techniques based controller was much advanced than the conventionally tuned system.

Ratna Ika Putri et al.[40] designed an Adaptive fuzzy PI controller for speed control of induction motor on a centrifugal machine that can maintain speed according to reference speed with load and reference change. In this paper, the strejc method used for Centrifugal system modeling. Simulation studied performance analysis and designing with Simulink MATLAB. The centrifugal machine plays a vital role in the process of centrifugation to separate the molasses and sugar crystal. The centrifugal machine driven by an induction motor which has non-linear characteristics. The load changes on the induction motor will result in motor speed change.

Omar Bendjeghaba [41] proposed new continuous firefly algorithm (CFA) tuning method for AVR system. Simulations results show the effectiveness and the efficiency of the proposed approach. The proposed plans compared CFA with PSO. The CFA has better performance parameter in set-point tracking terms and time domain specification as compared to PSO.

S.M. Giriraj Kumar et al. [42] developed a PSO algorithm to optimize the parameter in the design of a PID controller for a high-performance drilling system. The offered approach has exceptional features including robust, stable and functional computation efficiency compared to Ziegler-Nichols method for FOPTD model. The proposed plan is useful for improving time domain specification and integral of absolute errors (IAE) performance indices.

R. Matousek et al. [43, 44] proposed an HC12 optimization algorithm based on soft computing for Magnetic Levitation System which In this work, they have compared an HC12 algorithm design method for Zeigler- Nichols, and Modulus optimum. The correction of the solution is done by Nelder-Mead algorithm (NM) optimization methods which give more stability and optimal solution result.

Ugur Guvenc et al. [45] proposed biogeography-based optimization (BBO) for an AVR System. They have compared the BBO algorithm with the ABC, PSO, and DE algorithm and have reported better tuning performance in term of robustness, Bode plot, root locus and transient response. The comparison shows that the BBO algorithm has the better result than the other heuristic algorithm.

Chhaya Sharma et al. [46] have developed a mathematical model for temperature control of a heat exchanger which is used in soda recovery by using input-output data. The performance analysis of the model examined by altering the controller parameters at different set-point for PID controller.

Majhi S et al. [47] proposed a new controller design approach based on model and lower order model from a high order or sizeable dead time stable, integrating and unstable plants, with a longer time delay. In this approach response of the plant is assumed to be first or second order. Moreover, peak amplitude and frequency obtained from single relay feedback test used to precisely analyze the control parameters.

Wang Y.G et al. [48] presented a method of PI controller relying on load disturbance rejection along with constraint optimization, where a Nyquist plot of a transfer function is tangent to the line which is parallel to the imaginary axis, lying on left half of the complex plane.

Tan K et al. [49] developed an online relay automatic PID control tuning method, wherein a relay placed in the inner loop of a processing system of controller-stabilizer unusually. Moreover, controller settings may be re-tuned non-iteratively by applying induced limit cycle oscillations achieved from a closed loop system for enhanced performance without interrupting the closed-loop control system.

Hang C. C et al. [50] has proposed a method for Internal model control (IMC), based single loop controller design method, wherein to look for the best approximation to IMC controller using model reduction technique. Automatic online tuning can be achieved by this way, by choosing an option of either PID or high-order controller which is suitable for the application. This approach facilitates to perform the specified performance of the closed loop for the sake of complexity of the controller or to preserve un-complex PID controller which would possibly deteriorate the performance of a closed loop, thereby, limiting this method to higher order processes to obtain the desired response with PID controller.

Yang et al. [51] proposed an approach to designing of a controller based on time domain analysis or frequency domain analysis viz. rise time or overshoot, stability margin, and resonance peak. This approach is not suitable for the higher order systems but applies to the time delay systems.

Astrom et al. [52] presented a review of relay feedback auto-tuning approach which includes the methodologies of refinement of PID tuning for a process with various estimations viz. long dead time, oscillatory dynamics and multivariable methods.

Nagaraj B et al. [53] proposed a PID controller tuning method which based on soft computing techniques like using GA, EP, PSO, and BFO for real-time control of a blend chest consistency system in the papermaking. The results obtained reflect that use of soft computing based controller improves the performance of the process regarding time domain specifications and performance index. This controller tracks the set- point much faster and also maintains a steady state. The performance of Soft Computing Techniques based controller was much better than the conventional tuned system.

W.W.Cai et al. proposed a PSO-PID controller tuning method for the first order and second order which gave time delay using a size of system error. In this paper, particle swarm optimization (PSO) techniques are used to optimize the tuning parameters by searching in the given controller parameters area to solve the problem in lag, time-variety, and non-linearity system. This method provides better-optimized result by minimizing the performance indices [54].

Y. Bo et al. proposed a dynamic performance comparison between PSO-PID and IMC-PID method for FOPTD process. The proposed method is efficient for small and quite substantial time delay. Tentative results demonstrate that the dynamic PSO-PID controller performance has significantly improved than the IMC-PID controller [55].

A.El-Gammal et al. [56] proposed an adaptive PID controller using PSO algorithm by adjustment of gains between speed demand and output response. The different techniques obtain a single cumulative objective function using chosen weighting factors. Even the weighting factors are also engaged in dynamic optimization for evaluating PID parameters. The results reveal that the proposed technique gives significantly improved outcome than the traditional method.

G.P.Liua et al. [57] presented time domain, frequency domain, and multi-objective optimal PID controller design schemes for the gasifier industrial control systems, the rotary hydraulic speed control system and the hydraulic position control system. This proposal mainly works on model estimation, system specifications, procedure and optimal tuning of a PID controller with different kinds of system performance. Simulation results and real-time experiments show significantly better system performance, and very well handled with changes in the process dynamics.

Sridhar N. et al.[58] proposed an optimal auto-tuning of the PID controller with latest performance index M_x and worldly optimization of performance achieved with the use of adaptive social behavior optimization (ASBO) for different applications like quad-rotor, DC motor, and automatic voltage regulator. The proposed method, performance comparison with the Genetic algorithm (GA), self-organize genetic algorithm (SOGA), Differential Evolution (DE), Chaotic estimation of distribution algorithms (CEDA), Chaotic optimization and Convex-Concave optimization presented with various fitness criteria's. A proposed method of auto-tuning showed the generalized applicability for PID controller design with different types of systems in an optimum manner.

M. Hast et al. [59] design a PID controller by using Convex-Concave Optimization. The criterion is to minimize IE or maximize intrinsic gain subject to robustness constraints. The design problem method acknowledges general process descriptions regarding frequency response data, and it can deal with various restrictions and solved by grinding for three PID controller parameters. Convex optimization applied to another controller such as multivariable PID structures or fixed higher-order controllers.

R. Toscano [60] proposed a simple and effective method for well-built PI or PID controller design problem which is sorted by the numerical maximization optimization approach with a finite interval and the closest distance from the Nyquist plot of the open loop transfer function to the critical point. These simulation results show the electiveness of the method.

Lin et al. [61] proposed adaptive fuzzy PID controller that not just considered as a changing system dynamics but also can carefully planned as a general fuzzy PID controller with more extensibility. The offered gain scheduled fuzzy PID controller performs very well if system controlling done without varying dynamics.

B. Nagaraj et al. [62] proposed the Bio-Inspired algorithm for PID Controller Tuning for Pulp and Paper industry process. The proposed heuristic algorithm based PID controller which is concerning Evolutionary programming (EP), a Genetic algorithm (GA), Bacterial foraging optimization (BFO) and Particle swarm optimization (PSO) improves the performance of a process and offer optimum stability. The feature of the designed controller in terms setpoint tracking of time domain specification and regulatory changes compared, and simulation results demonstrated.

Ashutosh Kr Agarwal et al. [63] proposed genetic algorithms which established on the philosophies of evolution. A genetic algorithm holds a population of encoded solutions plus guiding the community towards an optimal solution. In this paper, this valuable property of the genetic algorithm was used to soothe the pendulum system which is inverted. This article emphasizes on the applications of the inverting pendulum and also the stability of the same using PID controller with fuzzy logic supervised PID controller optimized by genetic algorithm. Some well-built search techniques in use contained by the information technology industry are also there. The proposed genetic algorithm method gives a better result by reducing the steady state error and overshoot using the technique.

Muhammad Unal et al. [64] in their study focus on a performance comparison of a GA and ACO optimization method for PID controller tuning on a pressure control process. In this paper, predefined trajectory reference signal was used only for tuning of the PID controller using GA and ACO optimization method. In this work, dynamic model of a pressure process system was obtained by NARX type ANN and validated by regression analysis and mean square error. A cubic trajectory function employed as an input reference signal. In this paper, they were design cost function to minimize the error along the trajectory for the GA-PID and ACO-PID controller, and PID controller was also tuned by traditional approach Ziegler-Nichols (ZN) method to compare the results. Finally, it concluded that both ACO and GA algorithms could be used to optimize the PID controllers in the pressure process with exceptional performance.

2.2.2 Review of Work based on Performance & Robustness

Farhan A. Salem [65] has proposed an efficient PID controller design method which based on Plant's parameters. This traditional approach tested for the various types of a model like first-order systems, second-order systems, and third and fourth order systems. The first-order process with dead-time (FOPTD) compared with other design methods. The study shows that the working method has better MATLAB simulation results than other conventional techniques like Ziegler-Nichols and Chein-Hrones-Reswick (CHR) regarding stability and time domain specifications.

Skogested [33] proposed a new analytic method for PID controller tuning which provides better-closed loop response with easy implementation. Initially, IMC-PID tuning applied which is accepted widely. Moreover, to improve the disturbance rejection, an integral part of the system is changed. In this approach, single tuning rule for SOPDT or FOPDT models obtained, but this method is a drawback that for higher order systems, a model reduction is necessary.

R. Vilanova [34] in their design work to the tune of PID controller for step response for First Order plus Time Delay (FOPTD) model by considering robustness to handle robust stability & model uncertainty. In their design work on tuning parameters of the ISA-PID are determined for robustness and the desired closed-loop time constant. The final result, relations of PID tuning are directed by other two parameters like TM and z to express the desired time constant and model uncertainty in nominal condition. The proposed method is simple automatic tuning rules that directly give the controller performance parameters regarding the process model parameters of robustness level and the desired closed-loop time constant for the complete plant.

Kaya [66] proposed an approach to evaluate the process with a considerable time constant, with or with an inclusion of an integrator for the process with improperly located poles.

In another paper of Kaya et al. [67] presented PI-PD controller, model-based approach wherein PD feedback was applied to change poles of a transfer function of a plant to desirable locations for control by a PI controller. Standard form integral time multiplied square error (ITSE) method was used to estimate the parameters of PI-PD controller.

Vrancic D et al. [68] proposed a new approach in which to optimize the disturbance rejection response. The magnitude of the optimum criterion is modified resulting in improved basic set-point filtering PI controller structure. This revised process applied to several another second degree of freedom PI controllers. The drawback of this approach is similar to that of the previous magnitude optimum approach where reduce order controller used. The stability of closed loop response cannot strongly guarantee.

Edgar T. F et al. [69] presented an ISE and IMC method based tuning strategy wherein, using weighted least square method tuning parameters considered and applied to SISO or complex MIMO processes.

A. Leva [70] presented the design to reject load disturbance, proposed an auto-tuned process controller where a process with necessary rational dynamic and overshoot or smaller oscillations in step response implemented. The resulting controller in this approach may be the standard PID structure, but non-PID structure can be converted into PID with simple cases.

Tan et al. [71] presented the design of PI controllers to obtain the time domain and frequency domain specifications. Gain Margin and Phase Margins, performance measures of a frequency domain, was defined before the design. Also, time domain performance indices, settling time and overshoot were also determined. Moreover, a graphical approach was used to the design of PI controller and extension to the PID controller is not cleared.

Clarke D.W. et al. [72] proposed a new approach to an alternative PID auto-tuning to relay based methods and step response methods. This plan includes injection of a variable frequency probing signal into the closed loop. This online approach was described by Strmcnik S which differs in turning from the existing methods. Also provides single shot auto tuning but a simultaneous continuous adaption of the controller.

Dey C. et al. [73] proposed a new model-independent auto tuning scheme Z-N tune PI controller. Moreover, Ziegler Nicholas tuned PI controller's parameters tuned through a single nonlinear parameter which defined on process states.

Sundara Moorthy et al. [74] presented a direct synthesis approach for designing a PID controller which is based on the impulse response of a plant only, then transfer function models which derived from the step response. Moreover, the authors have calculated the mean, statistical distribution and the variance of the distribution and used them in the evaluation of PID controller parameters.

In a paper of Dey et al. [75] Ziegler Nicholas tuned PID controller auto-tuning scheme. In this approach, the Z-N controller modified with heuristic rules via online gain modifiers which are defined by the instantaneous process states, whereas, in conventional Z-N PID controllers, large overshoot for high-order nonlinear processes.

Waghmare et al. [76] proposed a model based designing of PID controllers for higher order oscillatory systems. This approach facilitates to eliminate the limitation over systems orders, time delays, load changes, and oscillatory behavior. Moreover, the selection of coefficients achieved through the use of frequency response with a reduced model based on third-order modeling. Using the reduced higher order model, tuning of PID controller parameters obtained. Simple, efficient and improved performance of the complete system achieved in the proposed approach.

Matausek et al. [77] proposed a method for PID controller tuning based on parameter plane. In this approach, the process is distinguished using ultimate frequency ω_u, the angle ϕ of the tangent to the Nyquist curve in ultimate frequency, the ultimate gain Ku and the gain G_p (0). Moreover, by normalizing time and amplitude, two parameters of $G_n(sn)$, the normalized gain ρ and also angle ϕ, are obtained, and these are the coordinates of the classification $\rho - \phi$ plane. Further, using these two parameter plane model, the required closed loop system performance in the region desired of the classification plane is estimated, and the formulae for tuning derived for PID controller.

Gaoxi Xiao et al. [78] presented a new analytical approach for PID controller tuning including specified gain. It also gives a proposal to the phase margins for an integral time delay process. Moreover, the proposed method illustrates generalized PID parameters and utilizes some rules which already exist as PI/PID/PD controller tuning with a variety of GPM specifications. The system realized by conventional rules of PID tuning and computed, documented and presented as a guideline parameter for the control engineers to tune the PID controller.

Qing-Guo Wang et al. [79] has proposed PID controller tuning method for linear self-regulating processes which for a variety of dynamics, together along with the low-order and high-order, monotonic responses and oscillatory responses, and small dead time and large dead time. The now developed method is all based upon a second-order in addition to modeling techniques of the dead time and poles of the closed-loop can easily be assigned by the conventional methods of root locus analysis. Simulation results and real-time experiments show the consistent and satisfactory responses of the controller in different processes.

K.J. Astrom et al. [80] recommend the status ability of PID control and focus on the future. In this paper discussed include design, stability, specifications, performance, and applications. The article ends with a discussion of substitution of PID and the future of PID.

Naseer A. Habobi [81] developed a PC-based controller for Shell and tube heat exchanger for regulating the desired outlet temperature of hot water. In his work, the dynamics of cross-flow shell and tube heat exchanger modeled identified with the highly nonlinear process which is first order plus dead time (FOPTD). It estimates the controller parameter and tuned by MATLAB Simulink by using Ziegler-Nichols method and compared with PI controller regarding process performance (percentage overshoot, rise time, and settling time). The results show that the PC-based controller performance shows good conformity for PC-Based to control the system at a low cost.

Emine Dogru Bolat [82] designed and implementation of an experimental set of MATLAB-Simulink which based on real-time temperature control of oven using various kinds of auto-tuning PID methods. Disturbance criterion methods are used to control a temperature of the experiment set. These include Ziegler-Nichols Step Response Method, Integral Square Time Error (ISTE) and Relay Tuning Method. MATLAB-Simulink software is used to simulate these methods. Subsequently, simulation is recognized using these parameters. In the end, real-time temperature regulator of the experiment set is realized using the similar parameters, and the outcomes deliberated.

K.J. Astrom et al. [13] in their paper reread tuning of PID controllers that based on step response in the mettle of Ziegler and Nichols. In this paper, large test batches of a process have applied to simple tuning rules from the robust loop shaping point of view. The processes are estimated by a model that represents the first order in addition to a time delay which is in KLT form. The results of PI and PID control within complex tuning rules giving a performance which is robust for processes with step responses.

Shamsuz Zoha and Lee [83] reported that IMC demonstrates sluggish disturbance rejection, especially when the dead time to time constant ratio is small. To improve this problem, they proposed an IMC-PID tuning method for improved disturbance rejection. It claimed that the proposed rule provides a better response for lag-dominant processes where the controllers are tuned to have the same degree of robustness based on maximum sensitivity.

A. Keshtkar et al. [84] proposed a synthesis method for design of bulky PID controllers toward a description of uncertainty and also keeping sound quality along with maximum sensitivity. The synthesis method requires to automatize the checking of possibility and looking for an initial value for the optimization numerical. Simulation results offered for Anti-lock Braking System (ABS) where the design method used was successfully coping with uncertainty.

Astrom, K.J et al. [85] proposed an advanced design method for PID controllers which based on optimization techniques of load disturbance rejection with constraints in robustness to model uncertainties. This design also brings parameters to understand along with measurement disturbance and set-point response. Therefore, the formulation of the design problem summarizes four essential features of industrial control problems, which lead to a constrained optimization problem which could be resolved iteratively.

Manjunatha Reddy H. K [86] describes the implementation of real-time dc motor speed control with PID Controller in MATLAB environment. The obtained MATLAB results show better performance of control action relates to rise time and steady-state response.

Chandrasekhar T et al. [87] designed and developed embedded based DC motor speed control system in which PID controller was implemented successfully using the CY GNA microcontroller (C8051F020) and verified by a DC motor speed control system. The microcontroller applied for PID control action to correct the errors in the form of voltages to the motor through a built-in 12-bit D/A converter, actuator, and PWM circuit. For speed control, the test results showed better-desired output speed was obtained by incorporating PID controller. This design based on a technique of frequency domain in which optocoupler is used to sense the speed of the motor in the pulse form, which given to frequency to voltage (F/V) converter. An output of the F/V converter voltage delivered to a built-in 12-bit Analog to Digital Controller. The converted value which digitally applied in a linear equation for the following conversion of frequency and where speed displayed on LCD.

Subrata Chattopadhyay et al. [88] in their study focuses on PID controller tuning of control parameters to their optimum value by using Lab VIEW software. The effectiveness of the controller for controlling different physical process variables like Pressure Measurement and Control, Temperature Control, Level Measurement and Control, Flow Measurement and Control, etc. are studied using a proper tuning. The designed virtual instrument comprises the components which are essential for PID controller to function appropriately and they also control all the linear processes.

Silva, G.J, Datta, A. et al. [89] proposed the problem of stabilizing a first-order with dead time plant using a PID controller. Account of the Hermite-Biehler theorem which is relevant to quasi-polynomials, the full array of stabilizing PID parameters explained for open-loop stable plants and unstable plants. The range of adequate proportional gains explained in closed form. In this range, each of the proportional gain, stabilizing set in the space of the integral and derivative gains is to be a trapezoid, triangle or rectangle. An essential and sufficient condition on time delay actuated for the survival of stabilizing PID controllers in the case of an open-loop unstable plant.

Maruthai Suresh et al. [90] proposed a controller tuning of the process to achieve the optimum response to the controlled process by adjusting the parameters of the selected controller. With numerous control problems, acceptable performance attained by using PID controllers. One of the main difficulties with mathematical models is that the parameters used in the models cannot be dogged with complete accuracy. The values of the parameters may try to change the time or different effects. In such cases, conventional controller tuning methods suffer to produce an optimum response. To prevail over these difficulties proposed an internal model control based PID controller tuning method which is fuzzy logic based set-point weighting. The effectiveness of the planned scheme is analyzed through simulation using MATLAB Simulink software. Fuzzy logic based simulation results compare with Cohen-Coon, Ziegler- Nichols, Ziegler – Nichols with set-point weighting, Internal Model Control (IMC) and Internal model control based PID controller responses (IMC-PID). The result of process modeling errors and the significance of controller tuning have been understood using the proposed control scheme.

M.B.B. Sharifian et al. [91] discussed controller design for the process and its implementation requirements. They offered first, a PID compensator which tunes by a genetic algorithm then an additional compensator is designed by combining methods of optimal state feedback controller with an integral controller. In the second compensator, design specifications, depend on choosing weighing matrices using the Genetic Algorithm (GA) to find the proper weighing matrices. Obviously, Kalman filter is used as a system observer to increase the robustness of the mentioned system. After that the performance of both control techniques is comparable regarding rise time, tracking error, robustness, and settling time concerning disturbances and modeling errors. Next, the comparison between the PID control and the optimal control demonstrates that the optimal controller considerably reduced the overshoot, settling time and gets the best performance comes across with system uncertainties.

Mehdi Nasri et al. [92] offered a particle swarm based optimal design of PID Controller for a linear brushless dc motor. The proposed approach has enhanced features with stable convergence characteristics, trouble-free implementation, and excellent computational efficiency. This brushless DC motor first modeled in Simulink, and in MATLAB the PSO algorithm is implemented. The comparison with genetic algorithm and linear quadratic regulator (LQR) method and also the proposed plan has to get better step response characteristics by reducing different time domain specification like steady-state error, maximum overshoot, settling time and rise time in a linear brushless dc motor.

W.K. Ho et al. [93] proposed studies that correlated between the integral square error (ISE) performance indices, gain margin (GM), phase margin (PM) and gives a suggestion for gain and phase margin specification to acquire more phase margin and performance out of PID controllers. His research paper showed how this could be made to use and simplify by the PID controller design with design equations set. If the gain and phase margin specified with care, then the design might not be appropriate in the logic that could be more robust, that could give a much better performance. It would be enviable to be able to have specific phase and gain margin that would give the best control design involving a trade-off between robustness and performance.

Leandro dos Santos Coelho [94] proposed a systematic way to tune PID type controllers for an AVR system taking approaches of chaotic optimization based on Lozi map (COLM). This tuning method uses closed-loop data to estimate the settings of PID parameters. The COLM methodologies efficiently legitimated for tuning of PID controller for the AVR system of different working conditions. From the results compared, it is shown that the step size k parameter is essential for an excellent convergence profile. The parameter k regulates the accord between local and global investigation abilities of the chaotic local research. Numerical simulations which based upon proposed PID control of AVR systems for step reference voltage input and nominal system parameters reveals the better performance of chaotic optimization and show the effectiveness of the proposed approach.

Emre Sariyildiz et al. [95] proposed a new practical PID tuning method for the Disturbance Observer (DOb) based robust position control system with velocity feedback for motion control systems. The robustness and performance of the motion control system can be adjusted independently because the performance of the motion control systems may appreciably be deteriorated by the nonlinear uncertainties of the plant and unidentified external disturbances (like as inertia variations, external loads, and friction). The authors always advised that the robustness variable (R) should be increased until the servo system is influenced by practical constraints such as disturbances and noise. The PID controller proposed here is not really susceptible to inertia variation that stable controllers can be primarily designed in practice. Therefore, this proposed method has a very high impact, not just in academia but also in the industries.

M.A.A. Shoukat Choudhury et al. [96] has been developed for a generalized definition of valve stiction with the help of data-driven empirical stiction model. This study pays to focus on the understanding, from real- plant data of the mechanism that causes stiction and proposes an innovative data-driven stiction model that can be directly related to real values. It also permits the simulation results to produce using the model which is proposed with from a physical model of the valve. Both closed-loop and open-loop effects have been offered and validated to demonstrate the capability of the model. Finally, model valuable insights on stiction have been getting from the function analysis described.

D. C. Tsamatsoulis [97] developed a design to unify criterion of together performance and robustness led to highly efficient PID controllers for cement milling process. This study gives a focus on the M-Constrained Integral Gain Optimization (MIGO) loop shaping method which determines PID values satisfying a certain robustness constraint. The maximum sensitivity was utilized as such criterion. The MATLAB simulation is applied to all the PID sets that aim to find parameter region which provides minimum integral of absolute error (ISE), which functions as performance indices. For each cement type, a PID set is chosen and kept in operation in a closed circuit cement mill.

B. Lennartson et al. [98] presented an analytical PID-design method based on a regular controller evaluation method, also taking into account both robustness and performance in deviating frequency region. It is related to the internal model control (IMC) based lambda tuning approach for a non-minimum phase second-order plant model. In this paper, an analytical method introduced two tuning parameters, such that one which guarantees specified stability margin and another one also which can adjust the control action to a level desired for the given model. The suggested robust IMC method gives independence to control mid- frequency robustness and high-frequency robustness. Extensive evaluation procedure also demonstrates how efficiently PI and PID controllers can control time delayed plants using a Smith predictor (SP). In analytical PID-design method suggested RIMC is exposed to be good as compared to the ordinary IMC and lambda tuning as well as other PID design principles used.

M. C. Leiva et al. [99] proposed a new tuning rule for PI controllers and first-order in order and time delay plants. This tuning rule presents a set of equations which is based on a Pareto-Optimal Criterion with a closed-loop robustness criterion for input and output disturbances rejection. The set of equations permits the control engineer to select the weight given to each response to the compromise between input and output disturbance rejection optimality with robustness constraint.

Olof Garpinger et al. [100] have introduced a graphical tool for control design which provides the trade-offs between performance and robustness for PID control by consideration of numerous issues such as set-point tracking, load disturbance attenuation, robustness concerning process deviation and model uncertainty and sound effects of measurement noise. In their work, they introduce charts to provide intuition about tuning which is expressed by integrated absolute error (IAE), and the maximum sensitivity (M_{st}), which is trade-offs between performance and robustness for an understanding of design compromises for PID control method.

Md Nishat Anwar et al. [101] have proposed design method for IMC based PID controller. In this method, they derived equivalent feedback PID controller to internal model control by an estimated the frequency response that matched at two low-frequency points. Two low-frequency points are desired to match the frequency response, and a criterion has been provided for such two frequency points which do not require complex frequency response analysis. The method does not require an approximate of the delay term for the answer of linear algebraic equations. This method is so mathematically simple and has a very small computational load.

Massimiliano Veronesi et al. [102] in their paper proposed an algorithm for the load disturbance rejection closed-loop response with other performance evaluation of a PID controller and the returning of the parameters in the case when the achieved response is not adequate. Also, the techniques proposed merely by the automatic tuning of a set-point filter with an address the following task. This technique is quite robust concerning measurement noise due to uses of integral computations, so it does not depend on the initial PID settings. Performance indices are given with PID parameters returning formulae for both PI and PID control. In addition to a set-point filter is automatically tuned to improve the performance of set-point.The effectiveness of the methodology has been shown by simulation results.

Saxena Nikita et al. [103] proposed continuous cycling method which was improved to tune the proportional-integral-derivative (PID) controllers for systems which were unstable. In this work, method concerns the determination of the PID controller settings by solving the phase angle criterion and the magnitude criterion for the system. In their study of the proposed method is applicable for simulating (a) second-order system with one pole which is unstable (b) a model of a bioreactor which is nonlinear. This method is extended to automate the improved continuous cycling method for the relay tuning method. The controller setting significantly enhances the robust performance and performance indices (ITAE) for both the servo and the regulatory control. The proposed method is compared to other reported methods as proposed by Jeng and Fu, which are based on the ultimate cycle.

Zhuo Yun Nie et al. [104] proposed an analysis and designing of scaling optimal GPM-PID control for control of the liquid level of coke fractionation tower. In this paper, for specified gain and phase margins (GPM) constraints, integral of time absolute error (ITAE) index is minimized, thus the robustness and transient performance both are satisfied. The desires of gain and phase margins are innovatively formulated by areal part and imaginary part constraints (RPC & IPC). These arrangements of constraints are fundamentally related to three parameters and decoupling of staying four unknowns, as well as three controller parameters and the gain margin, in the nonlinear and coupled characteristic equation concurrently. Finally, this method demonstrates that the proposed method gives a better disturbance rejection and robust tracking performances than some PID tuning methods that are widely used.

G. Ellis [105] proposed PID controller method based on a trial-error method which is based on low and high-frequency zone. Commonly the output response to a square or step input can be taken as the value of performance criteria regarding overshoot, peak value, and rise time for the quality of the controller. The disadvantage is that it takes much time. Satisfactory performance is not guaranteed and little information about the robustness of the system.

2.3 Research Gap

After having read a review of the literature, the following different theoretical views that have applied in previous studies on PID controller tuning.

- Most of the conventional methods work satisfactorily. However, they are laborious and time- consuming.
- For optimum tuning, there is a need to develop a highly accurate mathematical model and its validation with real measurement data.
- Present methods are not very efficient and take a long time for convergence.
- Current methods are not robust in the presence of abnormalities such as model-plant-mismatch and valve stiction, noise and saturation.
- To estimate the performance of the controller for different time response and frequency response specification which used simultaneously.
- Most of the work has done in exclusive either in the time domain or frequency domain.

2.4 Problem Statement

In the sugar factory, the centrifugal machine is determining the quality of sugar to separate the molasses and sugar crystal in this PID loop; there is a requirement of the 105 -110 degree C water temperature. One PID controller of M/s Forbes Marshall makes installed to maintain temperature via Steam flow rate, temperature sensor, and linear control valve.

The objective of work is to suggest a PID controller tuning algorithm for centrifugal machine temperature system to the desired temperature value through overcoming the effects of the constrained. For optimum tuning, there is a need to develop a highly accurate mathematical model and its validation with real measurement data. Some of the tuning strategies have considered objectives as a criterion for their tuning algorithm. In this study, select a different algorithm for performance and robustness against constrained.

A simulation study proposed for first, second order systems with the delay time for better dynamic response. The response based on control objectives such as % of overshoot, settling time, time & frequency domain performance indices.

2.5 Summary

The following chapter describes the proposed contribution on PID controller tuning of the developed model using different techniques for performance against robustness discussed.

Each control system designed for a particular application using some of the performance criteria. The required specifications decided in the form of a balanced transfer function designated as the reference model. For a process where performance is not satisfactory, such a controller designed that performance of the whole system matches with the reference model.

It showed that the controller design methods discussed in this literature review are useful for a wide range of linear time-invariant systems such as lower order, higher-order and time delay oscillatory systems. Several examples are also simulated by researchers in their literature to verify the pertinence of the methods and also the experimental results. Improved results are shown in previous research work for processes with a variety of dynamics, even including that with low-order and high-order, small dead time and sizeable dead time, and responses of oscillations.

It can conclude that various methods have developed for tuning of PID controllers for the category of systems. However, there is expected to be very few methods available for higher-order a system which produces satisfactory to poor results for some cases. Thus, there is a further need to develop tuning method for PID controllers applied to higher order systems with and without time delay.

In the literature review, an abundant number of approaches used in PID tuning observed again. A short-lived depiction of the technique accompanied by a discussion of the work done in tuning and self-tuning of PID controller using a different method. If some comparative exploration was carried out, it mentioned, and the results of the comparison further expounded. A complete comparative study of all the techniques verified concurrently under different conditions. Still needs to be steered to estimate the relative performance of unique methods on a common platform.

CHAPTER - 3

MODELING AND IDENTIFICATION

In this chapter, the basic model of a centrifugal machine temperature system has discussed. Modeling and identification method to estimate the parameters of a model proposed for better performance requirements.

3.1 Overview

In the process industry, the parameters of models are in form of linear differential equations are well known and constant and are conventionally used in control system designs is achieved by a step response. The first step is to identify a model of the real process. It attained by applying a step input to the process and logging the data via a data acquisition, filtering of the data is carried out to remove high-frequency noise by MATLAB. Collected data from the plant best fitted to the transfer function model for algorithm polynomial curve fitting.

Once the model structure is characterized, the stride is to pick the correct value for the parameter using the classical method (the reaction curve method) for identification. The reaction curve method is most likely methods used in industry for identifying the dynamic system [for detail refers to chapter1]. For design, a controller, the initial step is to decide a well-ordered mathematical model for a system that has controlled.

System identification techniques are used to identify the nature of the system using the inputs and outputs data which includes building a mathematical model of a dynamic system based on a set of measured stimulus and response data sample. The MATLAB environment simulation gave the better result which is identical to the ideal model of the plant. Identification techniques will discuss in this chapter.

3.2 Case Study of Centrifugal Machine Temperature System

3.2.1 Overview

The centrifugal machine in sugar manufacturing plant plays a significant role in the process of centrifugation to separate the molasses and sugar crystal. Centrifugation process plays an essential role in determining the quality of sugar. Loss of sugar can occur at each cooking station especially on crystallization and centrifugation station so that it can affect the quality of sugar is produced [106]. The Centrifugation process aims to separate massecuites into crystal sugar and molasses by using the centrifugal machine. It's done by adjusting

The massecuite flow rate on the control unit
The steam and water quantities (feed pipe)
The Water flow of the washing system

Figure 3.1: Photograph of the process setup in the sugar mill

Centrifugal machine control system consists of a control valve, heat exchanger (heating element), chamber and thermocouple as shown in Figure 3.1. The centrifugal machine uses the spin motor at the suitable speed which will suppress loss of crystal sugar in the molasses.

In sugar factory, the massecuite going to the centrifugal machine should be at a specific temperature to minimize its viscosity and to avoid overloading of a centrifugal motor. Massecuite cooled in the crystallizer to extract maximum sugar from molasses, but the disadvantage of cooling is massecuite while cooling gets more viscous, sticky & does not flow freely up to the centrifugal machine. The machine also gets uninformed overloaded which gives the need for a heater that raises the temperature of massecuite. The heater should fulfill following things.

The heater design should be such that the massecuite gets heated quickly during its transit time from the pug mill to a centrifugal machine. If not then the problem raised in molasses purity arises.

The heater must have minimum retention time and it should be dimensionally small and compact so that it can installed on the centrifugal machine, below pug mill.

Heating media for the heater should be such that the coefficient of heat transfer should be high so that the massecuite gets heated quickly during transit time.

3.2.2 Description of the Process

Self-generated low-temperature vapors used as heating media in the transient heater. Input energy required to run the heater is only about 20 kg at 100 PSIG steam per hour. Heat energy of steam transferred to distilled water (Condensate) filled in the part of heater called ‘Vaporizer'. Condensate in the vaporizer gets evaporated and vapors produced. These vapors used as heating media in the Transient Heater which circulates through S.S. tubes and gets condensed again after letting out the latent heat to the massecuite. Condensate flows back into the vaporizer, and still vapors produced which are kept under vacuum to generate vapors at low temperature and heater becomes self-regulating of maintenance free.

Here regulating the steam supply to the vaporizer controls the vapor temperature. A temperature of massecuite before entry to the centrifugal machines shall control by controlling the flow of hot water to the transient heaters. The flow of massecuite to centrifugal machine shall also be controlled based on the load on the machine.

In Figure 3.2, feedback control controls the controlled variable using the negative feedback and taking corrective action via controller and changing the manipulating variable consequently. The controller provides the controlling action to the final control element via the actuator. The sensor senses the process output and gives the signal to the controller by feedback.

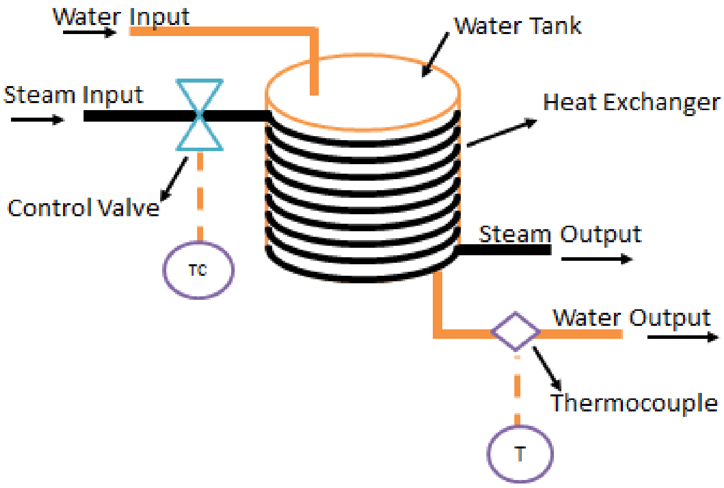


Figure 3.2: Schematic representation of the process installed in the mill

A single element control loop, receive water from the condensate of the steam in the centrifugal machine for filtering sugar and molasses these are a requirement of the 105 -110 °C water temperature.

Triveni sugar plant has installed one PID controller of M/s Forbes Marshall make, the temperature of the required water taken through temperature sensor. The linear control valve is used to limit the flow of steam through the valve so that temperature of the water is maintained as per requirement. Heat exchanger steam flow in spiral tube form around the water tank, the temperature of the water maintained. In the centrifugal machine, there is a requirement of water temperature to be around 105-110^{o}C for filtering sugar and molasses.

Strejc method used to identify the centrifugal system, which determines the response of the plant in order to get the model plant based upon the transient system response. Method requires precision to draw a tangent to the transient response of the transfer function of the system parameter [6].

MATLAB software has completed the designing and implementation of the system loops. The reaction curve method used as a model reduction method with the intention to attain low-order models for design purposes. Model reduction methods are legitimate for high-order processes to achieve simple models for design purposes. The PID-DESIGN software could be a very beneficial tool for simple step-response primarily based identification of a controlled process.

3.3 Mathematical Model of the System

In this work, the considered model consists of single element control for maintaining the temperature of the water required by the centrifugal machines for performing the filtering process.

The control loop considered here has three essential components,

a) Heat Exchanger, b) Control Valve, and, c) Thermocouple.

3.3.1 Dynamics of Heat Exchanger

Heat exchangers are one of the imperial components in process control where we have to transfer the heat from hot fluid to a cooler liquid. The transfer of heat is through the thermal transfer, and heat exchangers can operate over broad range of pressure and temperature ranges. They are typically composed of a jacket called "shell" which is surrounded by a bundle of tubes in a spiral formation. The hot fluid (in this case steam) flows inside the tube and the liquid to be cooled inside the shell [9-11].

The water flows through an inlet with a constant flow velocity of "v" in the spiral tubes jacketing the shell. The temperature of the liquid by the amount of steam as a function of time. The heat-transference coefficient governs the transference of heat from steam (h_o) to liquid (h_i). The thermal resistance of the metal walls is neglected. The primary objective here is to derive the transfer function relating the outlet liquid temperature T(L, t) to inlet liquid temperature T(L, 0) and the steam temperature $T_v(t)$ [107].

In the proposed work, inject a step input voltage V to the valve and record the impact on the tank temperature T over time to fit the model data and apply the reaction curve method.

Mathematically, the transfer function of reaction curve is:

$$G\left(s\right)=\frac{e^{-\theta * s}}{\tau \cdot s+1} \tag{3.1}$$

The measured response is shown below in normalized scale:

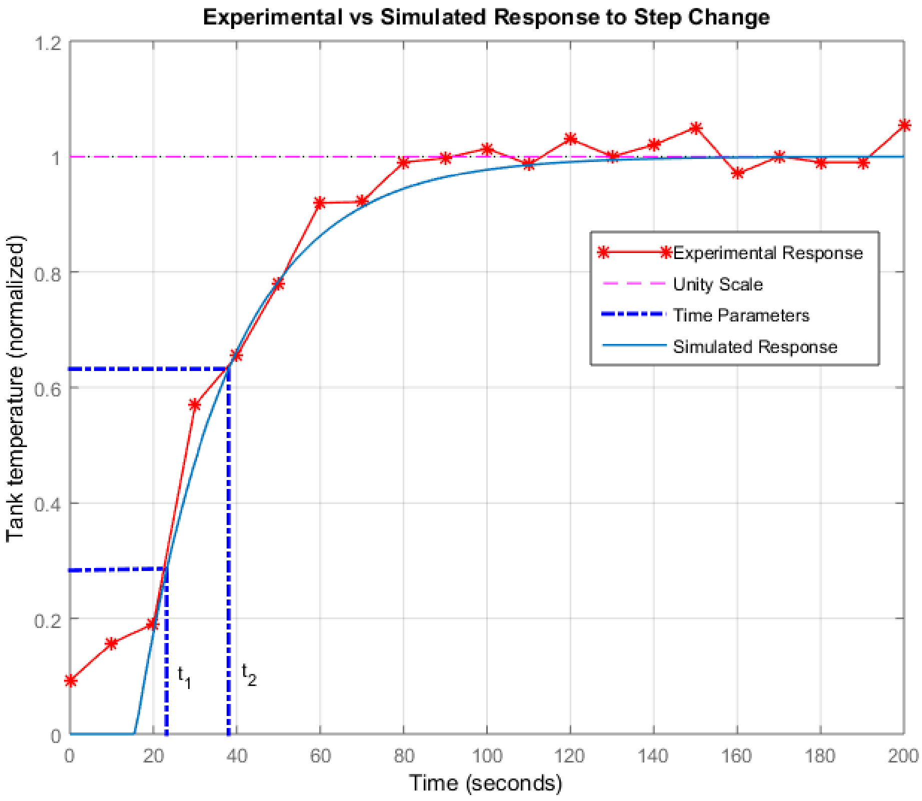


Figure 3.3: Experimental v/s Simulated Response in Step Change

t_1= time in which response attain 28.3% of its final response and t_2= time in which response attain 63.2% of its final response. By using these values estimate the time constant τ and dead time θ for the heating system

$$\tau = \frac{3}{2}(t_2 - t_1), \tag{3.2}$$

$$\theta = t_2 - \tau \tag{3.3}$$

In our proposed work t_1 = 23.15 sec and t_2 = 38.05 sec [from curve fitting graph]

Calculating the value of τ and θ , we get the value of transfer function as:

$$G(s) = \frac{1}{22.35s+1} e^{-15.7s} \tag{3.4}$$

3.3.2 Dynamics of Control Valve

The control valve controls the flow of steam which carried out by the PID controller used. The PID controller according to the set point adjusts the valve. The M/s Pneucon made linear pneumatic control valve is used in the factory setup. In pneumatic valves, the position of the stem determines the size of the opening of the valve for flow and thus consequently the flow rate. The position of the stem depends on the balancing of the force exerted by the compression of the top of the diaphragm; the force applies by spring attached to the stem, diaphragm, and frictional force [107,119].

Mathematically,
Force applies by compressed air: P.A
Force applies by spring: K.x
Frictional Force: C. $\frac{dx}{dt}$

Where: A= Area of the diaphragm, P= Pressure acting on the diaphragm, x= Displacement, K= Hook's constant, C= frictional coefficient between the stem and packing.

The maximum capacity of control valve is 2.14 Kg/sec of the steam, with linear mode characteristics and its time constant of 3 sec. The standard pressure is 3-15 psi for valve and a standard current signal is 4-20 mA.

Control valve gain = $\frac{2.14}{15-3}$=0.178

Control valve Transfer function = $\frac{0.178}{3s+1}$

I/P converter has a constant gain= $\frac{15-3}{20-4}$=0.75

Including the gain of the I/P converter, complete transfer function of control valve = $\frac{0.133}{3s+1}$

Thus the dynamics of the pneumatic valve can be given as:

$$G_{valve}(s)=\frac{x(s)}{P(s)}=\frac{A/K}{\tau\cdot s+1}=\frac{0.133}{3\cdot s+1} \tag{3.5}$$

Where
$K = P.A/x$

3.3.3 Transfer function of the sensor

In the system, thermocouple with a range of –100 to 800°C used which has calibrated to give the measurement of 0.04 mV for 1°C, which senses the temperature of the water, and is used in feedback of the closed control loop. Thus the thermocouple has a gain of 0.04mV/°C. [107,119]

Thus the transfer function for the sensor is:

$$G_{sensor}\left(s\right)=\frac{0.04}{2\cdot s+1} \tag{3.6}$$

In this work, we have not considered transfer function of a control valve and sensor in this loop. Other than in the design of the robust controller (Chapter 5), we have considered all process abnormalities and nonlinearities present in the process which not founded normally in the design process. It may include valve stiction and saturation, model uncertainty, and measurement noise based on the definition.

3.4 Identification from Step Response

The modeling of the plant is of great importance for its tuning. The controller tuning parameters are intensely dependent on the degree of accuracy of the plant model of the real system. Fundamentally, it is feasible to approximate the very-high-order authentic input-output mathematical model, complex dynamic plant with first or second order system combined with a delay time [108]. Thus a typical practice followed by engineers in industries for the control design and analysis is identical to model the dynamics of the plant close to the operating point by simpler models such as FOPTD.

Identification of step response belongs to deterministic methods. In this method, if a transfer function of the plant is unknown, the PID design software enables to identify the plant from its step response. The strejc method [108,109] is used for identification for the aperiodic step response or damped periodic step response.

$$G(s)=\frac{K}{(\tau s+1)^{n}}e^{-\theta s} \tag{3.7}$$

$$G(s) = \frac{K}{\tau^2 s^2 + 2\xi\tau s + 1} e^{-\theta s} \tag{3.8}$$

Here n is the order of the system, K is the gain, τ is the time constant, ξ is the damping factor and θ represents the delay time.

For identification, identify the data measured and recorded step response obtained from controlled process directly. If step–response data is noisy, then PID software permits to filtration; enabling to identify process model with required properties of the transfer function, e.g. the order n, to make the process model more tractable or to increase the scale of suitable PID controller tuning algorithms. The Butterworth low-pass 3rd order filter with filter frequency has been applied to reduce the noise of data.

The step response of identified transfer function can be modified by changing the slope of its tangent [108]. The difference between the original step response and the step response obtained by the identification using the modified position of a tangent is directly displayed as a red area in the window **(**Figure3.6**).** This ability of the software enables to check the quality of identification visually. In software window, the calculated value of identification error is also shown.

If the controlled process has been identified using the strejc method, the tangent to the step response depicted and its equation is given (Fig. 3.4).

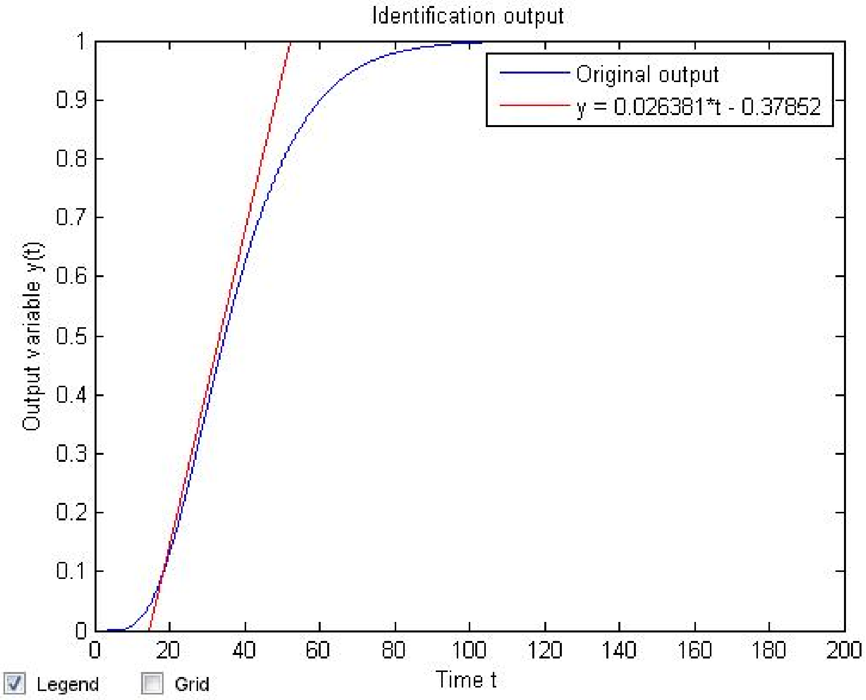


Figure 3.4: Step response of identified process

In the (Figure 3.5) the step response of identified transfer function can be modified by changing the slope of its tangent [108,109].

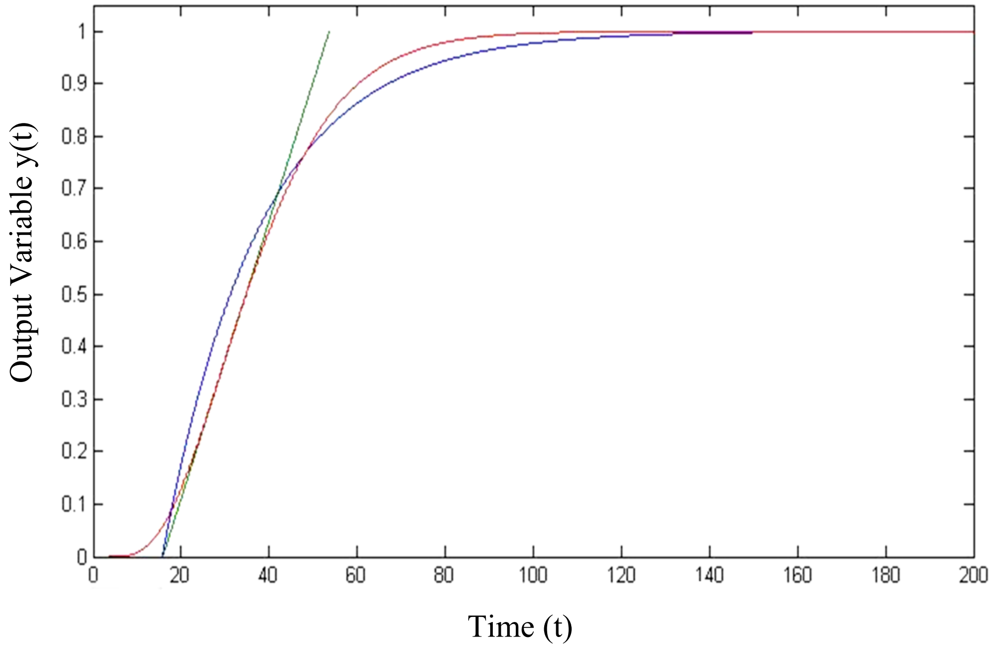


Figure 3.5: Step-response-based Identification Tuning

(based on changing the slope of tangent)

The difference between the original step response and the step response obtained by the identification using the modified location of a tangent is directly displayed as a red area in the window (Figure 3.6). This ability of the PID design software enables the user to check the quality of identification more visually. In this window, it is also shown the calculated value of the square error of the original and identified step responses for analytical evaluation of quality. The background color changes according to the value of square error. In case the value of square error has increased, a red color shown. In fact, the identification precision has increased, the green color displayed (Fig. 3.7). This process is called identification tuning.

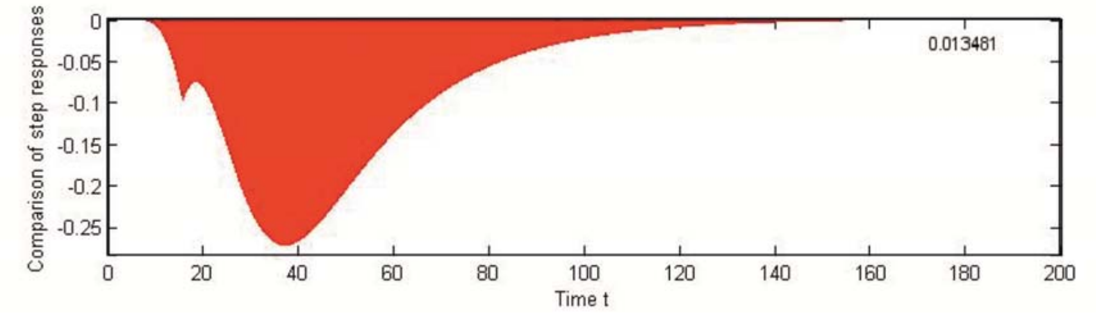


Figure 3.6: Identification quality check before identification tuning

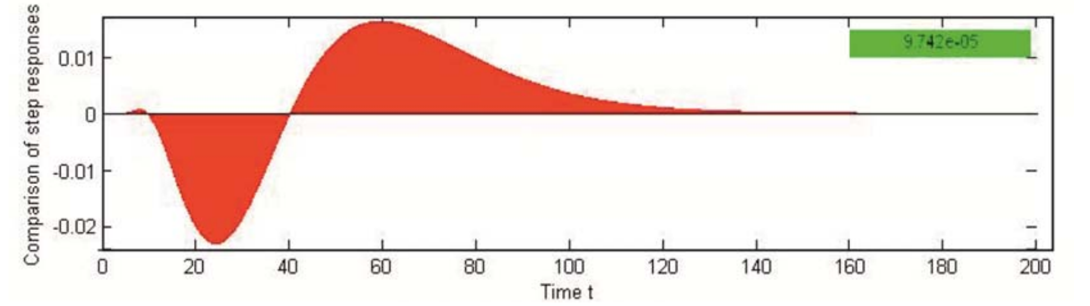


Figure 3.7: Identification quality check after identification tuning

[Identification error =0]

Transfer function calculated by strejc method

Table 3.1: Transfer function calculated by PID design

n	2	8
K	0.99974	0.99974
τ	8.2245	3.1065
θ	13.3757	1.3519

After identification tuning, Plant equation is

$$G(s) = \frac{0.99974}{(8.2245s+1)^2} e^{-13.37s} \text{ for order 2} \tag{3.9}$$

After identification tuning, Plant equation is

$$G(s) = \frac{0.9997}{67.64s^2 + 16.45s + 1} e^{-13.4s} \text{ for order 2} \tag{3.10}$$

For 8th Order, Plant equation

$$G(s) = \frac{0.99974}{(3.1065s+1)^8} e^{-1.3519s} \tag{3.11}$$

It can be useful in the case, while the user desires to decide whether it is higher to apply the 1st order or the better order transfer function of the controlled process (Figure 3.8).

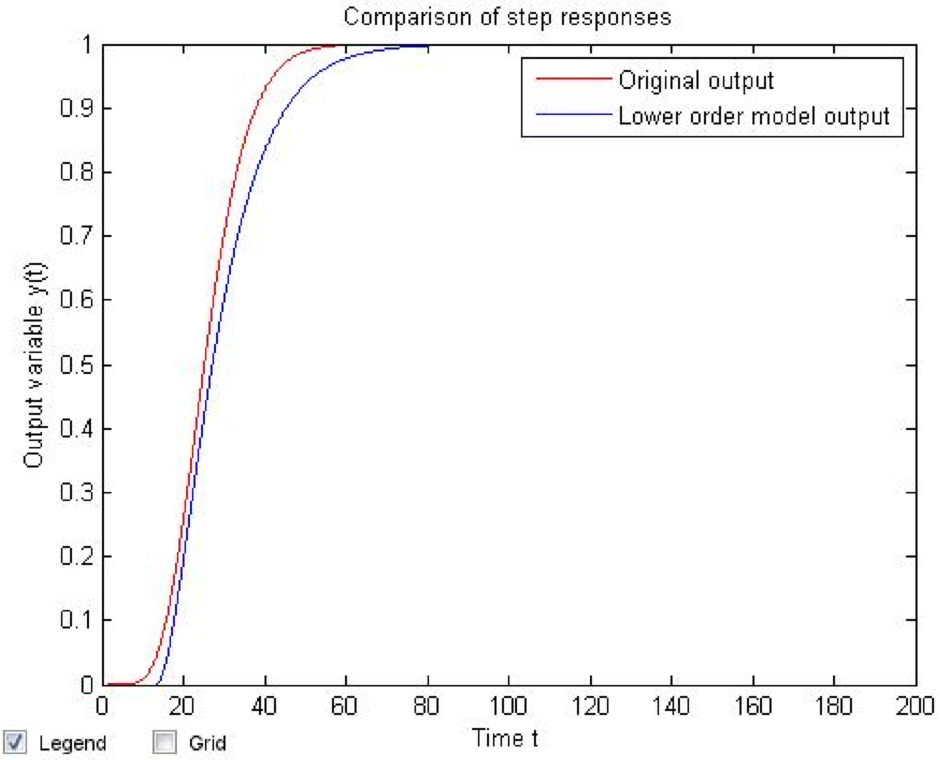


Figure 3.8: Comparison of the 2nd and the 8th order transfer functions step response

Comparison of the original and identification output step response shown in figure 3.9

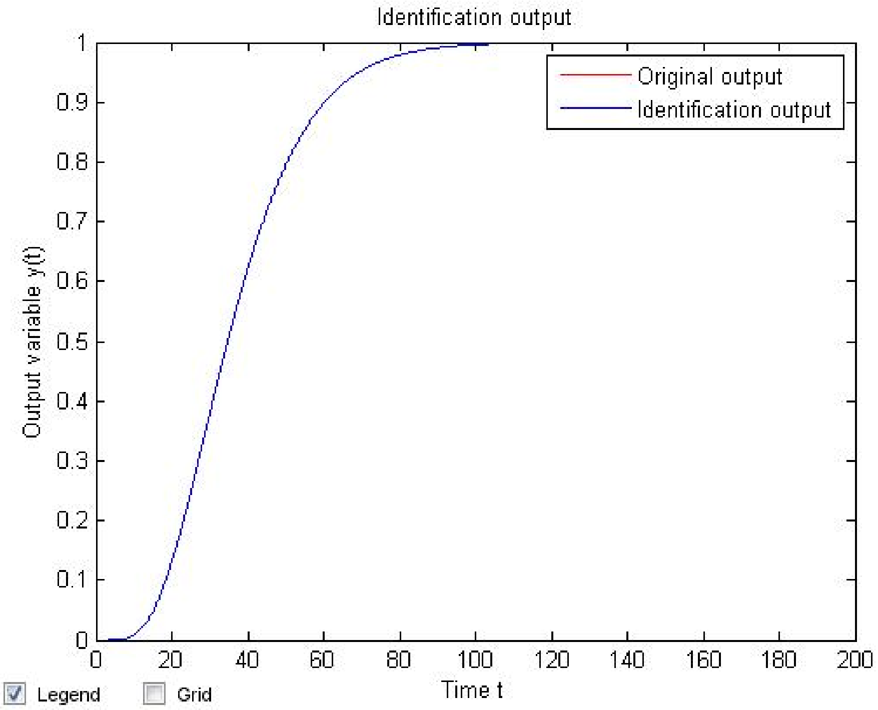


Figure 3.9: Comparison of the Original and Identification Output Step Response

3.5 System Identification

3.5.1 Overview

Models may be calculated using either a theoretical method or an experimental approach based totally on observed data from the plant. Identification approach deals with the difficulty of building a mathematical model of dynamic systems which is based on recorded data from the plant and is as a consequence an experimental modeling approach popular these days. A discrete-time model is received in classical identification. Such models may be beneficial for simulation and prediction or for a design of manipulating systems. [112]

The reaction curve method is sufficient to obtain the model of controller design. This simple method for experimental design. For the most accurate model, the system identification approaches useful for starting values of parameter iteration [112].

PC-based fitting has numerous advantages compared to manual fitting. It could offer very detailed and accurate models and it may be faster and much less steeply-priced without any particular input signal. In this method, models fitting is primarily based on measured data and it transformed into an optimization problem. It evolves numerical techniques for the minimal search. Simulators are based on the principle of analogy and their primary functions are:

- To attain consideration of the system
- System output prediction in future
- Systems design and testing
- Development of optimization
- Experimenting with a model in place of real system
- Model parameter estimation from experiments

For estimating physical parameters the steps of model structure are as follows:

- The system is excited by a suitable input signal, and corresponding sequences of input and output signal values measured and stored in a computer.
- The system simulated work by the PC with having the presumption that initial values of the unknown parameters. The simulation model exhibited by the sampled input sequence.
- The model parameters adjusted until the model output error is achieved to minimum.

System identification can be categorized into two types based on their technique:

- Parametric model identification
- Nonparametric model identification

Parametric model identification gives the entire model explanation which virtually expressed within the physical dynamics of the plant. In this model identification, a linear model may also encompass a transfer function in the type of weighting function or frequency response. Different model structures like, Box-Jenkins (BJ), Output-error (OE), Auto-Regressive Moving Average Exogenous Model (ARMAX), Auto-Regressive Exogenous (ARX), and State Space Model used in parametric identification which might be reviewed in modeling literature [111]. The other types of nonparametric identification techniques have the simple implementation but are comparatively less accurate. For more comprehensive information about the overview of different model refer to **Appendix A**.

3.5.2 Methodology

Identification tool has used to decide mathematical model for a actual measurement data, taken directly from the machine. It provides MATLAB simulation with several iteration facilities to pick up the best model for minimum model fitness error (FPE) by way of assessment and confirmation.

First load input-output data with sampling time and initializes a MATLAB workspace input–output signal.

Figure 3.10 shows the time domain representation of experimental data; output temperature and input voltage is plotted with respect to sampling time period is in sec. System used OE, BJ, ARMAX and ARX model structures to find the optimum model for a proposed system.

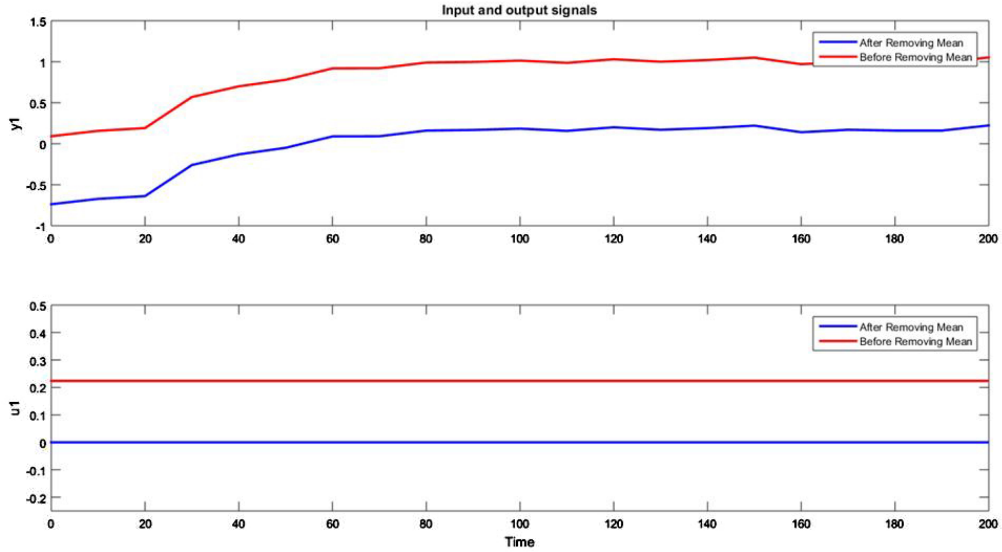


Figure 3.10: Real measurement data before and after removing mean

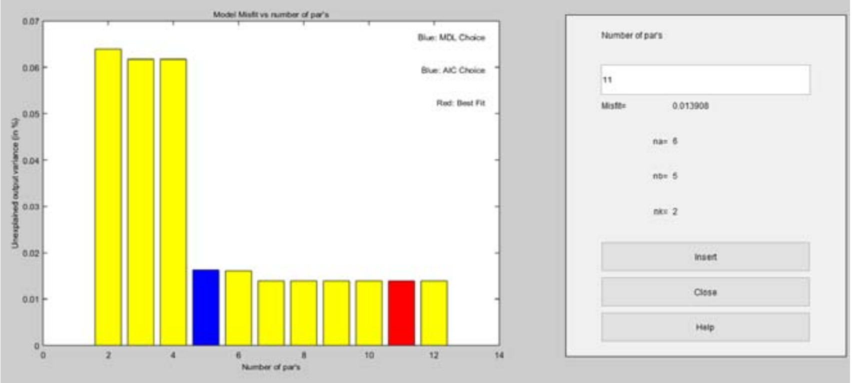
A parametric model gives the complete model description of the physical dynamics of the plant. While stochastic models are taken into consideration, a random aspect white noise will be assumed.

Overview of different type of system models discussed in **Appendix-A**

3.5.3 Result and Discussion

Auto- Regressive Model (ARX)

In existing models, pick and calculate ARX model with suitable delay and order. The structure entirely defined by the n_a, n_b, and n_k integers. ARX model a function of number of parameters which may calculated for various combinations of A (z) and B (z) polynomial. Figure 3.11 shows the optimum fit for its verification data in ARX models. When the order of A (z) and B (z) polynomials is picked up six and five, best estimation of the model is achieved.



Number of par's

11

Misfit= 0.013908

na= 6

nb= 5

nk= 2

Figure 3.11: Best fit for its verification data for ARX models

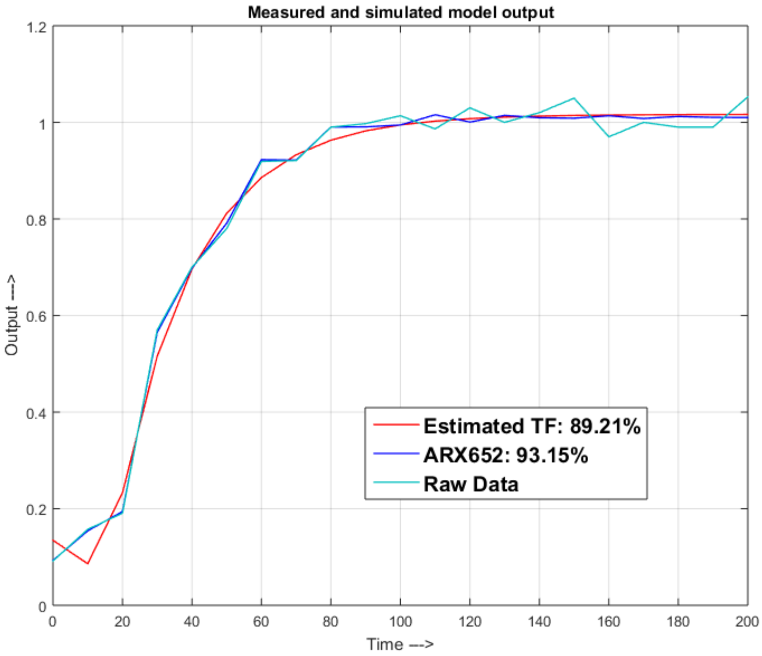


Figure 3.12: Best fit % of ARX model

Figure 3.12 shows best fit model for its validation data. For this we get a possible model fit up to 95.95% best-fit prediction focus and 93.15% best-fit graphical focus.

Figure 3.13 indicates the auto-correlation and cross-correlation of residual analysis for ARX model. The performance of residual analysis also shows model reliability. Residual analysis has been performed to quantify the error between the expect output and measured output based on a predicted model from the validation data set. The optimum value of the fit prediction error (FPE) and mean square error (MSE) is 0.0004636, 0.0003353 observed respectively.

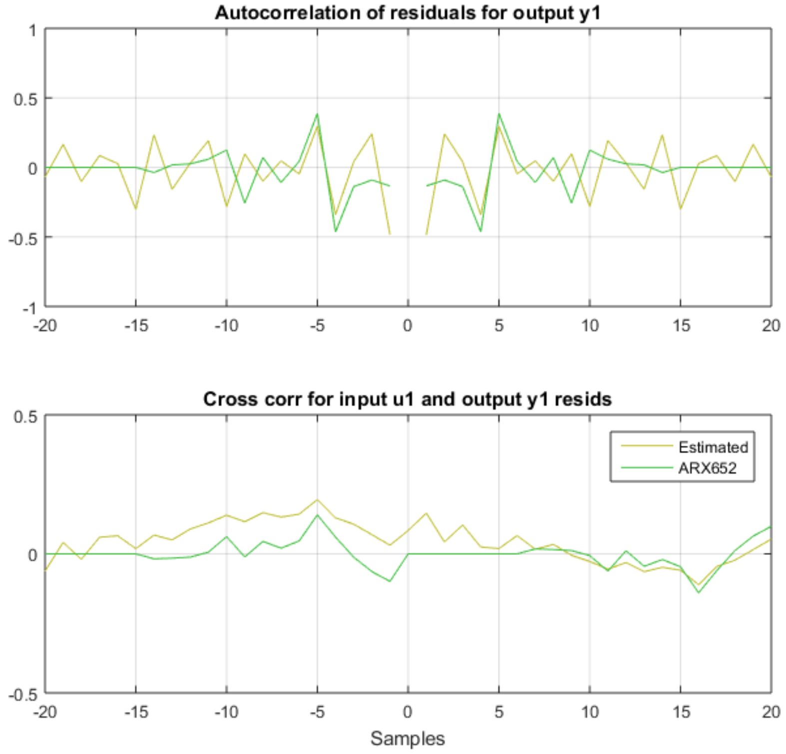


Figure 3.13: Auto and Cross-correlation of residual analysis for ARX model

Residual analysis tests have model structures, which includes the output errors structure and identity techniques. In the residual analysis, residuals used to estimate the identity of the identified model and the employed input data [118]. If possible the residuals must be white and not dependent of the input signals. The residuals can test through numerous approaches:

- Autocorrelation of the residuals,
- Cross-correlation amongst the residuals and the input,
- Residual zero distribution.

The estimated mathematical ARX model with A(z) and B(z) polynomials for a system can be written as;

Discrete-time ARX model: A(z)y(t) = B(z)u(t) + e(t)

A(z) = 1+0.1274 z^-1 - 0.1467 z^-2 - 0.1808 z^-3 + 0.0607 z^-4 - 0.1159 z^-5 +0.06577 z^-6

B(z) = 3.659 z^-2

Parameterization:

Polynomial orders: na=6 nb=5 nk=2

Number of free coefficients: 11

Auto-Regressive Moving Average Exogenous Model (ARMAX)

Likewise, ARMAX model picks up and calculates the same with suitable delay and order. In comparison with ARX model, this model comprises of flexibility to the disturbance separately. When the order of A(z), B(z) and C(z) polynomials picked five, five, five, best estimation of the model is attained.

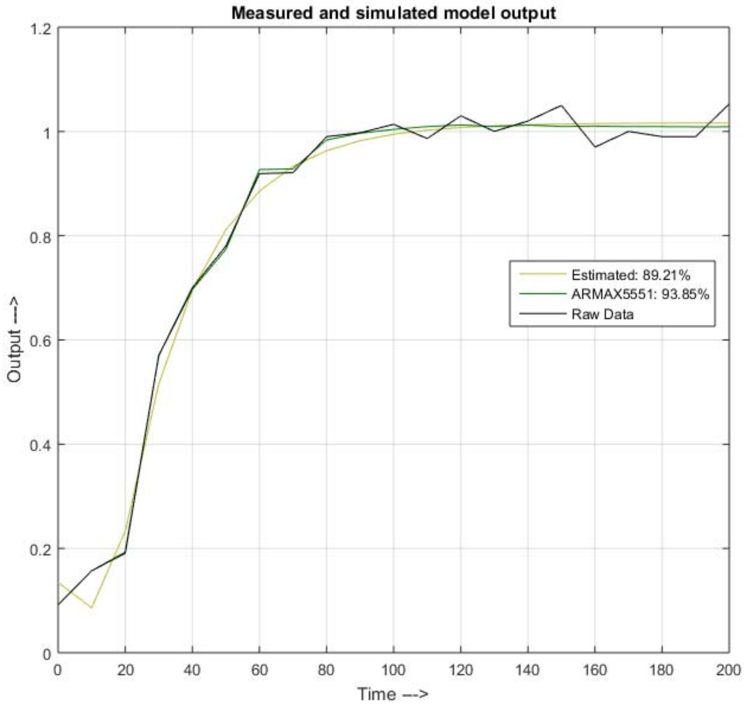


Figure 3.14: Best Fit % of ARMAX model

Figure 3.14 show model fit for best validation data, for the possible model fit up to 95.35% best-fit prediction focus and 93.85% best-fit graphical focus.

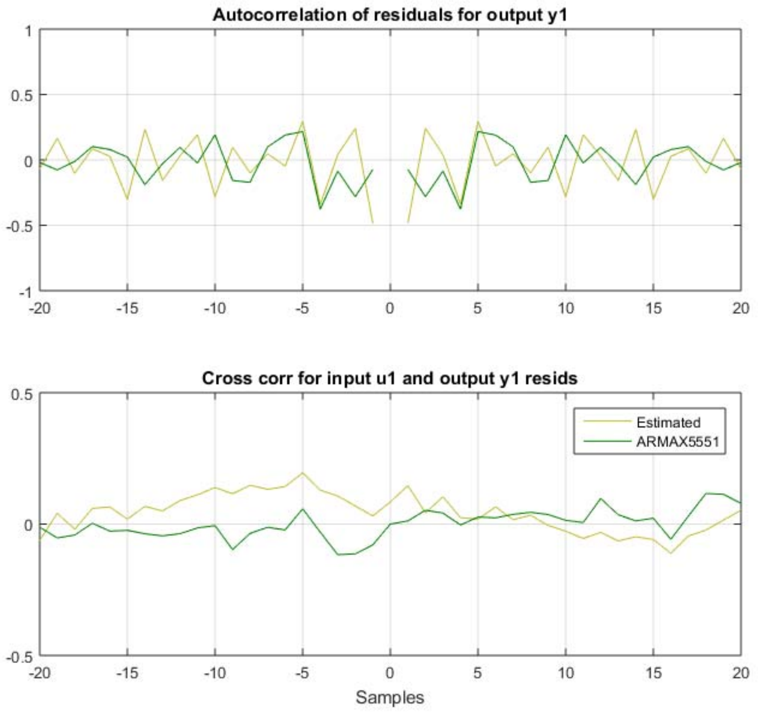


Figure 3.15: Auto and cross-correlation of residual analysis for ARMAX model

The estimated mathematical ARX model for a system with the A(z) and B(z) polynomials can be written as;

Discrete-time ARMAX model: A(z)y(t) = B(z)u(t) + C(z)e(t)

A(z) = 1 + 0.3653 z^-1 - 0.5178 z^-2 - 0.3325 z^-3 + 0.05459 z^-4 + 0.1117 z^-5

B(z) = 0.6141 z^-1 + 0.6141 z^-2 + 0.6141 z^-3 + 0.6141 z^-4 + 0.6141 z^-5

C(z) = 1 + 0.4209 z^-1 + 0.03169 z^-2 - 0.2634 z^-3 - 0.9262 z^-4 - 0.263 z^-5

Parameterization:

Polynomial orders: na=5 nb=5 nc=5 nk=1

Number of free coefficients: 15

It can be concluded here, that ARMAX model provides a better best- fit result in prediction focus amongst all model structures.

Box-Jenkins (BJ) Model

Similarly, this model has selected for the system. Figure 3.16, shows best-fit % between measured and simulated model output. After choosing B(z), C(z), F(z) and D(z) polynomials order value up to 3, 3, 3, 1 respectively, to get a possible model fit up to 94.24% best-fit prediction focus and 93.06% best-fit graphical focus.

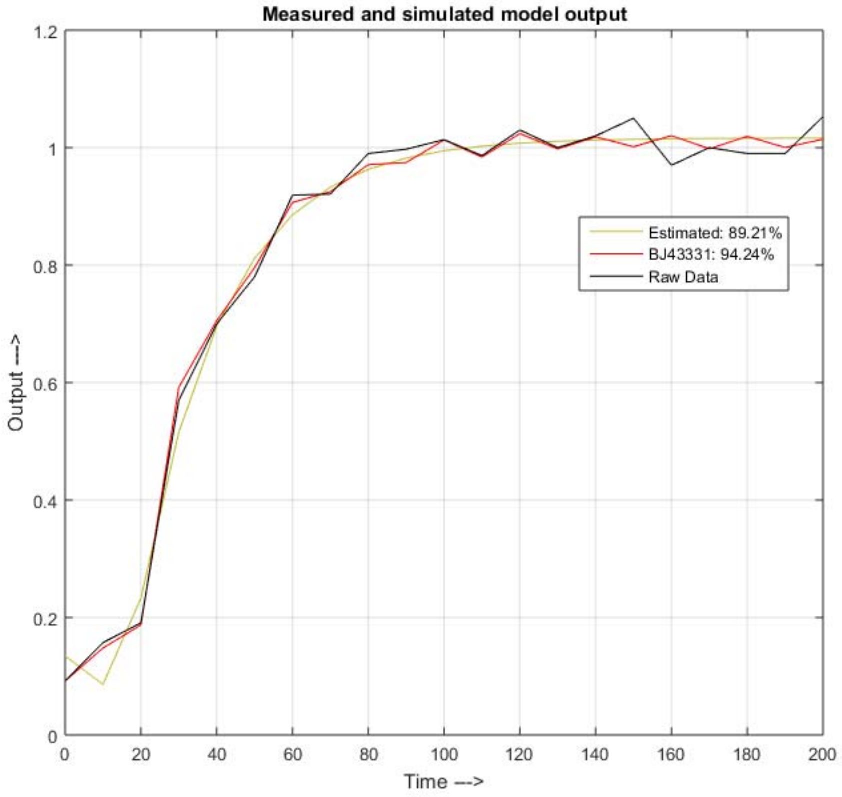


Figure 3.16: Best fit % of BJ Model

Figure 3.17, depicts the autocorrelation and cross-correlation analysis of residual for BJ model. The value of the FPE and MSE is 0.0009716, 0.0003037 respectively which shows the model’s capability of validating actual data.

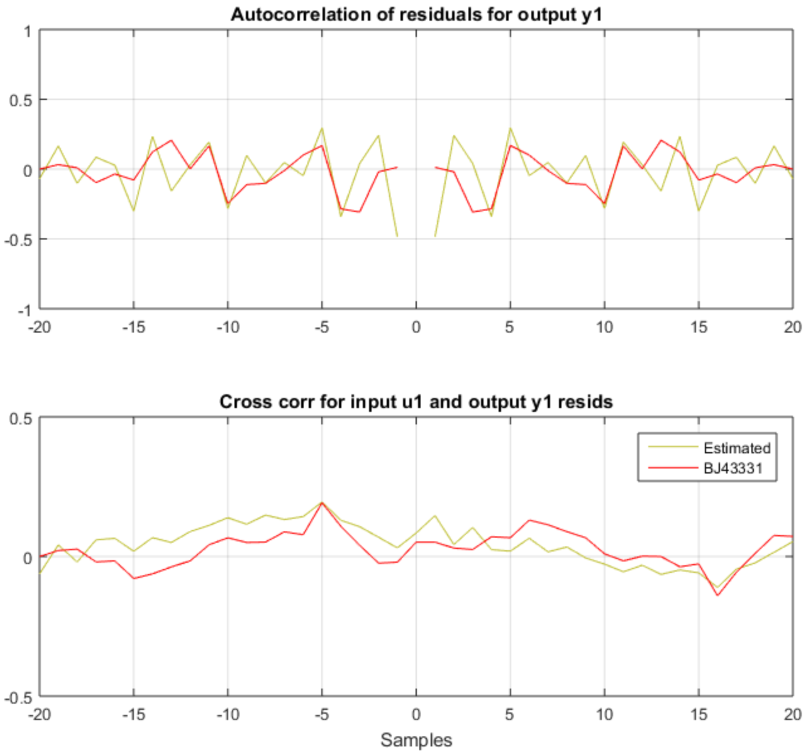


Figure 3.17: Co-relation Analysis of BJ Model

The estimated mathematical BJ model in the form of polynomial may be written as;

Discrete-time BJ model: y(t) = [B(z)/F(z)]u(t) + [C(z)/D(z)]e(t)

B(z) = 0.9295 z^-1 + 0.9295 z^-2 + 0.9295 z^-3 + 0.9295 z^-4

C(z) = 1 - 0.1515 z^-1 + 0.4091 z^-2 - 0.6537 z^-3

D(z) = 1 + 0.1272 z^-1 + 0.05812 z^-2 - 0.5359 z^-3

F(z) = 1 + 0.7434 z^-1 - 0.5591 z^-2 - 0.3566 z^-3

Parameterization:

Polynomial orders: nb=4   nc=3   nd=3   nf=3   nk=1

Number of free coefficients: 13

OE Model

Finally, OE model has selected for the system. Figure 3.18, shows best-fit % between measured and simulated model output. It offers the best possible model fit up to 94.01% best fit prediction focus, after choosing B(z), f(z) polynomials of an order up to 5, 5 respectively.

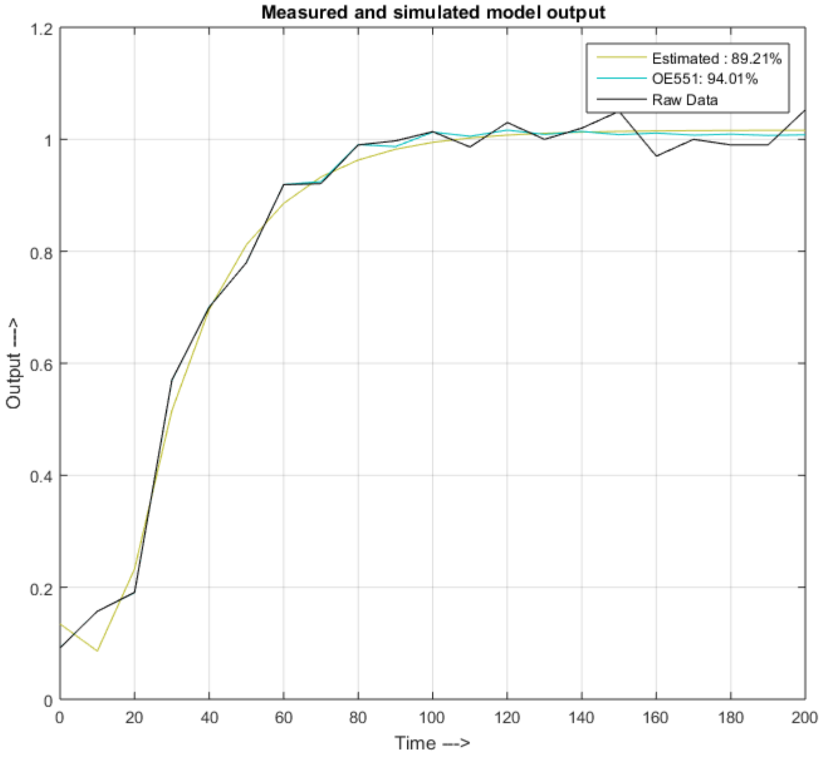


Figure 3.18: Best Fit % of OE Mode

Figure 3.19, depicts the autocorrelation and cross-correlation residual analysis for OE model structure. The value of the FPE and MSE is 0.0009717, 0.0003291 respectively and shows the model's capability of validating actual data.

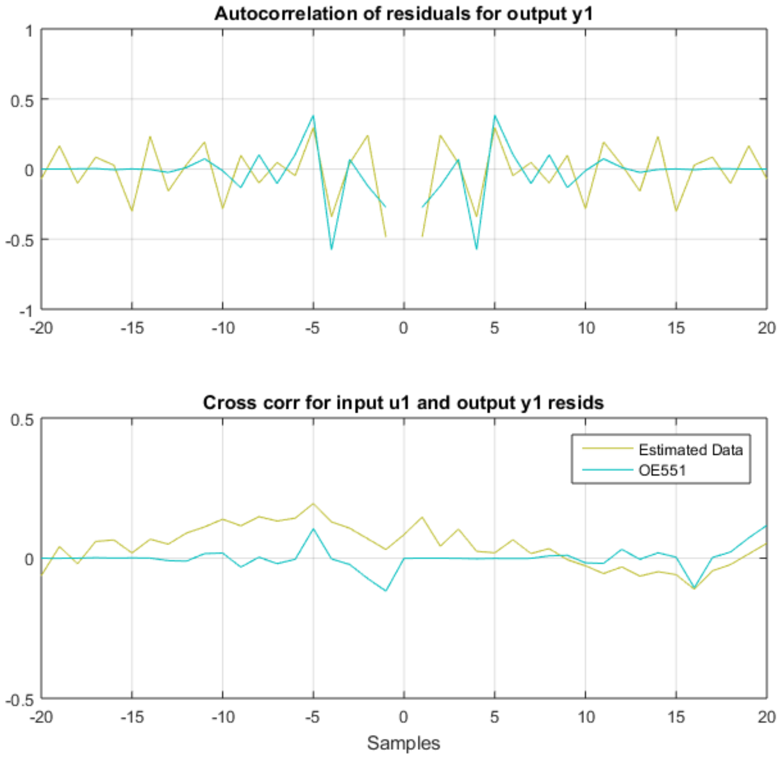


Figure 3.19: Co-relation analysis of OE model

The estimated mathematical OE model in the form of polynomial may be written as;

Discrete-time OE model: y(t) = [B(z)/F(z)]u(t) + e(t)

B(z) = 0.4589 z^-1 + 0.4589 z^-2 + 0.4589 z^-3 + 0.4589 z^-4 + 0.4589 z^-5

F(z) = 1 + 0.2108 z^-1 - 0.708 z^-2 - 0.1923 z^-3 + 0.1164 z^-4 + 0.08299 z^-5

Parameterization:

Polynomial orders: nb=5,nf=5, nk=1

Number of free coefficients: 10

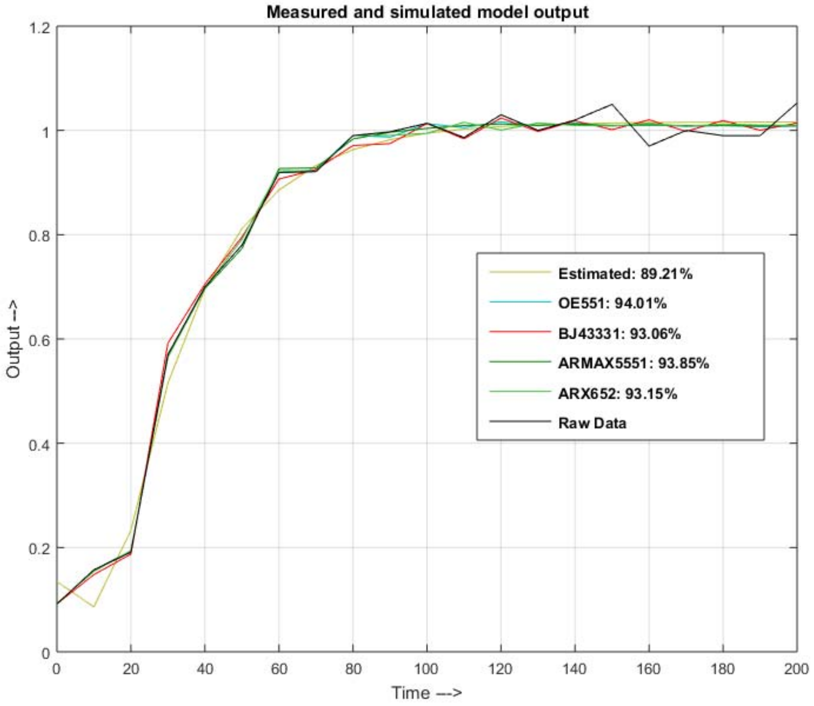


Figure 3.20: Best fit % for all Model

Figure 3.20 and 3.21 with Table 3.2 encapsulate model estimation and validation comparative best results amongst all ARX, ARMAX, BJ and OE model structures. It is an essential requirement to select the best model for a proposed system by analyzing and moderator its performance parameters. It is found that each model offers the best fit as much 93.06% -95.35% respectively with low FPE and MSE. Whereas, ARMAX model has an inclination to validate model fit up to 95.35% in addition to provide low FPE and MSE. Whereas, ARMAX model has an inclination to validate model fit up to 95.35% in addition to provide low FPE and MSE.

Table 3.2: Comparative result for Model Estimation and validation

Models	FPE	MSE	Best Fit Prediction Focus	Best Fit Graphical Focus
TF	0.001165	0.0008532	90.35%	89.21%
ARX652	0.0004636	0.0003353	93.95%	93.15%
ARMAX5551	0.0006503	0.000198	95.35%	93.85%
BJ43331	0.0009716	0.0003037	94.24%	93.06%
OE551	0.0009717	0.0003291	94.01%	94.01%

It has additionally been observed that each model structures exceeded validation test below residual analysis

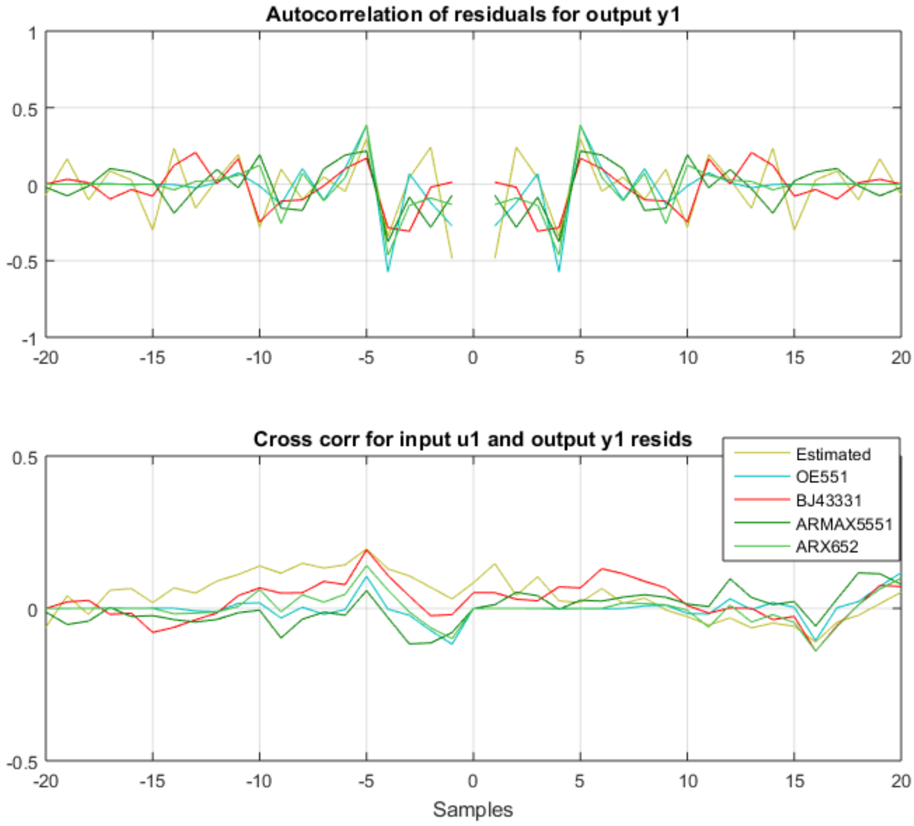


Figure 3.21: Co-relation analysis for all models

It is concluded that almost all model structures have less FPE and MSE as well. However, there is a tradeoff a number of the best % of model fit and system order.

The poles and zeros are properties of the transfer function, and therefore of the differential equation describing in the input-output system dynamics. Together with the gain constant K they completely characterize the differential equation, and provide a complete description of the system. The pole-zero plot of a system contains sufficient information to define the frequency response except for an arbitrary gain constant. It is often enough to find out the shape of the magnitude Bode plot without knowing the absolute gain. The method allows the magnitude plot to be sketched by inspection, without drawing the individual component curves. The method based on that the overall magnitude curve undergoes a change in slope at each break frequency. Any poles or zeros at the origin cannot be plotted on the Bode plot, because they are effectively to the left of all finite break frequencies.

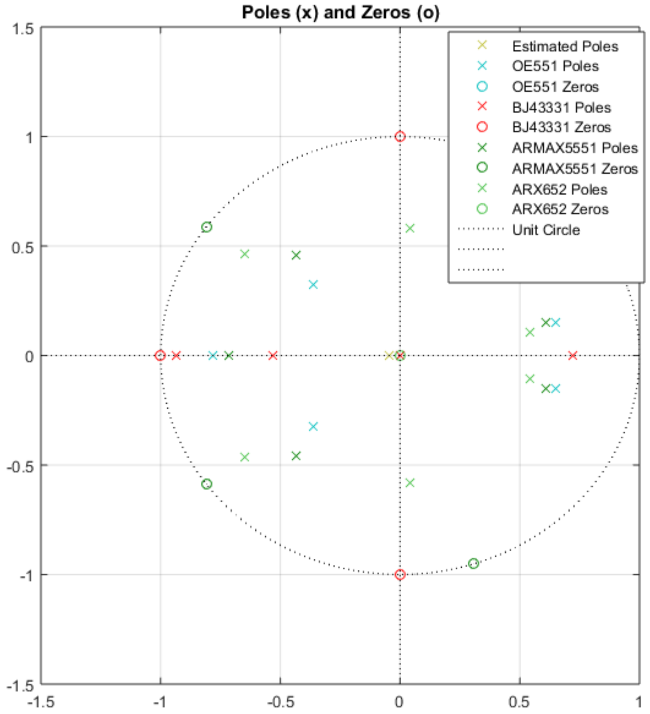


Figure 3.22: Pole –Zero Map for all models

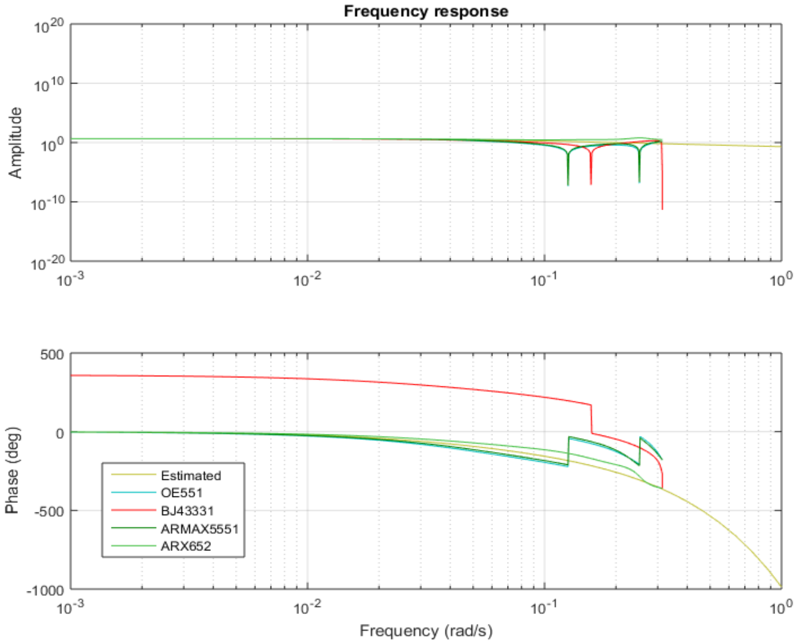


Figure 3.23: Frequency response for all models

Pole–zero and Bode plot techniques also used to affirm specific model invalidity criterion. Pole-zero plots propose a pole-zero cancellation, so that decreasing model order can degrade the fit. In a nonparametric method, bode plot and noise spectrum also used for the estimated polynomial model. It should consistent with the frequency analysis. Location of dominating poles and zeros and gain can check in the Bode plot [116,117].

The enhanced equivalence between the simulated and measured output is achieved by using the residuals cross-validation test.

3.6 SUMMARY

In this chapter, detailed study of centrifugal machine temperature control system in the sugar plant has done by input and output sample's data. Measured data be used to identify the open loop transfer function system by using reaction curve method, then strejc method applied for identification of aperiodic step response or damped periodic step response. PID-design software provides the ability to identify the plant from its step response. The controller tuning parameters intensely dependent upon the degree of accuracy of the plant model of the real system. System identification approach has implemented for estimation & validation plant model via FPE, MSE best fit % and co-relation analysis to accomplish the design requirement of the controller.

CHAPTER-4

DESIGN OF CONTROLLERS USING SOFT COMPUTING

This chapter introduces the different soft computing techniques for tuning, investigates the performance assessment of different methods and visualization of their solutions in high order dimensions.

4.1 Overview

As the real-world optimization problems are arduous and discontinuous, and to solve these, many optimizations methods are being suggested and evolved each day. Many postulated theories and principles based on principles of natural biological evolution are increasingly becoming very popular over the decade. Different Evolutionary Algorithm like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bat Algorithm (BA), Flower Pollination (FPA), Multi-Objective Genetic Algorithm (MOGA) and Multi-Objective Particle Swarm Optimization (MPSO) are some of the methods developed to resolve optimization problems.

Most of the industrial plants have complexities due to their high order, delays and non-linearity. Classical methods for tuning of PID controller are not used nowadays. With advancement in computing methods, an optimization algorithm is encouraged for good performance [121].

The optimization algorithm is a numerical method to obtain desired results by finding maxima and minima of a function by using some constraints. This is done to minimize the performance index of a controller to improve the overall performance with cost effectiveness. These algorithms are nature inspired, and as these are very diverse, formulations did for each type by using specific characteristics [123].

GA is drawn from Darwin’s theory with some biological features like crossover, mutation, and selection of the fittest. PSO based on the swarming behavior of birds and fish, mainly on swarm intelligence. Although useful, GA and PSO have certain drawbacks. While the firefly algorithm tackles the non-linear optimization efficiently due to its characteristics like light intensity coding, distance dependence and attractive behavior. Other theories like cuckoo search and eagle strategy are also very active. CS established due to good convergence and brooding parasitism of some cuckoo species [122,124].

Control system design is multi-objective design problem where the design objectives and several constraints have to be satisfied simultaneously. The controller design requirements ranges can either be from time domain specifications like rise time, settling time, overshoot percentages, etc. or from frequency domain like gain margin, phase margin, sensitivity etc. These design objectives/requirements are conflicting in nature, e.g. if we try to improve the rise time, the overshoot percentage gets deteriorated. A design of controller using conventional design a technique doesn't guarantee that an optimal controller has obtained that satisfies the design requirements and constraints. A design of controllers using meta-heuristic algorithms offers a solution for designing optimal control systems, which meets a set of design requirements and constraints. The various time and frequency domain objectives used in the controller design in this thesis already discussed in chapter 1.

In this thesis work, we have to apply GA, PSO, BA, FPA, MOGA, MPSO brief discussion is given as under.

4.2 Soft Computing Techniques

4.2.1 Genetic Algorithm

Genetic algorithms are optimization tools, which widely used nowdays for the design of intelligent adaptive control systems. Adaptive control can adjust its performance parameter so that performance index reaches an extremum value, most commonly a minimum values.

The simplicity of operation and power effect are advantages of genetic algorithms. It is a robust optimization technique and brings a perfect balance between efficiency and efficacy, which is necessary for the survival of optimal control systems in different environments. Genetic algorithms were developed by J.H. Holland in 1975 in USA [121]. In 1992, Onak. A et al. developed some more advanced genetic algorithms termed as genetic programming [125].

GA represents a class of general-purpose stochastic adaptive search techniques. Genetic algorithms simulate natural inheritance according to genetics and Darwin's survival of the fittest principle. Genetic algorithms eliminate many disadvantages like reliance on heuristics hence sub-optimal solutions and difficulty in obtaining feasible solutions. A data in the genetic algorithm considered as a chromosome.

Various subroutines, which used in genetic algorithms, are mentioned below:

- Selection of chromosomes
- Cross over of chromosomes
- Mutation of chromosomes

Selection, crossover, and mutation are three basic operators of genetic algorithms. Two main parameters, which are responsible for accuracy in genetic algorithm operations, are given below:

- Crossover probability
- Mutation Probability

GA operates on a potential population which set chromosomes or data for finding the most optimal solution based on the principle of survival of the fittest. Various populations created from the initial value and at each stage of generation; a new set of approximation generated by the process of selecting individuals according to their fitness level within the problem domain and breeding them together using genetic algorithm operators. This process leads to the evolution of the population of individuals which is a new set of chromosomes or data. It suited to their environment than the individuals (pervious chromosomes or data) that they were created from, just as in natural adaptation. A new set of individuals (chromosome /data) is produced every time by this process of evolution and is termed as sub-population. Evolution is a critical function in genetic algorithm operation; thus sometimes it is also referred to as an evolutionary algorithm [126].

It has vanguard advantage of broader adaptability to any constraints and as a result, is regarded as the one of the most robust optimization algorithm [127, 128]. The iterative process has the different step of selection, recombination, mutation and evaluation.

GA is predominantly parallel search techniques, which emulate natural genetic operations. Determination of the lower and upper bound limits to be used for the estimation of parameters.

Due to its high capability for optimization, GA has received attention in control systems such as the search for optimal PID controller parameters. In work, the completed optimization is taking place use of GA algorithm for deciding the best values of Ki, Kd and Kp by minimizing objective functions for a PID controller. Different performances indices are to be an objective function for the process of controller optimization. The algorithm assures to give best performance of controller by using minimizing the objective function by convergence in the direction of the global minima.

The steps involved in the implementation of the GA for a control system are as follows:

- Generating the initial, random population of the fixed numbered individuals for the declaration of the initial ranges for Kp, Ki and Kd.
- For the evaluation of the fitness integral, it minimizes the performance indices, followed by the selection of the fittest individuals of the population.
- Reproduction among members of the population.
- Crossover of the reproduced chromosome followed by the mutation operations, and the selection of the best individuals i.e. Survival of the Fittest.
- Looping the step 2 till the pre-defined convergence is obtained.

The Flow chart of GA shown in figure 4.1

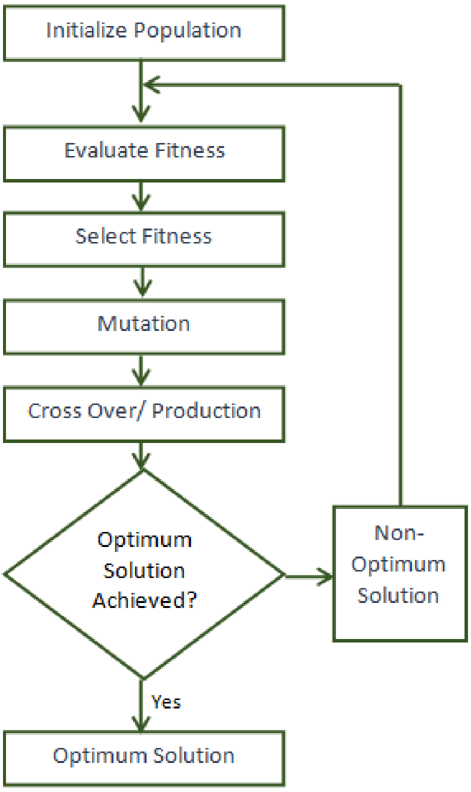


Figure 4.1: Flow chart of GA

The optimization of the system has designed and simulated in MATLAB; the parameters considered for the optimal tuning shown in table 4.1.

Table 4.1: Parameters Used in Optimization through Genetic Algorithm

Parameter	**Type/Values**
Population Type	Double Vector
Population Size	50
Fitness Scaling	Rank Based
Selection	Tournament
Reproduction Elite Count	2
Population Crossover Function	0.8
Crossover Function Type	Scattered
Mutation Function	Constant Dependent
Migration Direction	Forward
Migration Fraction	0.2
User Function Evaluation	Series Type

4.2.2 BAT Algorithm

The Bat algorithm developed by Xin-She Yang in the year 2010, which based on a bio-inspired algorithm [131]. This algorithm establishes on the characteristics of bat bio-sonar or echolocation features of microbats. Bat algorithm makes use of a frequency-tuning method so that in the diversity the solutions in the population are increased.

There are many divergent species of bats [135]. Most of the bats use echolocation technique to a certain degree amidst all the various species. This algorithm exploits the echolocation of bats. Sonar echoes utilized by the Bats to avoid and detect obstacles. Pulses of sound are transformed to the frequency which reflects back from the obstacle. Bats can also use of a time delay in the reflection from emission and for navigation purpose. They typically emit sound impulses that are short and loud. After hitting the obstacle and getting reflected by it, bats can also transform their own pulses useful information's to check and gauze the distance of its prey. The rate of pulse can based on a range 0 to 1, where 0 means no emission and 1 mean that the bats emitting maximum in implementation [122,123,124].

To formulate the bat algorithm, this type of behavior can use as well. The three generalized rules for bat algorithms used by Yang [131] are as follows:
To sense distance, all the bats make use of echolocation and they also guess the difference between their food and prey and background barriers in some magical way.
Bats randomly fly with a fixed frequency of f_{min}, at position x_i , having velocity v_i, with a loudness of A0 and considering varying wavelength to be λ for searching their prey. They can edit and adjust automatically their frequency or wavelength of pulses with rate of emission $r \in [0; 1]$, which depended upon the proximity of target;
Despite the fact that the loudness varies in a number of ways, we presume that the variation in loudness is from the large A_0 (positive) to the minimum constant value of A_{min}.

Every bat is linked with a location x^t_i and a velocity v^t_i, at iteration t, in d-dimensional search space. Amongst all the bats, there abides an existing best solution x∗. Hence, optimized rules could be converted into the amending equations for x^t_i and velocities v^t_i:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \quad (4.1)$$

$$v_i^t = v_i^{t-1} + \left(x_i^{t-1} - x_*\right) f_i \quad (4.2)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (4.3)$$

wherein β ∈ [0; 1] that drawn from a uniform distribution is a random vector.

For implementation, use either frequencies or wavelengths, use $f_{\min} = 0$ and $f_{\max} = O$ (4.1) depending on the problems of domain size. Eventually, each bat is casually assigned a uniformly drawn frequency from $[f_{\min}; f_{\max}]$. The pulse emission rates and the loudness provide a mechanism essentially for auto-zooming and automatic control with promising solutions into the region.

We need to change a few parameters to provide a productive mechanism. We need to control the rate (r_i) and also the loudness (A_i) of pulse emission in the process of the iterations.

Because the loudness decreases usually, as soon as that a bat finds its prey, while the pulse rate emission increases, the loudness may be chosen as any convenience value, between Amax and Amin, assuming that Amin = 0 means that a bat has recently found its prey and is temporarily stopping to emit any sound.

With those beliefs, we have

$$A_i^{t+1} = \alpha A_i^t,\ r_i^{t+1} = r_i^0[1 - \exp(-\Upsilon t)] \quad (4.4)$$

where γ and α are the constants. For any $0 < \alpha < 1$ and $\gamma > 0$, here α is like the simulated annealing cooling factor. We also have $A_i^t \to 0,\ r_i^t \to r_i^0$, as $t \to \infty$

In the most effective cases, we could use α = γ = 0:9 to 0:98 in simulations work. In the initial population, each bat uses echolocation way in a correlative manner to update its position. In echolocation of bats, a series of waves released which are loud and ultra-sound so that echoes created with delays. Various sound levels received back which helps the bats to find a particular prey.

When optimization takes place, the position xi and velocity v_i of each bat must updated and defined. v_i^t at time step. New solutions x_i^t and velocities v_i carried out by the following equations Where a is a random vector which drawn from a uniform distribution in the range of [0, 1] [129, 130, 131].

x* is the recent global best location among all n number of bats. $\lambda_i f_i$ is the increment in velocity.

For objectives, parameters of bat algorithm shown in Table 4.2 kept consistent.

Table 4.2: Bat Algorithm specific parameters

Bat Algorithm Parameters	**Value**
Population	50
No of Generations	100
Loudness	0.5
Pulse Rate	0.5
Minimum Frequency	0
Maximum Frequency	2

In the work, the completed optimization taking place use of bat algorithm for deciding the best values of Ki, Kd and Kp by minimizing objective functions for a PID controller. Different performances indices are an objective function for the process of controller optimization. The algorithm assures to give best performance of controller by using minimizing the objective function by convergence in the direction of global minima.

The overall procedure of BAT algorithm is shown by flow chart in figure 4.2

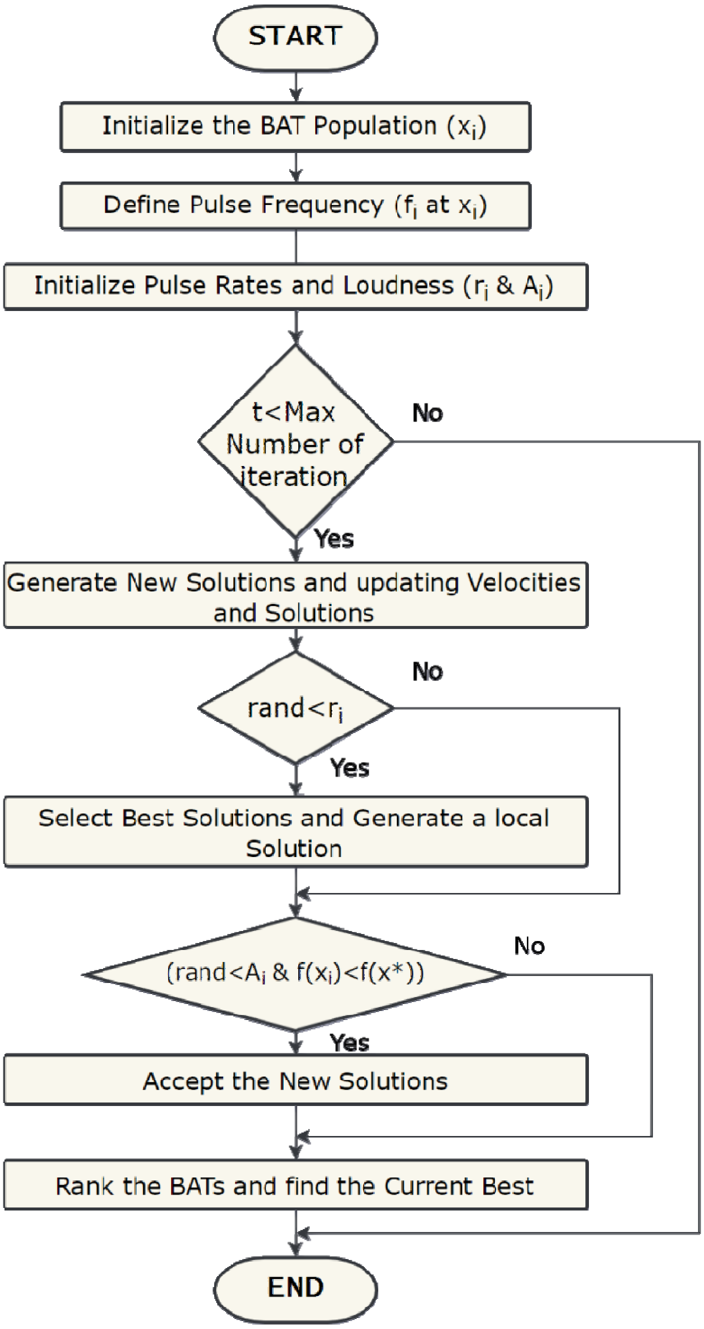


Fig: 4.2 Flow Chart of BAT Algorithm

4.2.3 Flower Pollination Algorithm (FPA)

Flower pollination is an intriguing process which inspired via the pollination manner of flowers. Flower pollination associated with the transfer of pollen. Its optimization algorithms depend on evolutionary characteristics. This algorithm indicates the exponential convergence rate which is use to resolve a nonlinear problem.

According to the biological evolution point of view, the objective of the FA is the survival of the fittest and the optimal reproduction of plants regarding most fittest. All the factors and processes of flower pollination work together to achieve optimal reproduction of the flowering plants [136].

Flower Pollination Algorithm are having based entirely on flower constancy and pollinator behavior.
Global pollination process is thought as biotic and cross-pollination with pollen carrying pollinators acting Levy flights.
Local pollination is believed abiotic and self-pollination.
Flower consistency can be accepted as the reproduction probability is corresponding to the likeness of two flowers involved.
Switch probability p ∈ [0; 1] is managed by way of a local pollination and global pollination.

Due to the physical proximity and different elements including the wind, local pollination can have a significant division p in the general pollination activities.

Table 4.3: Flower pollination algorithm specific parameters

Flower pollination algorithm parameters	**Values**
Population Size	50
Probability Switch	0.8
Iterations	100
β	1.5
Lévy Filght’s Step Size	0.01

There are two critical steps in FA algorithm; they are global pollination and local pollination. In global pollination, flower pollens carried through pollinators such as insects, and pollens can journey over a long distance and circulate in a much longer range. It ensures the pollination and reproduction of the most fittest (g_*).

The first rule plus flower constancy may be represented mathematically as

$$x_i^{t+1} = x_i^t + L\left(x_i^t - g_*\right), \tag{4.6}$$

Where x_i^t is solution vector xi at iteration t, and g∗ is the current best solution found among all solutions at the current generation/iteration. The parameter L is the strength of the pollination, which basically is a step size. Insects may move over a long distance with different distance steps, for this use a Levy flight to mimic this characteristic efficiently. Draw L > 0 from a Levy distribution

$$L \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, \left(s \geq s_0 > 0\right) \tag{4.6}$$

Here $\Gamma(\lambda)$ is the usual gamma function, and this distribution is valid for huge steps s > 0. In all our simulations below, we have used λ = 1.5 [137, 138].

The local pollination and flower constancy may be represented as

$$x_i^{t+1} = x_i^t + \in\left(x_j^t - x_k^t\right), \tag{4.8}$$

Wherein x_j and x_k are pollens from the different flowers of the identical plant species. Mathematically, if x_j^t and x_k^t comes from the same species or selected from the equal population, this end up a local random walk if we draw ∈ from a uniform distribution in [0, 1].The flow chart of FPA shown in figure 4.3.

Most flower pollination activities can get up at every local and global scale. For this, we use a transfer probability or proximity probability p to replace amongst interchange among commonplace global pollination to intensive local pollination. From our simulations, we found that p = 0:8 works better for our problem.

In bat, algorithm implementation assumed that each flower only produces one pollen gamete.

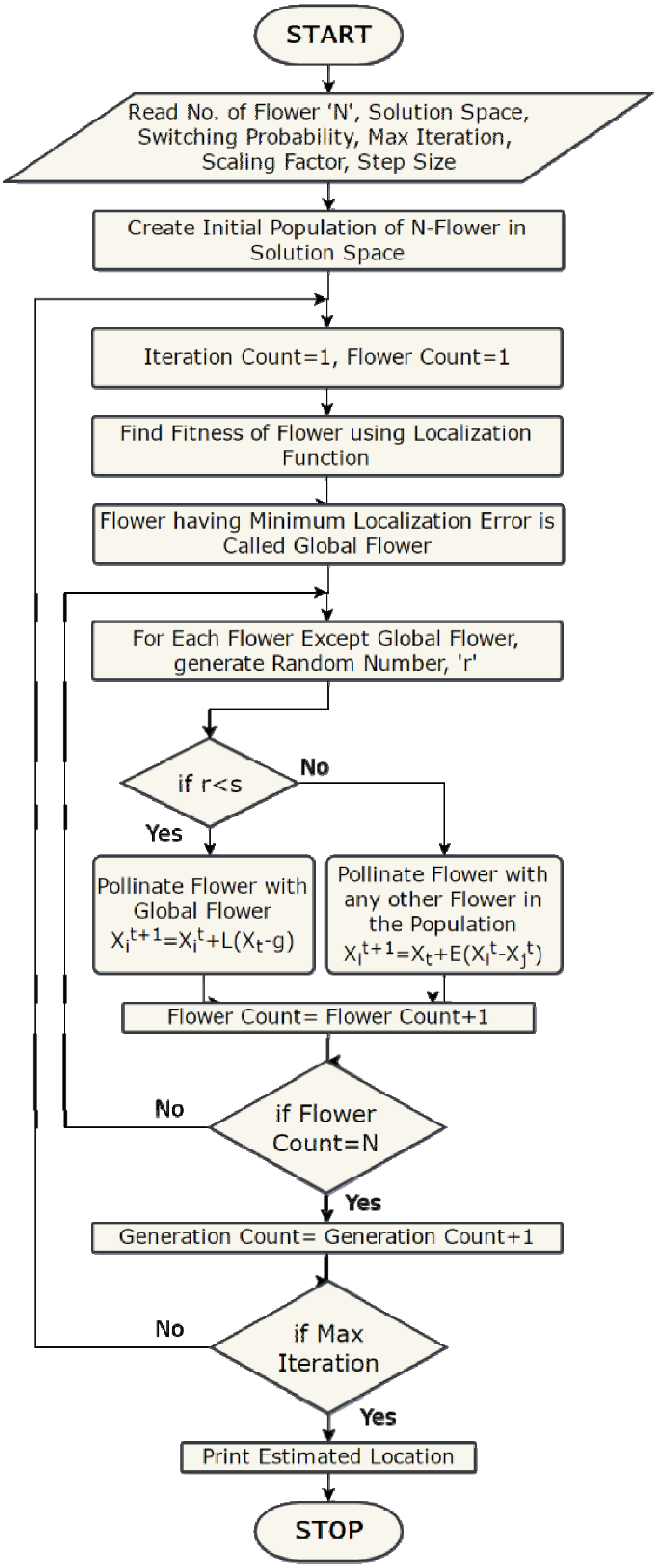


Figure 4.3: Flow chart of FPA

4.2.4 Particle Swarm Optimization

PSO is the expansion of animal social behavior that follows a population-based meta-heuristic strategy for optimization. It incorporates the acceleration by distance and velocity matching by nearest matching. In the mid-the1990s, it was introduced by J. Kennedy and R. C. Eberhart [129]. Initially, it was utilized to balance the weights in neural networks [20].

In PSO, the manipulation of a swarm is different from the evolutionary algorithms, because it promotes a cooperative model rather than a competitive model. An adaptable velocity vector is used by PSO, which changes particle position at each iteration of the algorithm. It exploits information springing from own previous experiences to move toward the promising regions of the search space [141]. To remember experience, it has a separate area of memory to store the best position visited in the search space.

PSO described in the context of single-objective optimization is summarized here

The particle movement is computed for the $(t+1)^{th}$ iteration as follows:

$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{4.9}$$

$$V_i(t+1) = V_i(t) + c_1 r_{i,1}(t) \times (pbest_i(t) - X_i(t)) + c_2 r_{i,2}(t) \times (gbest\ (t) - X_i(t)) \tag{4.10}$$

Where i=1, 2, 3…….n. The i^{th} particle position and velocity at the t^{th} iteration is denoted as $X_i(t)$ and $V_i(t)$ respectively. At the t^{th} iteration, the best position founded by the entire swarm and the particle swarm and the particle itself so far respectively, are denoted as $gbest(t)$ and $pbest_i(t)$. c_1 and c_2 are the two positive constant acceleration coefficients, which denote Cognitive and social parameters respectively. $r_{i,1}$, $r_{i,2}$ are two independent randomly distributed values within the range of [0, 1].

There are three significant components to update the velocity [142].

The first component (v_i) models the tendency to continue in the same direction.

The second component ($pbest_i$) is a linear attraction toward the personal best position ever found, which is scaled by random weight $c_1 r_{i,1}$.

The third component ($pbest$) is a linear attraction towards the global best position found by any particle of the swarm, which is scaled by another random weight $c_2 r_{i,2}$.

The components above indicate that the performance of PSO influenced by the personal best positions (pbest) and global best position (gbest) .Therefore; the best positions are heavily dependent on information exchange between neighborhood particles. The particles can connect to each other. Two general types of neighborhood topologies have studied for global best (gbest) and personal best (pets) [141,144]. Ring and wheel are the two most common topologies. Kennedy [23] suggested that a fully connected topology converges very fast, but there is a chance to be trapped in local minima. The overall procedure of PSO shown in the flow chart, Figure 4.4.

Table 4.4: Particle swarm optimization algorithm specific parameters

PSO Parameters	**Value**
Swarm Size	50
No. of Iterations	200
C1	1.2
C2	0.12
Inertial Weight (w)	0.9

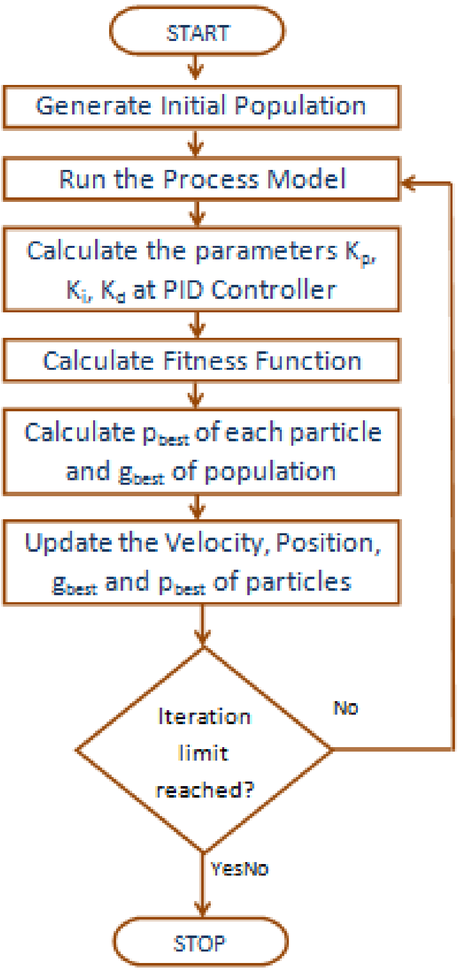


Figure 4.4: Flow chart of PSO Algorithm

4.2.5 Multi-Objective Optimization

Many varieties of real-world problems are available that are concerned with more than two conflicting objectives. These kinds of issues are known as multi-objective problems. The solutions to multi-objective optimization problems (MOOP) are those that have the best possible negotiation among all given objectives [145]. Therefore, the multi-objective optimization is required to find the best possible negotiated solutions.

Multi-Objective Optimization Problem (MOOP), PSO can modify in two ways. First, each objective function is treated separately, and second, all objective functions are evaluated for each particle. A non-dominant solution (best position) is used to guide the particles, called a leader. In each iteration, non-dominant solutions are stored to detect Pareto-optimal solutions which saved in the memory called an external archive. MOOP minimizes or maximizes the number of objective functions simultaneously [150].

It is essential to have some evaluation criteria to know the goodness of certain solutions. The requirement criteria to express as computable functions of the decision variable called the objective function [122]. The multi-objective optimization comprises a multi-dimensional space, called objective space. There are two Euclidean spaces which are considered in the MOOP, namely the decision variable and objective space. MOOP optimizes many objective functions. Therefore, it does not have a unique solution, but a set of solutions. Pareto optimality theory [145] is used to find the set of solutions [146].

In a multi-objective optimization algorithm (MOOA), the concept of the dominance is used to find the solution from their search space. Therefore, the concept of dominance and terms need to be defined properly.

The comparison of all possible pairs of solutions is performed to get the non-dominant set of solution for a given finite set of solutions [145].

Multi-objective optimization also has a local and global Pareto-optimal set, like the single-objective optimization local and global optimum solutions [147]. It is known that the Pareto-optimal set has a non-dominant solution set. On the other hand, a non-dominant set may have some Pareto-optimal and non-dominant solutions. Therefore, it can be concluded that the non-dominant solution found by an algorithm might not the ensured true Pareto-optimal set [147].

A. Multi-Objective Particle Swarm Optimization (MOPSO)

The following fundamental vital issues considered for the design of Multi-Objective Particle Swarm Optimization (MOPSO)

The MOOP has a set of unique solutions (Pareto-optimal Set); therefore it is necessary to modify the PSO to solve MOOP. Eckart Zitzler [149] identified three general goals to archive:

- A maximum number of solutions in Pareto-optimal set.
- Minimization of the distance between Pareto f00ront and the Pareto front produced by an algorithm.
- Maximum diversity in the solution set found.

There are two methods to find the non-dominant set; first, many runs of PSO where each run of the PSO produces a single solution. Therefore, after several runs of the PSO, a set of solutions is produced. Second, the PSO is a population-based optimization algorithm. Consequently, it provides a set of non-dominant solutions [28].

In the literature, many MOPSO approaches have been proposed. Pareto-based approaches use the concepts of the leader selection based on Pareto dominance. The leader guides the swarm during a search.

Table 4.5: Multi-objective PSO specific parameters

MOPSO Parameters	**Value**
Swarm Size	100
Repository Size	100
Inertia Weight	0.729
Inertia Weight Damping Ratio	1
Personal Learning Coefficient	1.4962
Global Learning Coefficient	1.4962
Leader Selection Pressure Parameter (β)	2
Extra Repository Member Selection Pressure (γ)	2
Maximum Iterations	100

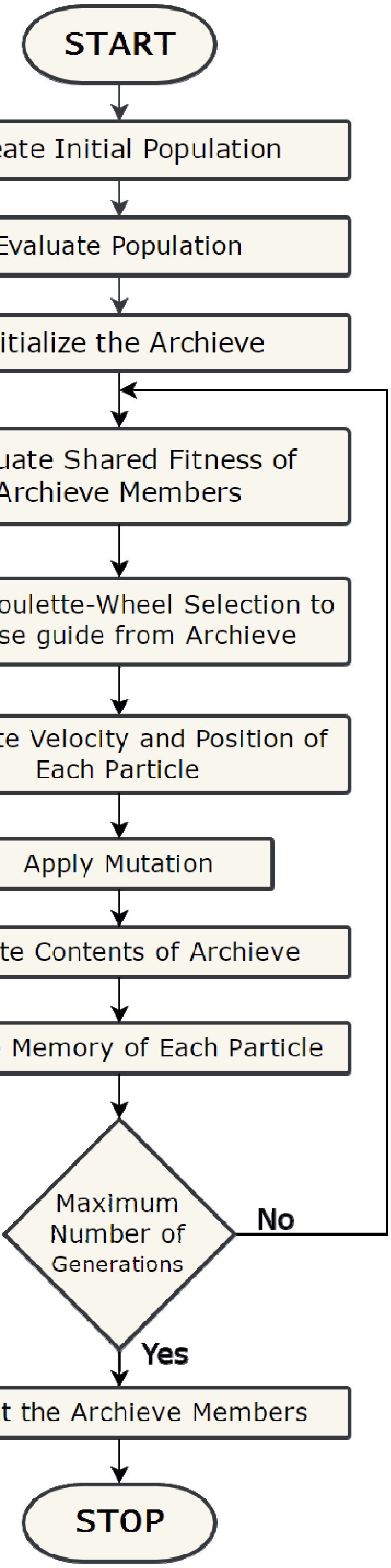


Figure 4.5: Flow Chart of MOPSO

B. Multi-Objective Genetic Algorithm Optimization (MOGA)

In recent days, Evolutionary Algorithm has got large extensive to the community as a fastest growing sector of computational intelligence issue [151].In this MOGA can solve a multi-objective optimization problem of PID controller tuning in a right way.

The multi-objective optimization based design of PID controller is similar to single optimization for PID tuning except the part where the more objectives are evaluated from the system responses and then the optimization is solved by MOGAs.

In this work, we add two more objectives to the steady state errors which are settling time and overshoot. In our investigation, the multi-objective PID tuning problems are mostly solved using a well-known algorithm, Non-dominated Sorting Genetic Algorithm (NSGA-II) [152,153,154].

Since, an unstable response is obtained while designing by Ziegler-Nichols methods; hence the controller parameters obtained from ZN are not optimum for the directly implementation for the plant, so their organized optimization must be carried out, that the better possible parameters can be estimated and implemented for the best performance of the system. Multi-objective genetic algorithm aims to boosts the better fitness value of the individuals. Fitness value increased the diversity of the population [156]. Diversity controlled by the elite members of the population; Pareto fraction control elitism, and Pareto Front also bound the number of individuals. The parameter determined by ZN helps in the determination of the initial lower and upper bound limits to be used for the optimization, and minimizing the performance indices.

The implementation of the system and its optimization has been carried out in MATLAB. Population size of 75 with adaptive feasible mutation function and selection of individuals by tournament with a tournament size of 2 has considered.

Optimization of the PID controllers using Multi-objective genetic algorithm aims at improving the objective function of the both the objectives used by obtaining an optimal Pareto solution.

The optimization is based on NSGA-II algorithm [156] which boosts the attaining of the best fitness value. The algorithm uses an elitist genetic algorithm which favors increasing the diversity of the population and prevents the algorithm from being struck in a local solution. Elitism controlled by Pareto fraction and the number of individuals is bounded by Pareto front [155].Tuning of PID controller parameters for an optimized control performance is a multi-objective optimization problem. The problem becomes particularly difficult if the plant to be controlled is an unstable, nonlinear and under actuated plant.

Table 4.6: Multi -Objective GA specific parameters

Parameter	**Type/Values**
Algorithm Variant	NSGA-II
Population Type	Double Vector
Population Size	75
Selection	Tournament Based
Tournament Size	2
Reproduction Elite Count	2
Population Crossover Function	0.8
Crossover Function Type	Scattered
Mutation Function	Adaptive Feasible
Migration Direction	Forward
Multi Objective Distance Measure Function	@distance crowding
Migration Fraction	0.2
User Function Evaluation	Series Type

This work presents the development of a multi-objective genetic algorithm to optimize the PID controller parameters for a complex industrial system.

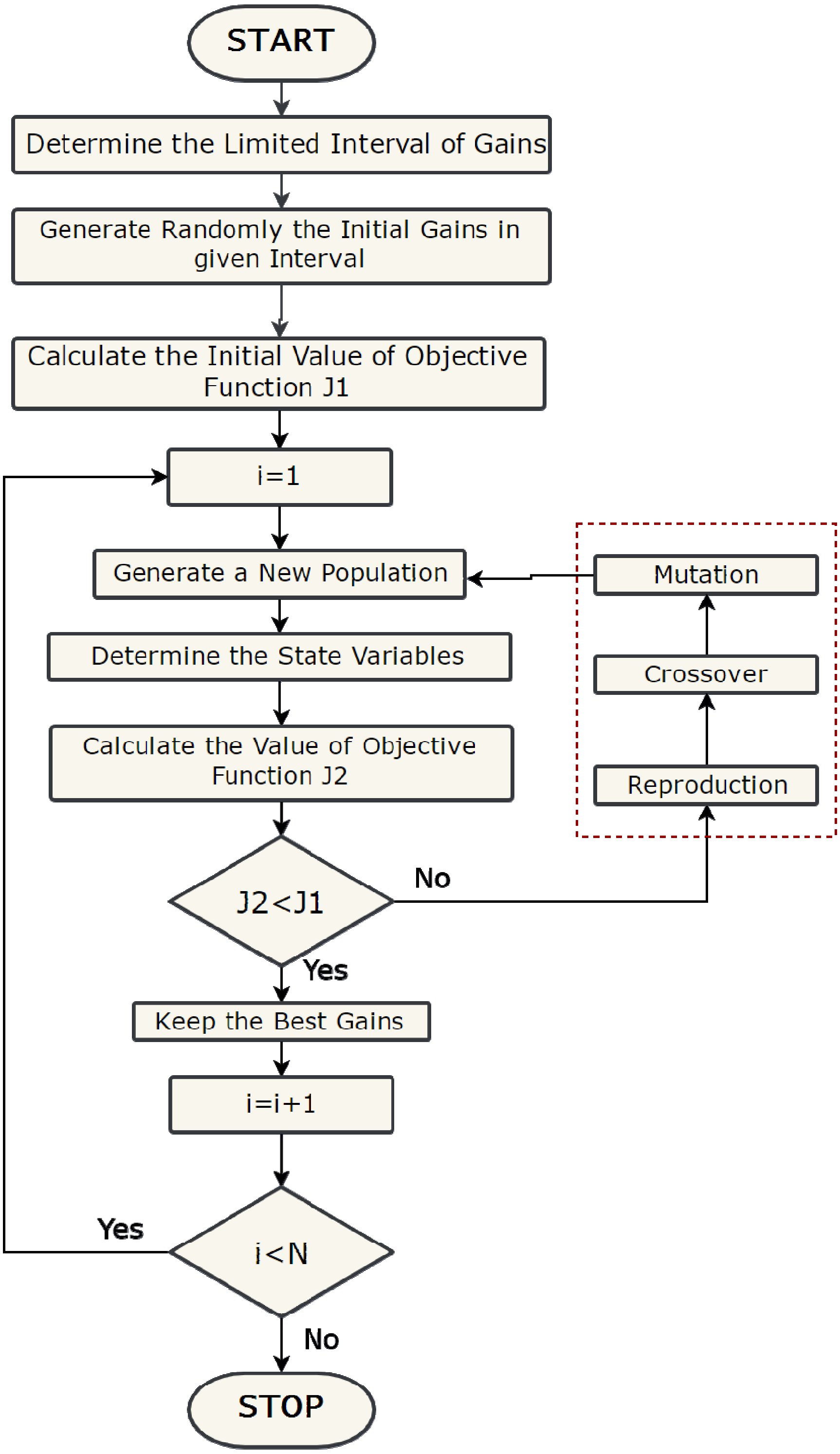


Figure 4.6: Flow chart of MOGA

4.2.6 Design Objectives

In this work, various time and frequency domain objectives have considered for designing the optimal controller for the control system. It has already discussed in chapter 1 (1.4.6).These are,

Integral Square Error (ISE) $ISE = \int_0^T (\varepsilon)^2\, dt$ (4.11)

Integral Time Square Error (ITSE) $ITSE = \int_0^T t(\varepsilon)^2\, dt$ (4.12)

Integral Absolute Error (IAE) $IAE = \int_0^T |\varepsilon|^2\, dt$ (4.13)

Integral Time Absolute Error (ITAE) $ITAE = \int_0^T t|\varepsilon|^2\, dt$ (4.14)

Sensitivity $S(j\omega) = \dfrac{1}{1+G(j\omega)C(j\omega)}$ (4.15)

Lower values of |*S*| suggest more attenuation of the exterior disturbance. The sensitivity function informs about the disturbances which influenced by feedback. Disturbances with frequencies such that |S(jω)| is less than one to the critical point -1 and disturbances with frequencies such that |S(jω)| is larger than one by the feedback.

Complementary Sensitivity

This name comes from the fact that S(s) + T (s) = 1. The minimization of complementary sensitivity gets better improves noise reduction.

$$T(j\omega) = \frac{G(j\omega)C(j\omega)}{1+G(j\omega)C(j\omega)} \qquad (4.16)$$

4.3 Methodology

The design of the controller using meta-heuristic algorithm has formulated as an optimization problem. Several time domain performances namely ISE, ITSE, IAE & ITAE have considered for the designing purposes, and different meta-heuristic algorithms have been used for minimizing the cost function. The controller has chosen as PID controller and the algorithms try to find the optimal values of the controller parameters K_P, K_I and K_D by minimizing the cost function. The transfer function of the PID controller is given by equation (4.17) as:

$$C(s) = K_P + \frac{K_I}{s} + K_D \cdot s \tag{4.17}$$

In this work, different meta-heuristic algorithms have used to find the optimum values of the PID controller parameters by minimizing the time domain performance indices, and their performances have been compared.

In this section, the following optimization techniques has used for FOPTD and SOPTD with different
Single- Objective Optimization
Multi-objective Optimization by aggregate of function (AOF)
Multi-objective Optimization by generate first choose later approach (GFCL)

4.3.1 Single-Objective Optimization

In this method, different optimization techniques like GA, BA, FPA, and PSO chose for minimizing the controller design objectives. The objective function is described by time domain performance indices which given in equation (4.11-4.14). The optimal values of controller gain parameters given by equation (4.17). Various algorithm-specific parameters considered in the optimization are defined in Table 4.1, 4.2, 4.3, 4.4. After minimizing the objective functions given by equation (4.11 – 4.14), optimal values of the controller parameters have obtained. These controller parameters have used for simulating the closed-loop response of the system. Finally compared closed loop time and frequency domain response of the designed control system. In these methods different optimization techniques like GA, BA, FPA, and PSO chose for minimizing the controller design objectives.

4.3.2 Multi-objective Optimization by aggregate of function (AOF)

In an optimization problem, the controller design requirements range from time domain specifications like rise time, settling time, overshoot percentage, etc. to several frequency domain specifications like gain margin, phase margin, sensitivity etc. Sometimes, response provides by the PID controllers using time domain performance indices not very optimal as they give very high values of overshoot percentages and in some cases an unstable response. So, in order to design a controller that offers an optimal response, the controller design problem has formulated as a multi-objective optimization problem. However, several conflicting design objectives can minimize simultaneously.

Multi-objective optimization may categorize into two sub-categories. In the first case, the optimization problem has expressed as the weighted sum of the objectives as the aggregate of function (AOF), and in the second sub-category, the simultaneous minimization of both the objectives has considered. In the latter case, at the end of the optimization, the Pareto optimal set (POS) of solutions are obtained, and the decision maker can choose the desired tradeoff amongst the design objectives using Pareto front visualization.

Aggregate of Function (AOF)

In this case, the design requirements of both the time domain and frequency domain performances have expressed as the weighted sum of the objectives. Here, three different objective functions have chosen given by equation (4.18 – 4.20).

For designing the controller, the meta-heuristic algorithms of GA, BA, PSO, and FPA have considered. The designed objectives are given as:

$$J_{ITAE+S} = ITAE + S = \int_0^T \left|t(\varepsilon)\right| dt + \left|S(j\omega)\right|_\infty \tag{4.18}$$

$$J_{ITSE+S} = ITSE + S = \int_0^T t(\varepsilon)^2\, dt + \left|S(j\omega)\right|_\infty \tag{4.19}$$

$$J_{S+T} = S + T = \left|S(j\omega)\right|_\infty + \left|T(j\omega)\right|_\infty \tag{4.20}$$

Where S is the infinity norm of the sensitivity function and T is the infinity norm of the complementary sensitivity function and are given by equation (4.15 & 4.16). In this thesis, we have implemented this technique for FOPTD & SOPTD using GA, BA, FPA, PSO techniques.

4.3.3 Multi-Objective Optimization by GFCL

In this technique, the design requirements of both the time domain and frequency domain have expressed as a multi-objective optimization problem. In previous methods, the multi-objective optimization based on a weighted sum of objectives/ aggregate of function (AOF) has explored. One of the most significant issues with AOF approach is that the formulation of objective function requires careful adjustment of weight parameters as due to poor choice of weighting functions may result in the dominance of one objective over the other. So, by simultaneous minimization of both the objectives in generate first choose later approach, the decision maker can visualize the design objectives using Pareto front and then select the desired trade-off amongst the design objectives.

In this work, design objectives of ITSE, ITAE, and sensitivity have been considered and have expressed as the multi-objective design problem, and the proposed cost function has been minimized using the multi-objective variants of GA (NSGA-II) and PSO. The cost functions used are given in equation 4.21 and 4.22 as:

$$J_1 = \begin{cases} \int_0^T t(\varepsilon)^2 \, dt \\ \left| S(j\omega) \right|_\infty \end{cases} \tag{4.21}$$

$$J_2 = \begin{cases} \int_0^T \left| t(\varepsilon) \right| dt \\ \left| S(j\omega) \right|_\infty \end{cases} \tag{4.22}$$

4.4 Results & Discussion

For first order plus delay system, GA, BA, PSO, FPA optimization techniques have implemented, but satisfactory results not obtained in all the cases. The time response of the controller is expected to be very slow and also the frequency response lies above the 0dB line in single and multi-objective optimization, thus, making the controllers not feasible for applications. So here, controller design for second order plus delay system has discussed.

The simulation results of first order plus delay system presented in the **Appendix-B**

Controller Design using Single-Objective Optimization

Using Genetic Algorithm

Genetic Algorithm specific parameters (from Table 4.1) used in the optimization. Optimal values of the controller parameters given in Table 4.7 and various time and frequency domain performance indices shown in Table 4.8

Table 4.7: PID Controller Gains Obtained using a genetic algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	349.804	236.69	349.99	249.9853
K_I	9.5456	7.272	9.99	8.4934
K_D	504.99	461.1825	424.5643	450.46

Table 4.8: Performance Indices of the Designed Controllers using Genetic Algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (sec.)	14.65	22.2	14.43	19.96
Settling Time (sec.)	189.94	127.46	226.35	137.29
Overshoot Percentage (%)	43.51	17.52	47.57	26.73
Gain Margin (dB)	0.63	1.38	0.61	1.21
Phase Margin (deg.)	-34.07	37.25	-37.27	17.14

These controller parameters have used for simulating the closed loop response of the system. Figure 4.7 shows the compared step response and the frequency response of the designed closed loop system.

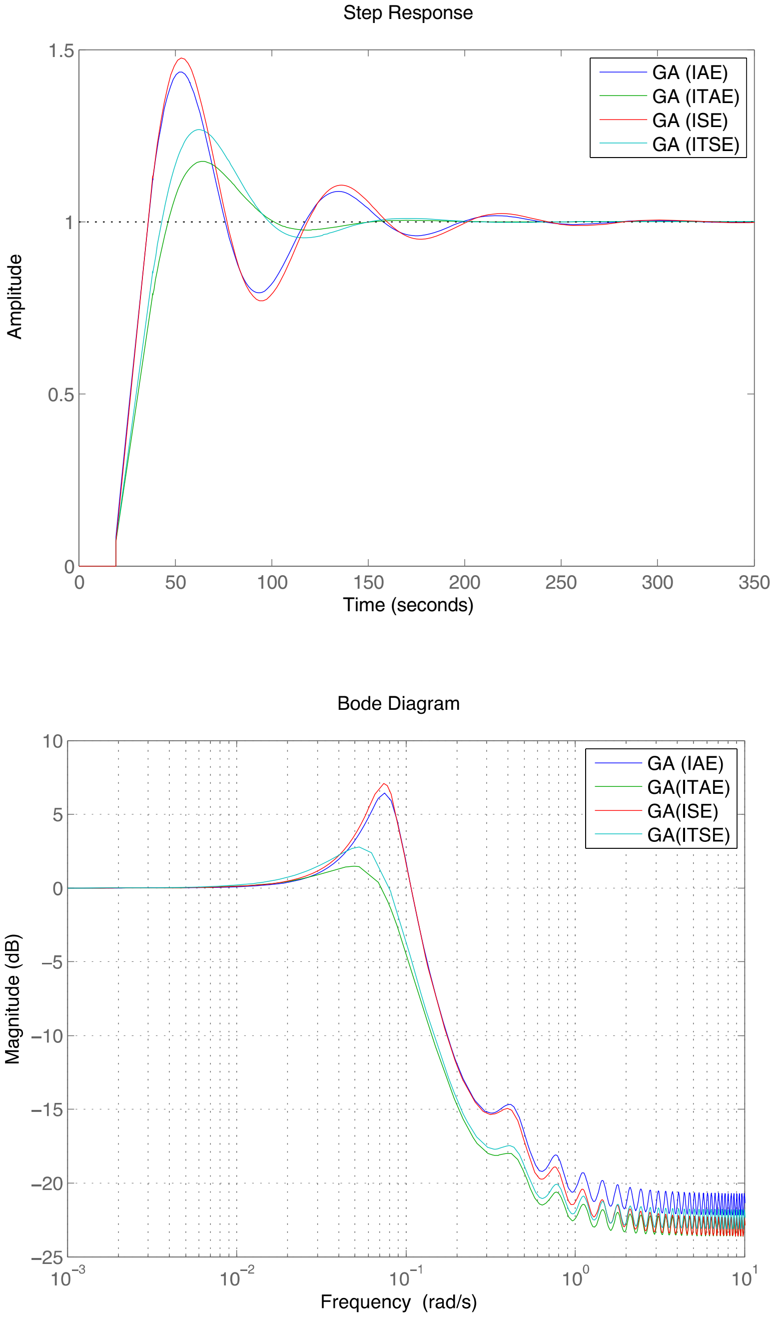


Figure 4.7: Step and Frequency response of the closed loop system with GA optimized PID controller parameter

From the Figure 4.7(a) it can be seen that the GA (ITAE) controller offers the least overshoot percentage but still, this value is very high and cannot use in the implementation. Also from the Figure 4.7(b), the frequency response of the closed-loop system has several peaks above the 0 dB line, and this response is not optimum for the design purposes.

Using BAT Algorithm

BAT Algorithm specific parameters (from Table 4.2) used in the optimization. Optimal values of the controller parameters given in Table 4.9 and various time and frequency domain performance indices shown in Table 4.10

Table 4.9: PID Controller Gains Obtained using Bat Algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	332.998	326.26	669.256	423.572
K_I	9.2	9.15	12.274	11.5132
K_D	567.885	533.574	1277.879	253.081

Table 4.10: Performance Indices of the designed controllers using bat algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (sec.)	15.47	15.71	∞	11.81
Settling Time (sec.)	185.19	184.25	∞	443.31
Overshoot Percentage (%)	38.05	37.4	∞	70.15
Gain Margin (dB)	0.74	0.77	2.14	0.32
Phase Margin (deg.)	-23.96	-22.04	-98.06	-65.38

These controller parameters have used for simulating the closed loop response of the system. Figure 4.8 shows the compared step response and the frequency response of the designed closed loop system.

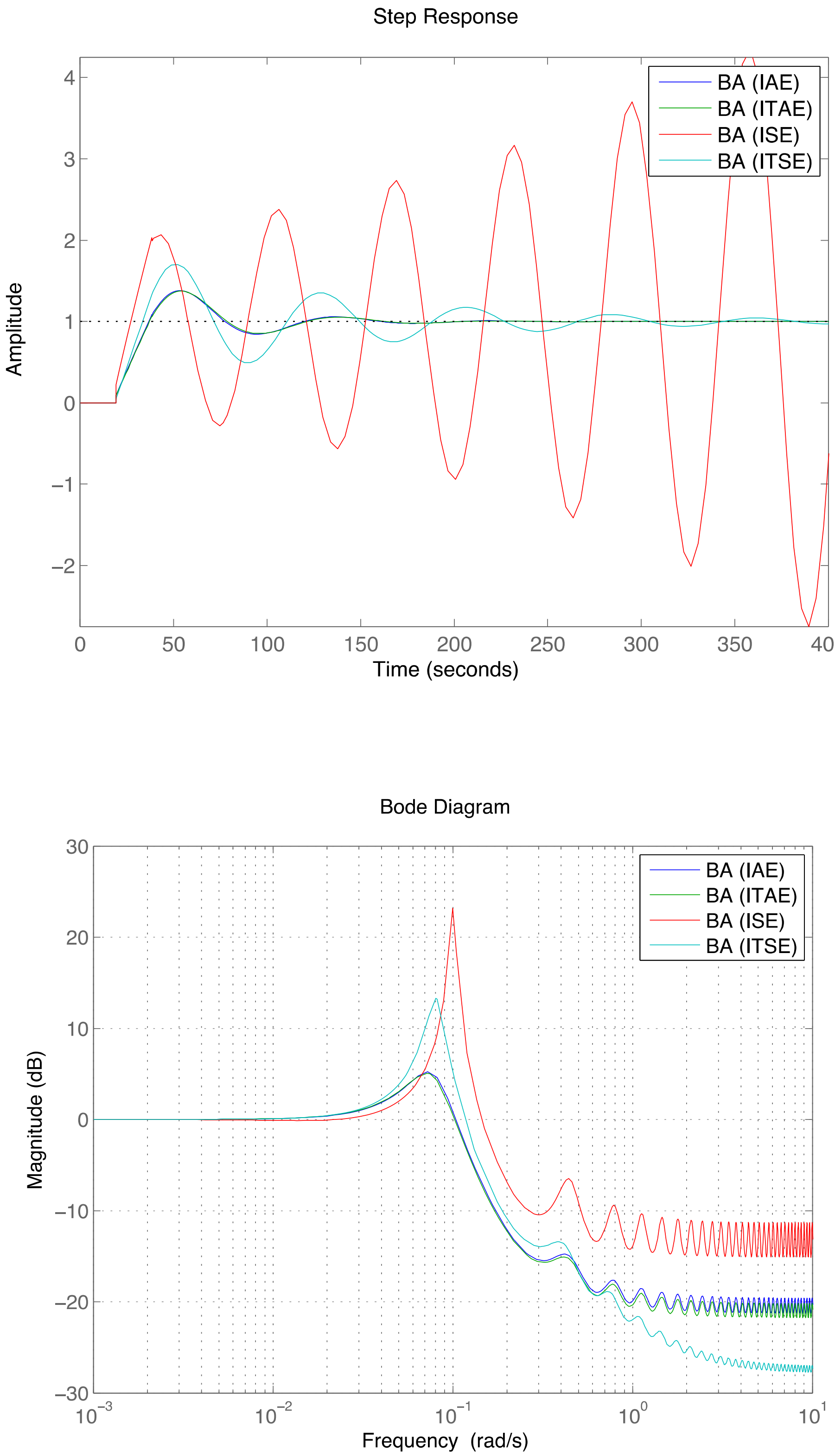


Figure 4.8: Step and frequency response of the closed loop system with BA optimized PID controller parameter

From the Figure 4.8 (a) it can be seen that the BA (IAE & ITAE) controller offers similar performance but still, this value is very high and cannot use in the implementation and also the response provided by BA (ISE) tuned controller is unstable. Also from the Figure 4.8(b), the frequency response of the closed-loop system has several peaks above the 0 dB line, and this response is not optimum for the design purposes.

Using PSO Algorithm

PSO Algorithm specific parameters (from Table 4.4) used in the optimization. Optimal values of the controller parameters are given in Table 4.11 and various time and frequency domain performance indices are shown in Table 4.12

Table 4.11: PID Controller Gains Obtained using PSO

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	3.651	-3.1457	15.848	45.1473
K_I	3.559	3.2622	8.1647	4.8477
K_D	-2.966	0.4108	-8.27	3.9648

Table 4.12: Performance Indices of the designed controllers using PSO

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (sec.)	63.75	68.01	33.04	49.47
Settling Time (sec.)	380.87	401.14	979.11	305.71
Overshoot Percentage (%)	24.43	23.18	70.16	25.61
Gain Margin (dB)	2.16	2.17	0.47	2.53
Phase Margin (deg.)	48.08	51.18	-25.75	49.70

These controller parameters have used for simulating the closed loop response of the system. Figure 4.9 shows the compared step response and the frequency response of the designed closed loop system.

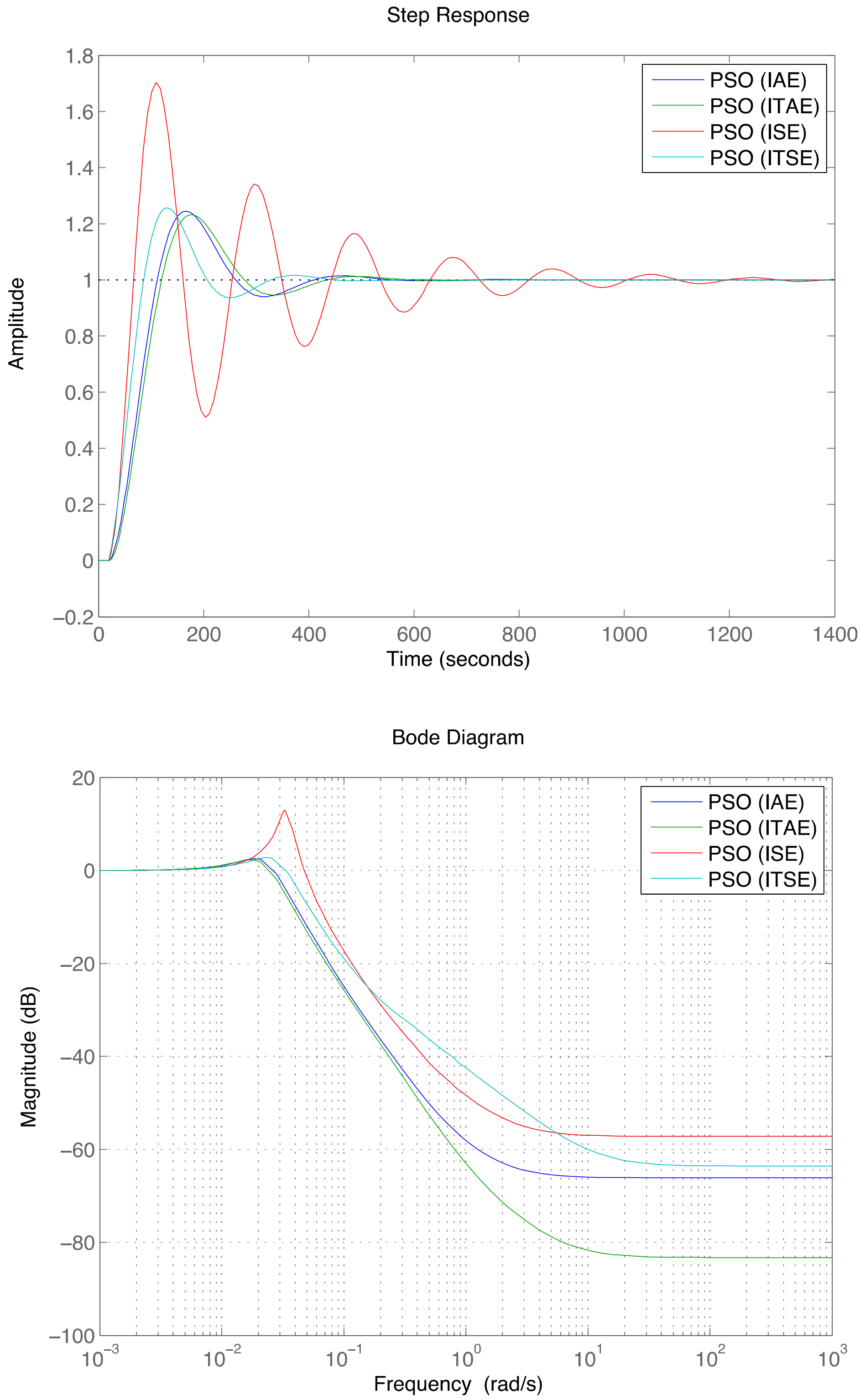


Figure 4.9: Step and frequency response of the closed loop system with PSO optimized PID controller parameter

From the Figure 4.9(a) it can be seen that the PSO tuned controller offers an oscillatory response. In figure 4.9 (b), the frequency response of the closed-loop system (ISE & ITSE) has peak above the 0 dB line, and the response is not optimum for the design purposes. While the perk response of the IAE & ITAE tuned controller lies near the 0 dB line, and the time response of IAE & ITAE tuned controllers are almost identical.

Using Flower Pollination Algorithm

FPA Algorithm specific parameters (from Table 4.3) used in the optimization. Optimal values of the controller parameters given in Table 4.13 and various time and frequency domain performance indices shown in Table 4.14.

Table 4.13: PID Controller Gains Obtained using FPA

Controller Parameter	IAE	ITAE	ISE	ITSE
K_P	454.0672	427.2594	427.0511	429.7505
K_I	9.2196	8.3579	8.1535	9.844
K_D	577.71	533.464	486.591	538.1493

Table 4.14: Performance Indices of the designed controllers using FPA

Controller Parameter	IAE	ITAE	ISE	ITSE
Rise Time (sec.)	11.64	12.47	12.49	12.14
Settling Time (sec.)	344.06	275.93	304.79	316.6
Overshoot Percentage (%)	58.65	49.95	49.72	57.85
Gain Margin (dB)	0.38	0.46	0.43	0.38
Phase Margin (deg.)	-65.11	-57.75	-57.84	-59.62

These controller parameters have used for simulating the closed loop response of the system. Figure 4.10 shows the compared step response and the frequency response of the designed closed loop system.

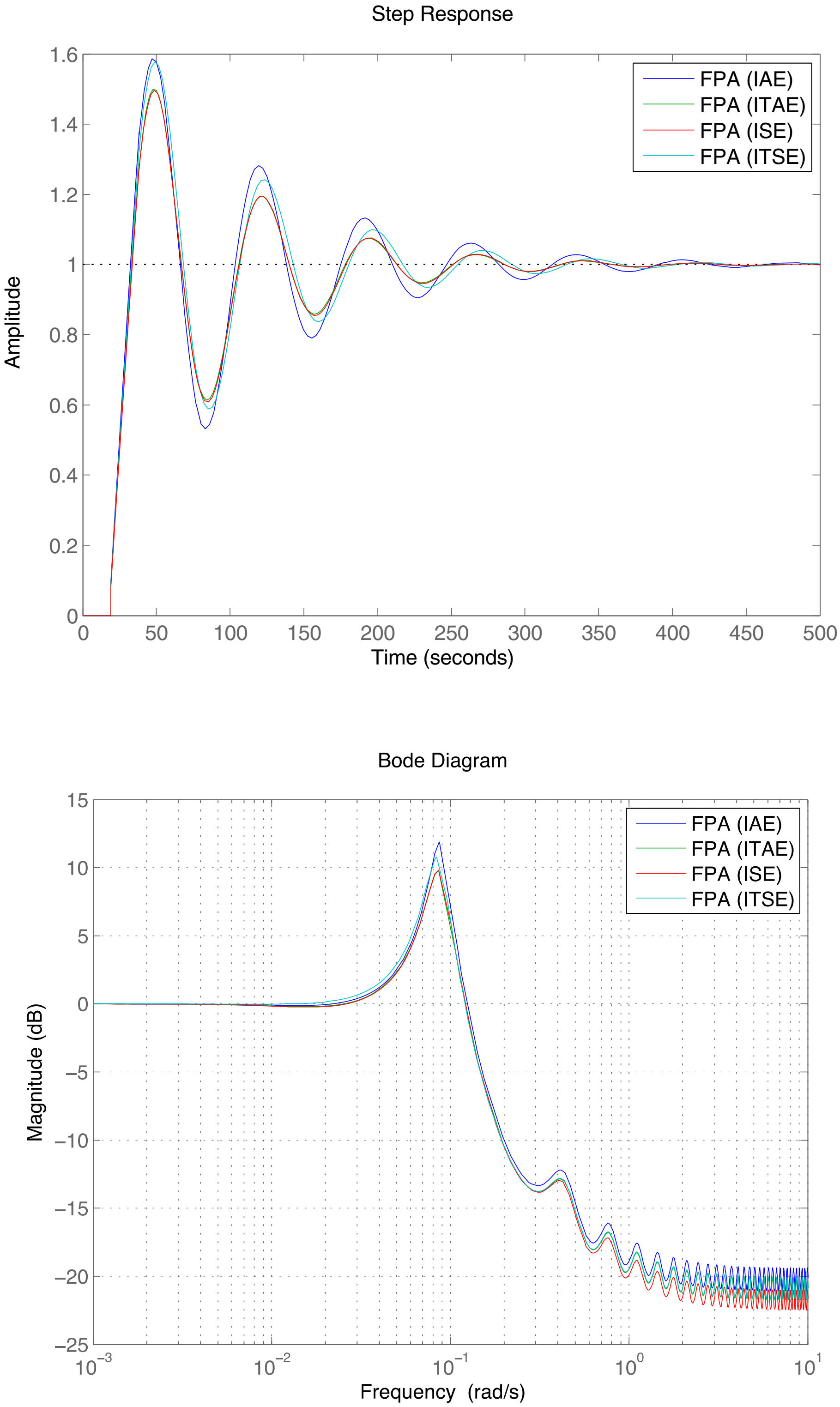


Figure 4.10: Step and frequency response of the closed loop system with FPA optimized PID controller parameter

From the Figure 4.10(a) it can be seen that the FPA tuned controller offers an oscillatory response. So the designed controllers are not optimal for implementation. Also from the Figure 4.10(b), the frequency response of all closed-loop system has very high peaks above the 0 dB line and this response is not optimum for the design purposes.

Multi-Objective Optimization Design of the Controller Using Genetic Algorithm

GA specific parameters (from Table 4.1) used in the optimization. Optimal values of the controller parameters given in Table 4.15 and various time and frequency domain performance indices shown in Table 4.16.

Table 4.15: PID Controller Gains Obtained using Genetic Algorithm

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	5.26	328.327	300
K_I	4.625	9.487	7.893
K_D	0.456	660.535	398.823

Table 4.16: Performance Indices of the designed controllers using Genetic Algorithm

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	50.87	15.47	17.23
Settling Time (sec.)	447.98	154.4	154.26
Overshoot Percentage (%)	36.6	37.47	28.37
Gain Margin (dB)	1.51	0.78	0.901
Phase Margin (deg.)	18.81	-21.2	-10.54

These controller parameters have used for simulating the closed loop response of the system. Figure 4.11 shows the compared step response and the frequency response of the designed closed loop system.

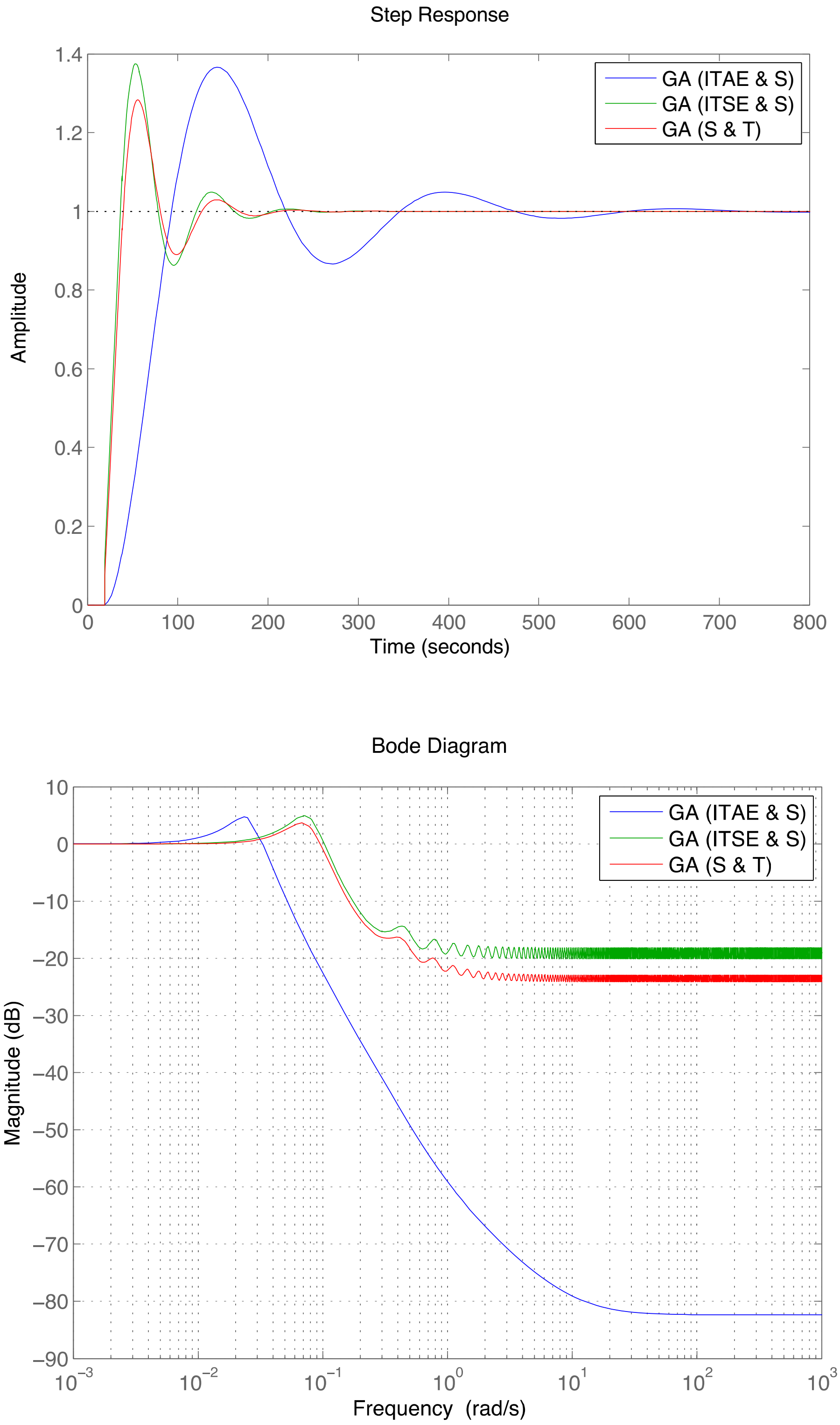


Figure 4.11: Step and frequency response of the closed loop system with GA optimized PID controller parameter

From the Figure 4.11(a) it can be seen that the designed GA tuned controllers has very high overshoot percentages and cannot use in the implementation. Also from Figure 4.11(b), the frequency response of the closed-loop system has several peaks above the 0 dB line and this response is not optimum for the design purpose.

Using BAT Algorithm

BAT Algorithm specific parameters (from Table 4.2) used in the optimization. Optimal values of the controller parameters given in Table 4.17 and various time and frequency domain performance indices shown in Table 4.18

Table 4.17: PID Controller Gains Obtained using bat algorithm

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	609.8	522.8967	20.784
K_I	12.9	13.5956	1.4889
K_D	1075.9	525.0693	981.586

Table 4.18: Performance Indices of the designed controllers using BAT algorithm

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	∞	9.68	225.23
Settling Time (sec.)	∞	1593.4	331.66
Overshoot Percentage (%)	∞	92	0.22
Gain Margin (dB)	2.56	3.66	5.11
Phase Margin (deg.)	-92.39	-83.07	180

These controller parameters have used for simulating the closed loop response of the system. Figure 4.12 shows the compared step response and the frequency response of the designed closed loop system.

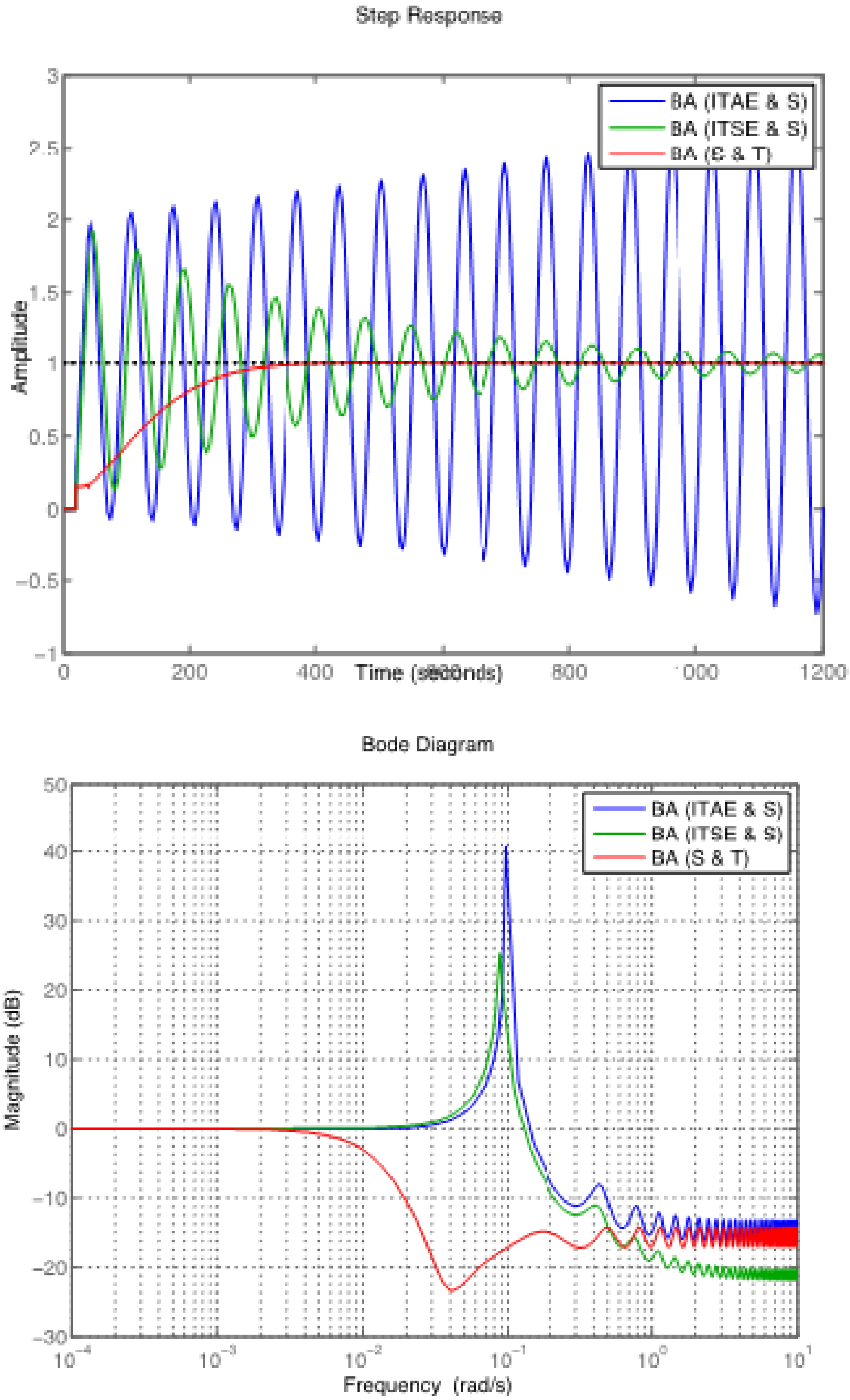


Figure 4.12: Step and frequency response of the closed loop system with GA optimized PID controller parameter

From the Figure 4.12(a) it can be seen that the BA (S & T) controller offer optimum performance with zero percent overshoot. Also from Figure 4.12(b), the frequency response of the closed-loop system (S + T) has zero peaks near the 0 dB line, and this response is optimal, suitable for the design purpose. The response offered by ITAE + S tuned controller unstable, and the response provided by ITSE + S tuned controller is oscillatory with high values of overshoot percentages. So, response offered by S+T tuned controller may use for application purpose.

Using PSO Algorithm

PSO Algorithm specific parameters (from Table 4.4) used in the optimization. Optimal values of the controller parameters given in Table 4.19 and various time and frequency domain performance indices shown in Table 4.20

Table 4.19: PID Controller Gains Obtained using PSO

Controller Parameter	**JITAE+S**	**JITSE+S**	**JS+T**
KP	10.71	16.634	12.78
KI	4.1505	4.3854	0.674
KD	-0.4429	-0.2134	-0.357

Table 4.20: Performance Indices of the designed controllers using PSO

Performance Index	**JITAE+S**	**JITSE+S**	**JS+T**
Rise Time (sec.)	56.19	53.85	543.62
Settling Time (sec.)	446.48	433.85	992.65
Overshoot Percentage (%)	29.01	29.64	0
Gain Margin (dB)	1.98	1.99	27.79
Phase Margin (deg.)	38.65	36.74	180

These controller parameters have used for simulating the closed loop response of the system. Figure 4.13 shows the compared step response and the frequency response of the designed closed- loop system.

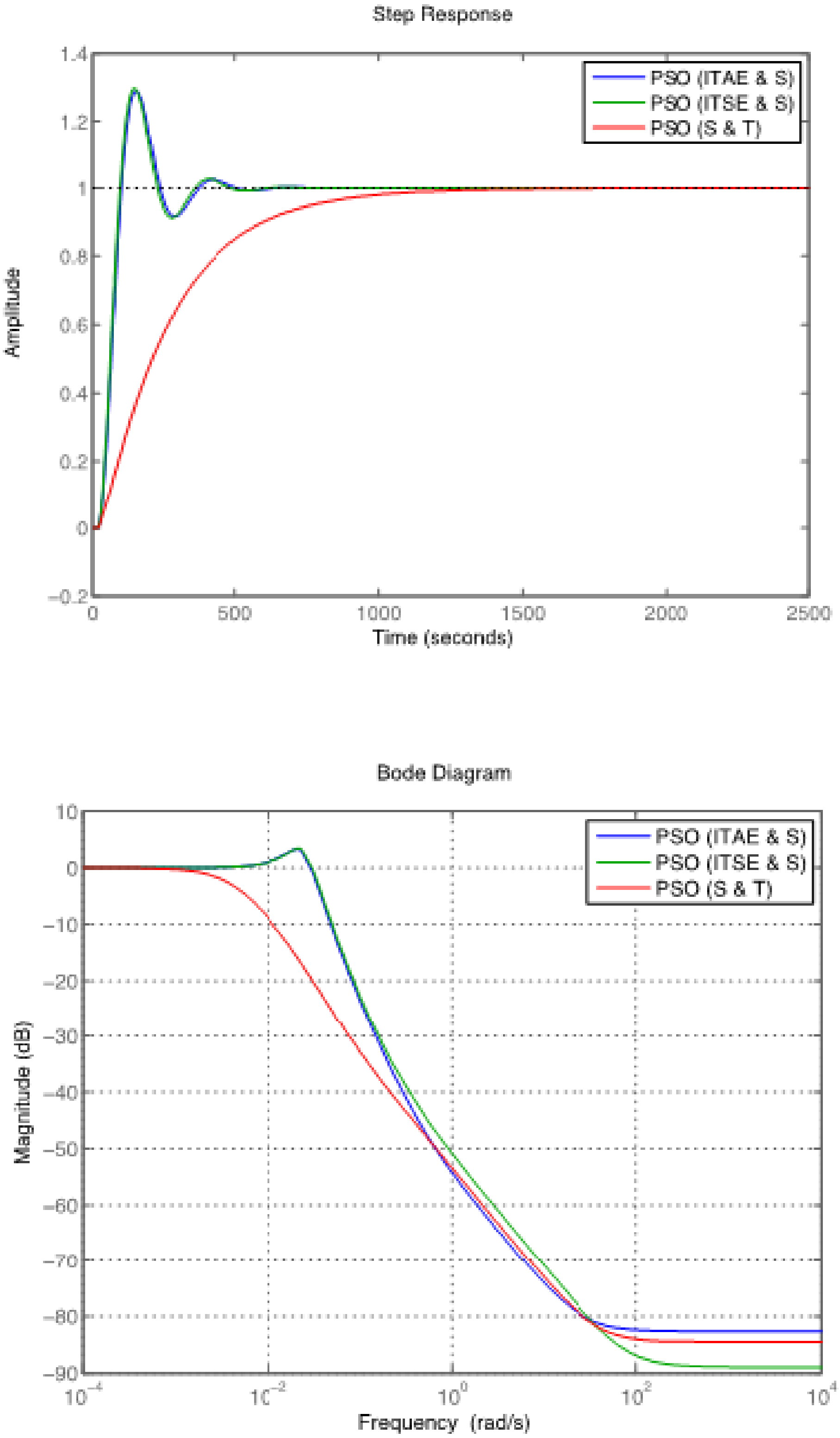


Figure 4.13: Step and frequency response of the closed loop system with PSO optimized PID controller parameter

From the Figure 4.13(a) it can be observed that the PSO (S & T) controller offer the best performance with zero percent overshoot. Also from Figure 4.13 (b), the frequency response of the closed-loop system (S + T) has zero peaks near the 0 dB Line, and this response is optimum possible for the design purpose. The response provided by ITAE + S & ITSE + S tuned controller is highly oscillatory with very high values of overshoot percentages. So, response offered by S+T tuned controller may be suitable for application purpose.

Using Flower Pollination Algorithm

FPA specific parameters (from Table 4.3) used in the optimization. Optimal values of the controller parameters given in Table 4.21 and various time and frequency domain performance indices shown in Table 4.22

Table 4.21: PID Controller Gains Obtained using FPA

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	377.6054	318.604	128.7882
K_I	9.6963	9.4239	4.1306
K_D	339.314	304.6531	579.7869

Table 4.22: Performance Indices of the designed controllers using FPA

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	13.52	15.64	63.47
Settling Time (sec.)	259.78	198.7	107.1
Overshoot Percentage (%)	51.51	42.16	1.42
Gain Margin (dB)	0.47	0.70	4.07
Phase Margin (deg.)	-48.02	-27.96	180

These controller parameters have been used for simulating the closed loop response of the system. Figure 4.14 shows the compared step response and the frequency response of the designed closed loop control system.

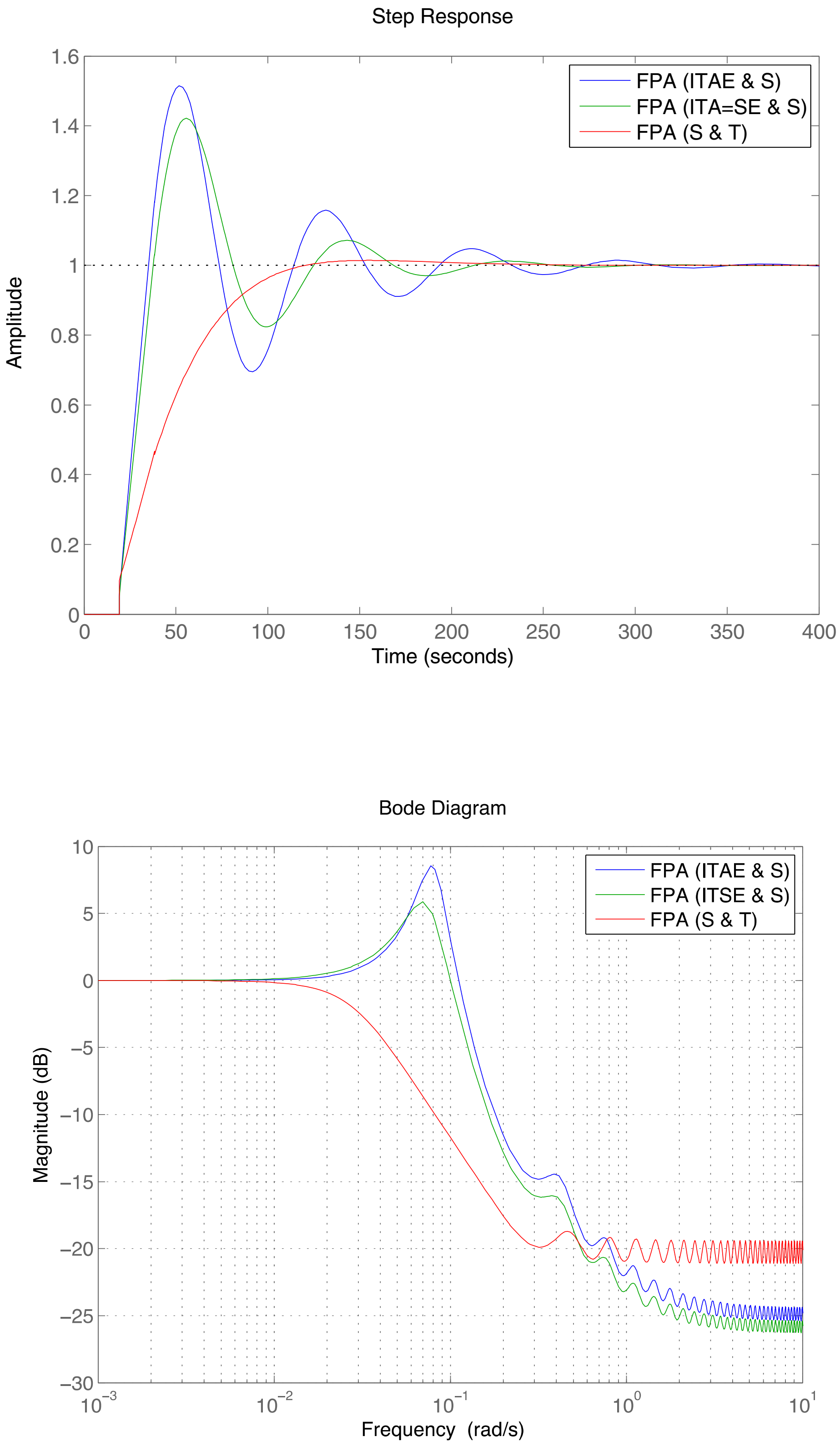


Figure 4.14: Step and frequency response of the closed loop system with GA optimized PID controller parameter

From the Figure 4.14(a), it can see that the FPA (S+T) tuned controller offer the best possible response. Also from Figure 4.14(b) the frequency response of FPA (S+T) tuned controller has zero peak-over 0 dB line, and this response is optimum for the design purpose.

Multi-Objective optimization using GFCL

In this work, design objectives of ITSE, ITAE, and sensitivity have been considered and have expressed as a multi-objective design problem, and the proposed cost function has been minimized using the multi-objective variants of GA (NSGA-II) and PSO. For cost-functions used the equation 4.21 and 4.22.

Using Multi-Objective Genetic Algorithm

Multi-objective genetic algorithm (MOGA) is one of the oldest and widely used multi-objective evolutionary algorithms used in optimization. In this work, GA has used for minimizing the controller design objectives defined in equation (4.21 – 4.22) to find the optimal values of controller gain parameters given by equation (4.17). Various genetic algorithm-specific parameters considered in the optimization defined in Table 4.6.

The minimization of both the objectives defined by equation 4.21 and 4.22 has been carried out in MATLAB. After the optimization, a Pareto optimal set (POS) of solutions has obtained. The plot of POS for the design objectives and the corresponding controller gains for objective J1 (ITSE + S) has visualized in figure 4.15, and the Pareto front visualization for objective J1 has shown in figure 4.16.

The closed loop step response and the frequency of the designed control system with the controller parameters obtained in POS shown in figure 4.17.

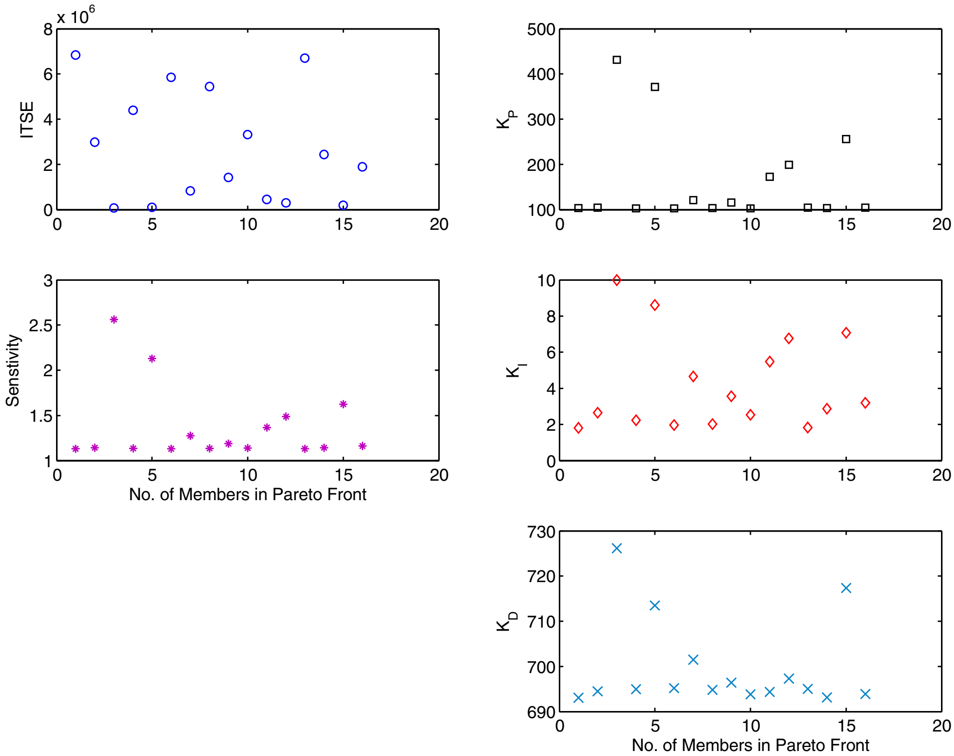


Figure 4.15: Plot for the Pareto Optimal Set of Solutions (Design Objectives and Controller Gains)

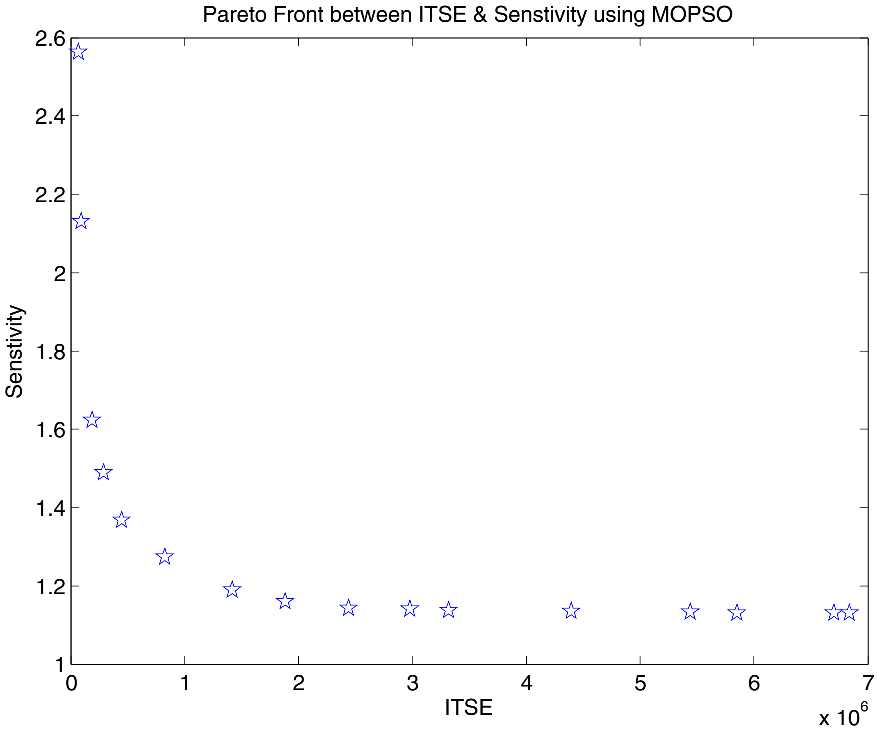


Figure 4.16: Pareto Front Visualization of Controller Design Objectives

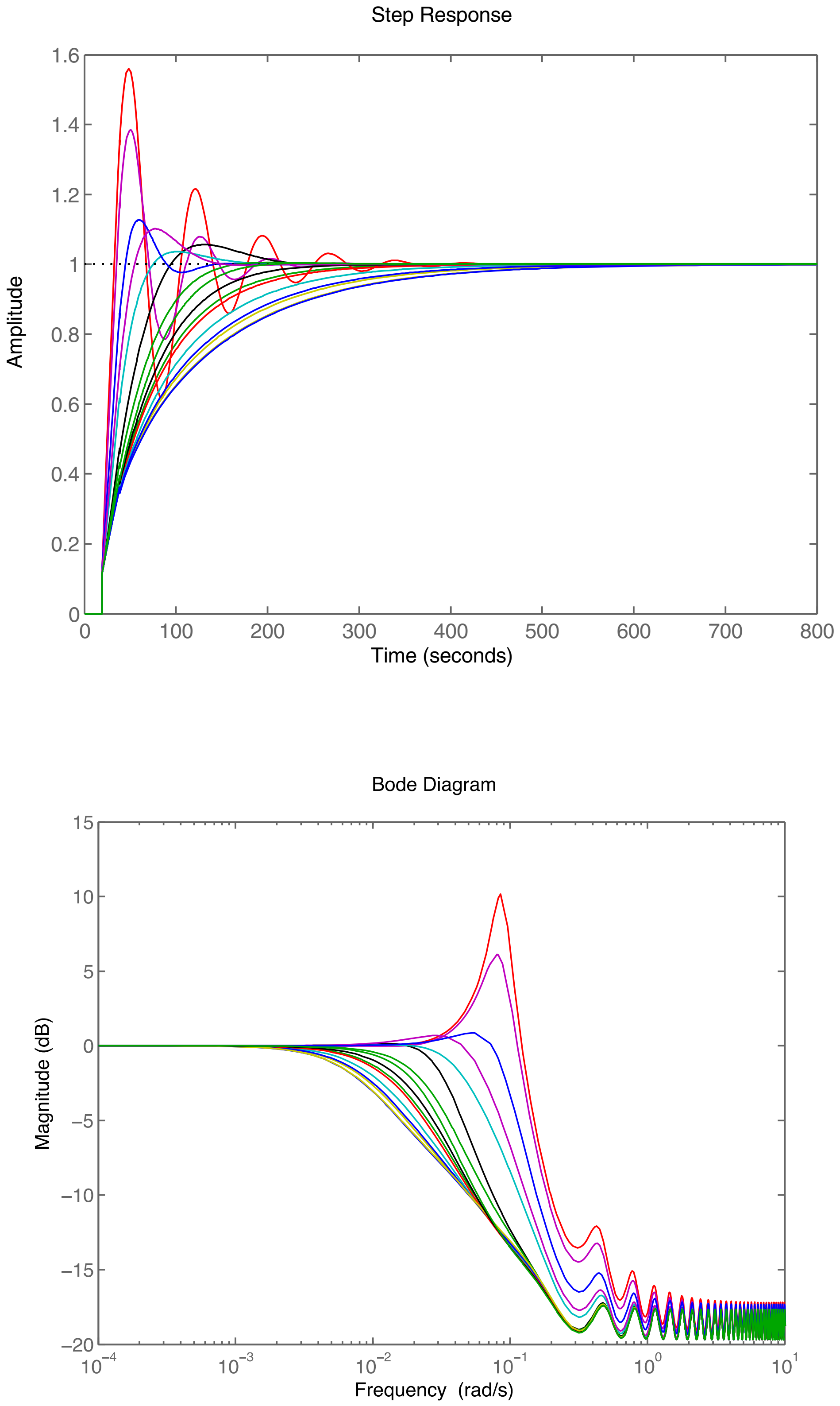


Figure 4.17: Step and frequency response of the closed loop system with Pareto optimal set of solutions

The best solution has been chosen using Pareto front and the response of the control system in figures 4.17. The controller parameters are offering best response is given in table 4.23 and their corresponding time and frequency domain responses in figure 4.18.

Table 4.23: PID Controller Gains Obtained using MOGA by minimizing J1

Controller Parameter	**K_P**	**K_I**	**K_D**
J_1	103.5	2.88	693.12

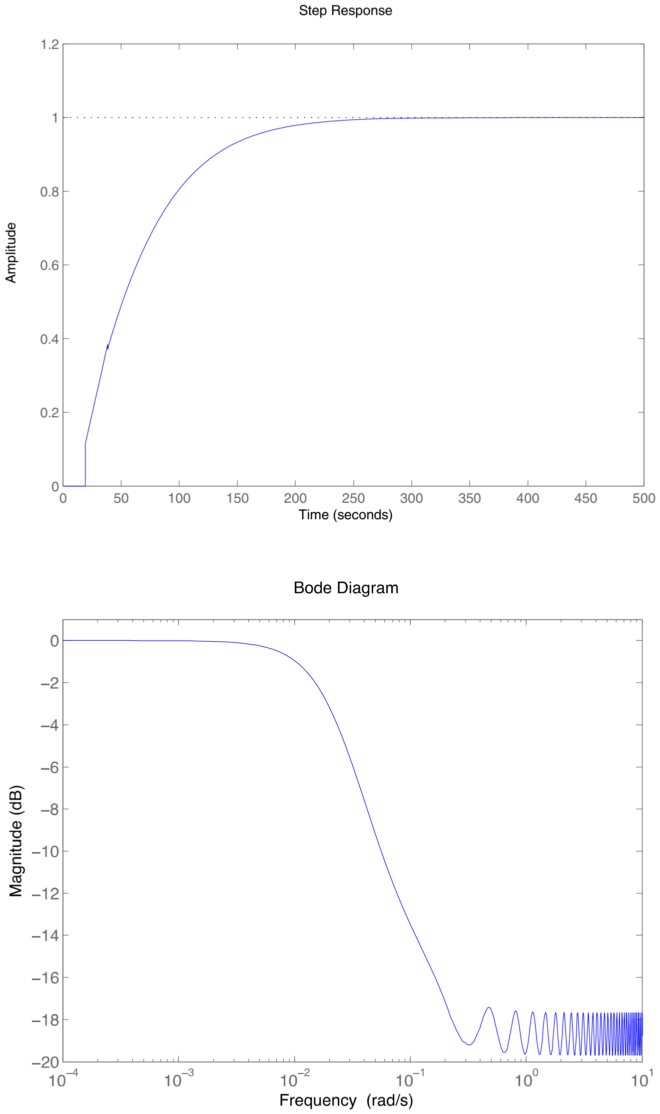


Figure 4.18: Step and frequency response of the closed loop system with best controller parameters chosen from POS

After the optimization, a Pareto optimal set (POS) of solutions has obtained. The plot of POS for the design objectives and the corresponding controller gains for objective J2 (ITAE + S) has visualized in figure 4.19, and the Pareto front visualization for objective J1 shown in figure 4.20.

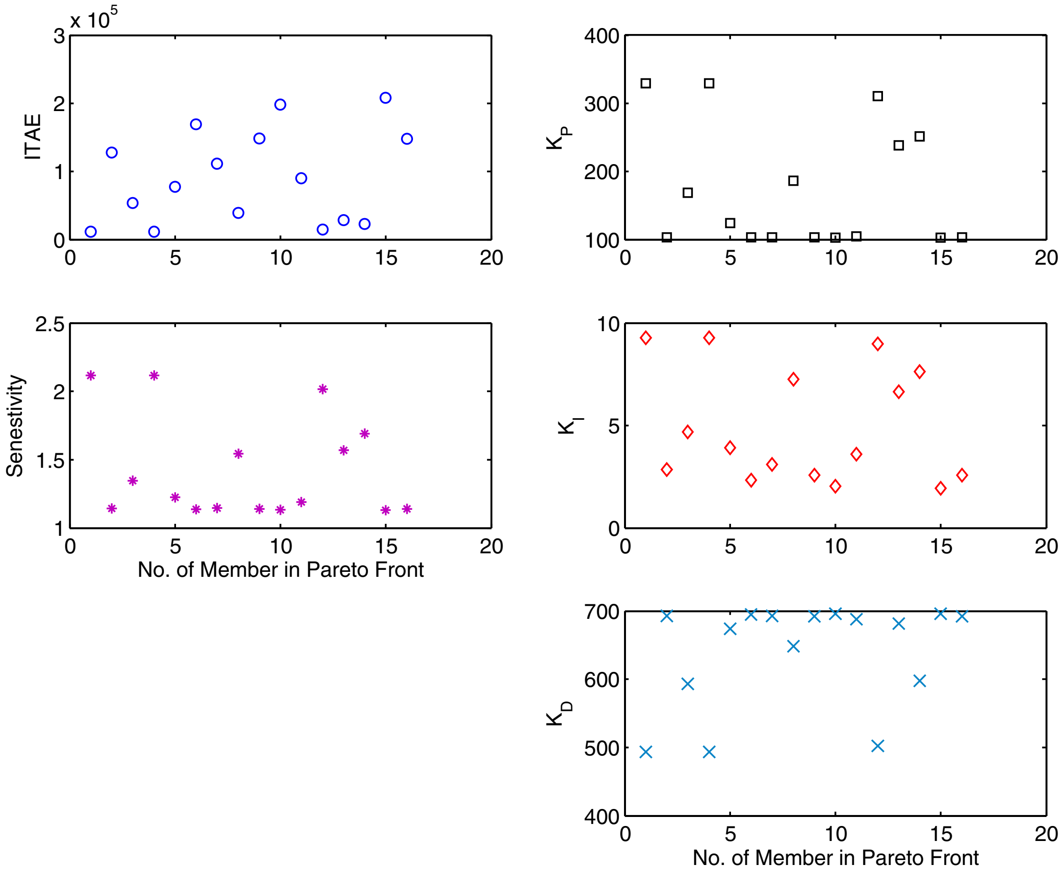


Figure 4.19: Plot for the Pareto optimal set of solutions (Design objectives and controller gains)

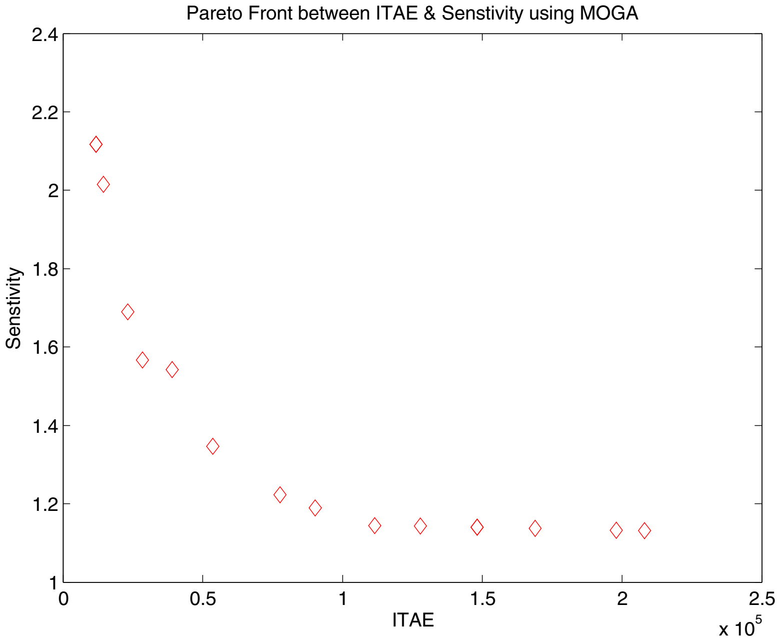


Figure 4.20: Pareto front visualization of controller design objectives

The closed loop step response and the frequency response of the designed control system with the controller parameters obtained in POS shown in figure 4.21

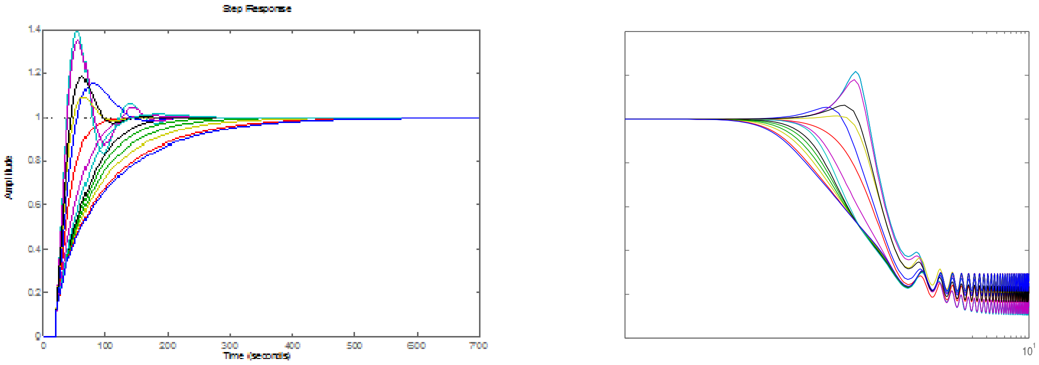


Figure 4.21: Step and frequency response of the closed loop system with Pareto optimal Set of Solutions

The best solution has chosen using Pareto front and the response of the control system in figures 4.21. The controller parameters offering best response given in table 4.24 and their corresponding time and frequency domain responses in figure 4.22

Table 4.24: PID Controller Gains Obtained using MOGA by Minimizing J_2

Controller Parameter	**K_P**	**K_I**	**K_D**
J_2	168.94	4.69	593.32

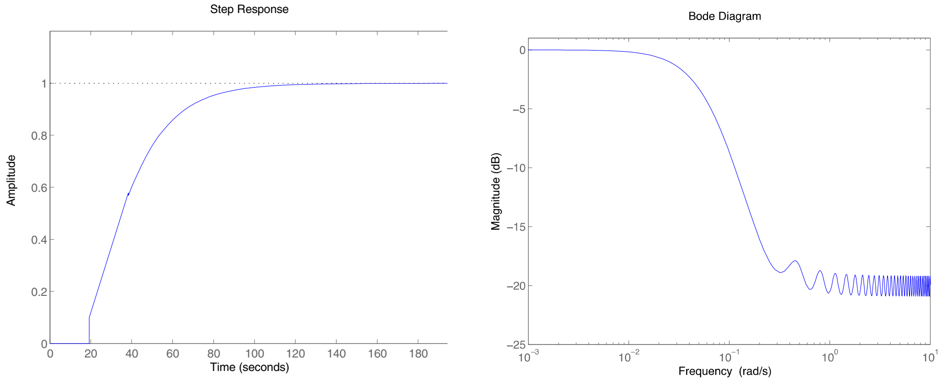


Figure 4.22: Step and frequency response of the closed loop system with best controller parameters chosen from POS

Compared time and frequency domain performances of the control system with finest controller chosen as in table 4.23 and 4.24 given in table 4.25 as:

Table 4.25: Performance Indices of the designed controllers using MOGA

Performance Index	**J_1**	**J_2**
Rise Time (sec.)	112.52	47.11
Settling Time (sec.)	202.39	95.70
Overshoot Percentage (%)	≈ 0	0
Gain Margin (dB)	5.31	2.77
Phase Margin (deg.)	180	180

Using Multi-objective particle swarm optimization

Multi-objective particle swarm optimization (MOPSO) is one of the oldest and widely used multi-objective swarm optimization algorithm used in optimization. In this work, MOPSO has used for minimizing the controller design objectives defined in equation (4.21 – 4.22) to find the optimal values of controller gain parameters given by equation (4.17). Various PSO algorithm-specific parameters considered in the optimization defined in Table 4.5.

The minimization of both the objectives defined by equation 4.21 and 4.22 has been carried out in MATLAB. After the optimization, a Pareto optimal set (POS) of solutions has obtained. The plot of POS for the design objectives and the corresponding controller gains for objective J1 (ITSE + S) has visualized in figure 4.23, and the Pareto front visualization for objective J1 shown in figure 4.24.

The closed loop step response and the frequency response of the designed control system with the controller parameters obtained in POS shown in figure 4.25.

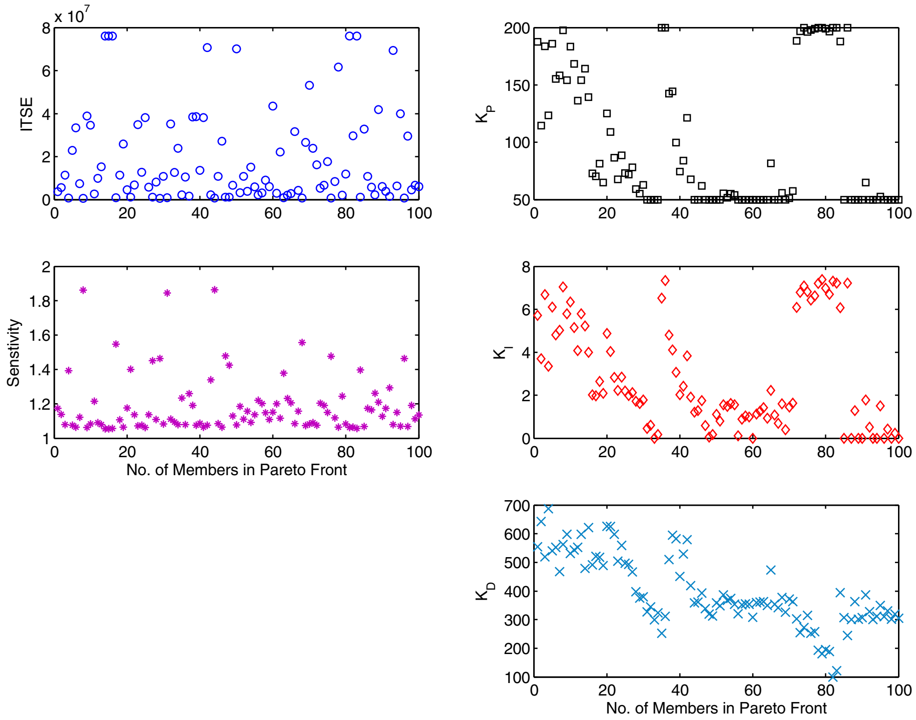


Figure 4.23: Plot for the Pareto optimal set of solutions

(Design objectives and controller gains)

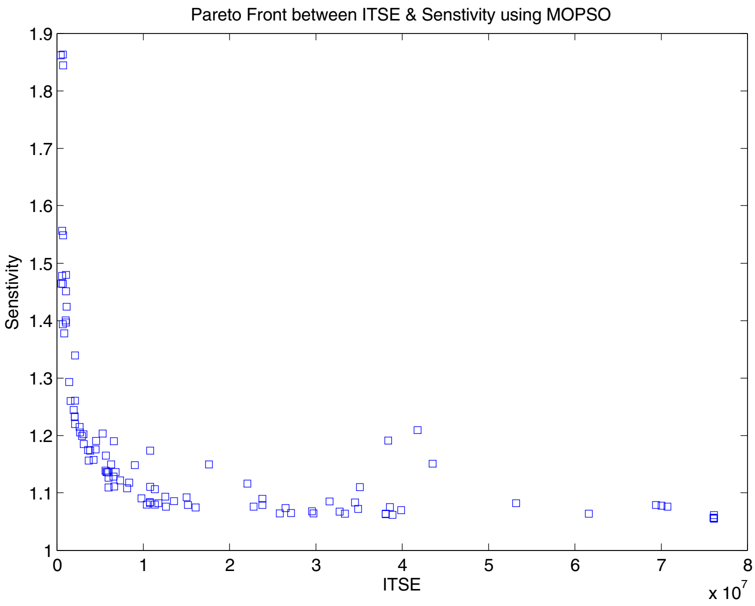


Figure 4.24: Pareto front visualization of controller design objectives

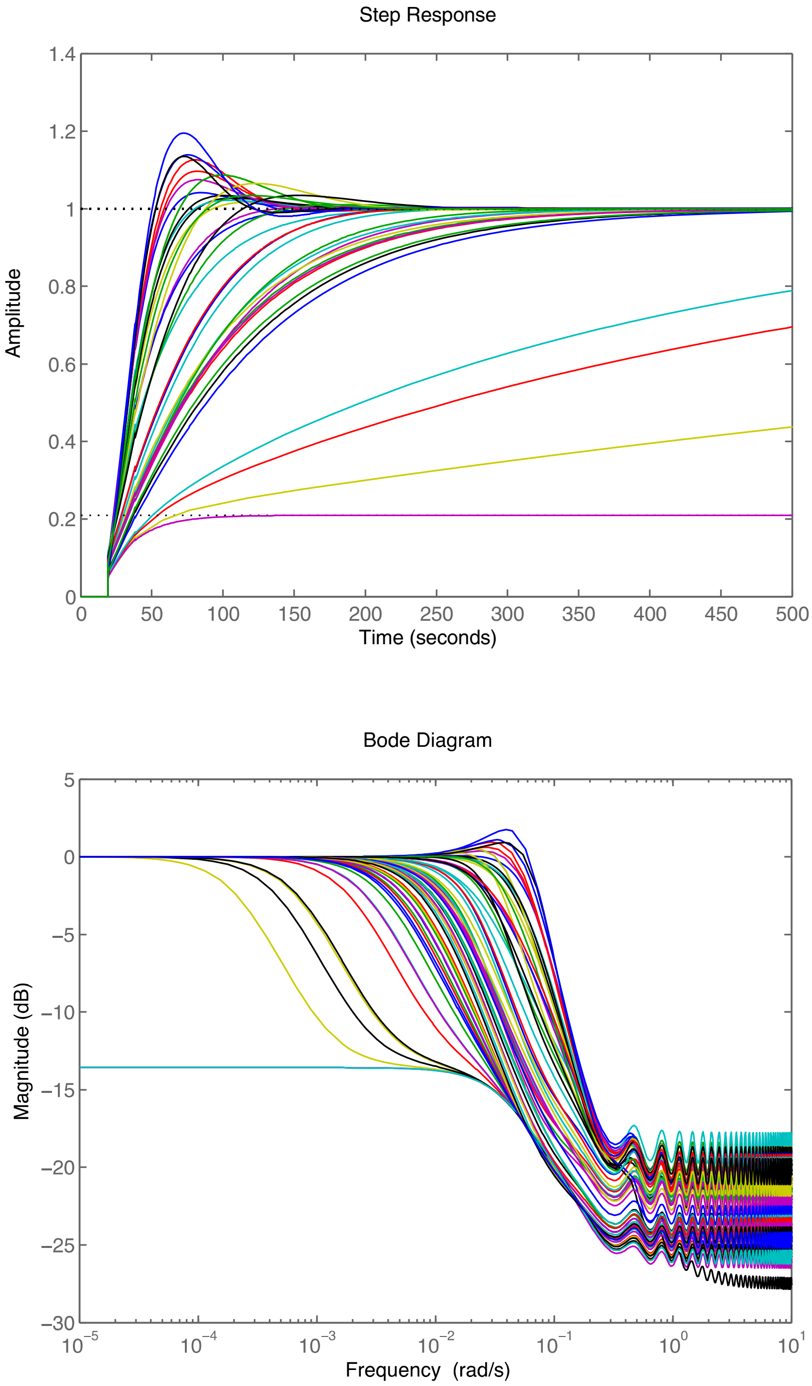


Figure 4.25: Step and frequency response of the closed loop system with Pareto optimal set of solutions

The best solution has chosen using Pareto front and the response of the control system in figures 4.25. The controller parameters offering best response given in table 4.24 and their corresponding time and frequency domain responses in figure 4.26.

Table 4.26: PID controller gains obtained using MOPSO by minimizing J_1

Controller Parameter	$\mathbf{K_P}$	$\mathbf{K_I}$	$\mathbf{K_D}$
$\mathbf{J_1}$	73.02	2.19	496.66

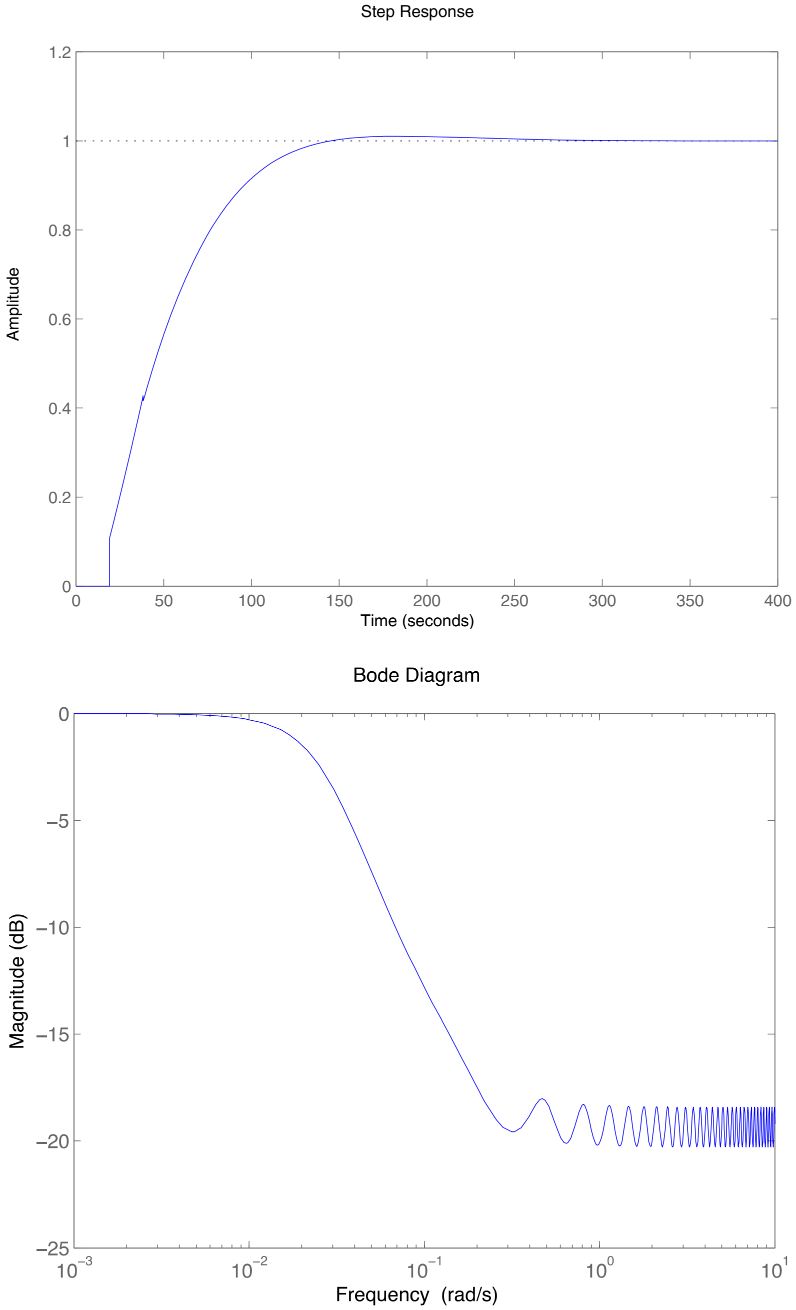


Figure 4.26: Step and frequency response of the closed loop system with best controller parameters chosen from POS

After the optimization, a Pareto optimal set (POS) of solutions has obtained. The plot of POS for the design objectives and the corresponding controller gains for objective J2 (ITAE + S) has visualized in figure 4.27, and the Pareto front visualization for objective J1 shown in figure 4.28.

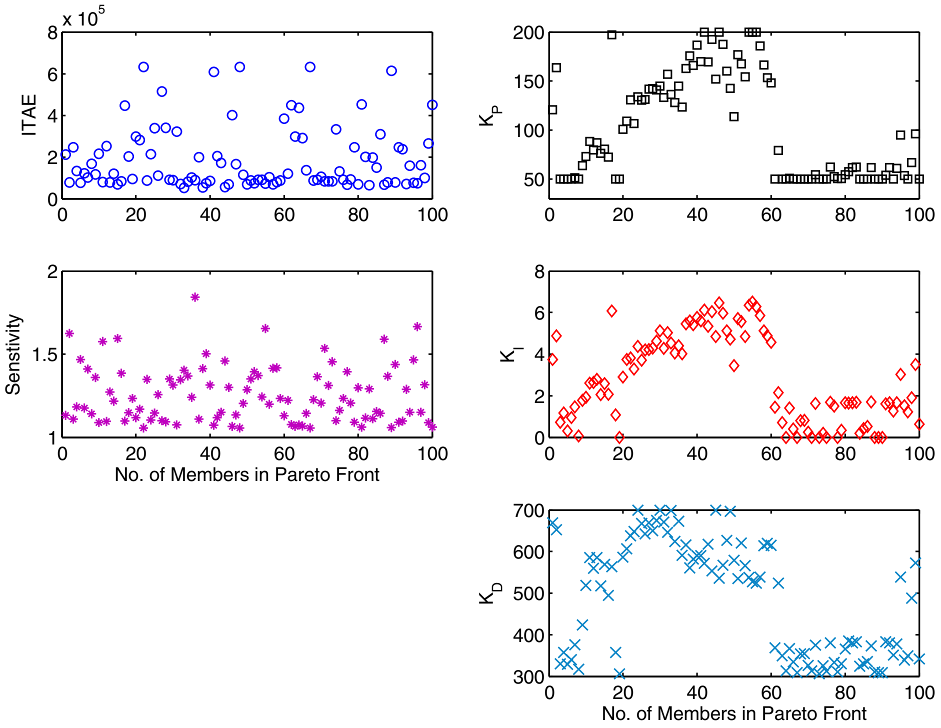


Figure 4.27: PID controller gains obtained using MOPSO by minimizing J_2

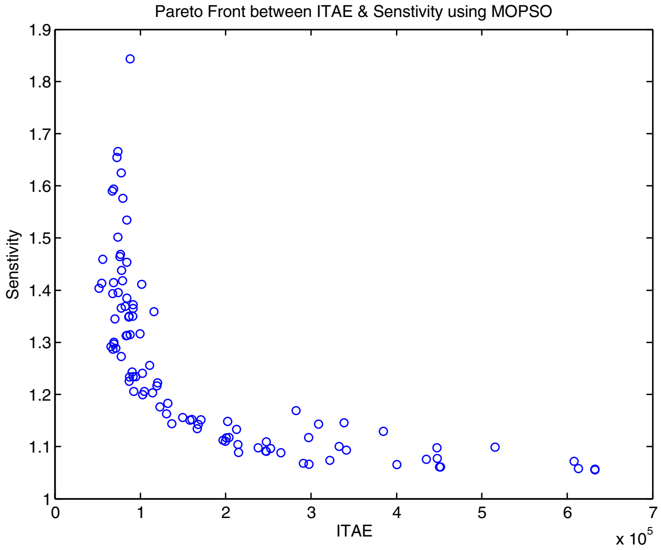


Figure 4.27A: Plot for the Pareto optimal set of solutions

(Design objectives and controller gains)

The closed loop step response and the frequency response of the designed control system with the controller parameters obtained in POS shown in figure 4.29.

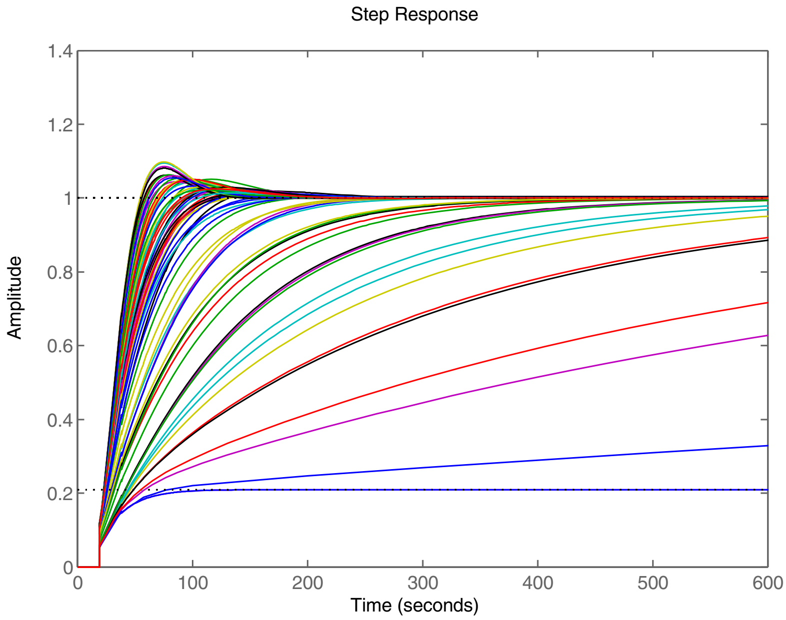


Figure 4.28: Pareto front visualization of controller design objectives

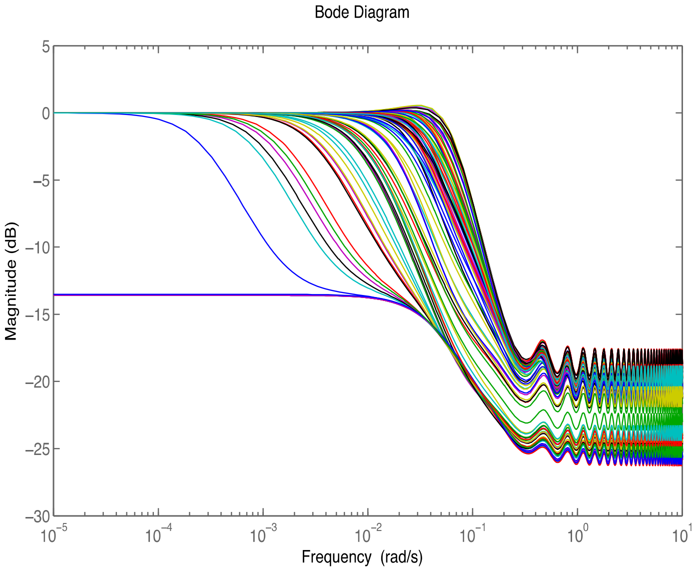


Figure 4.29: Step and frequency response of the closed loop with Pareto optimal set of solutions

The best solution has chosen using Pareto front and the response of the control system in figures 4.29. The controller parameters offering best response given in table 4.27 and their corresponding time and frequency domain responses in figure 4.30

Table 4.27: PID controller gains obtained using MOPSO by minimizing J_2

Controller Parameter	**K_P**	**K_I**	**K_D**
J_2	163.65	4.88	652.25

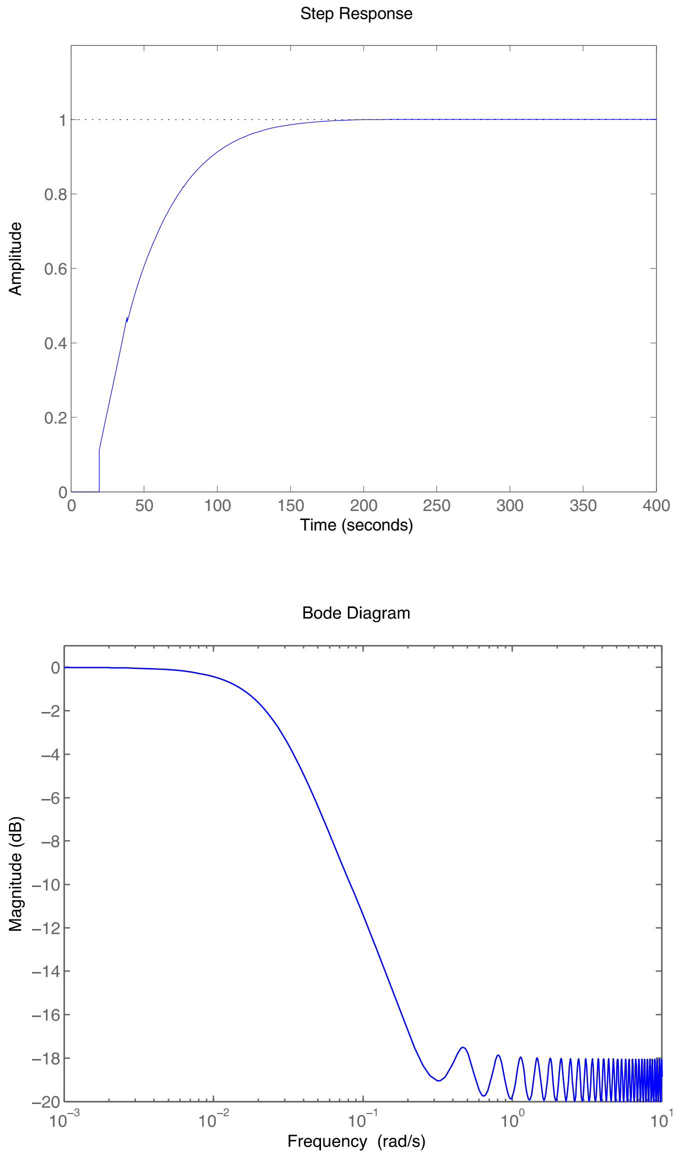


Figure 4.30: Step and frequency response of the closed loop system with best controller parameters chosen from POS

Compared time and frequency domain performances of the control system with the best controller chosen as in table 4.26 and 4.27 given in table 4.28 .

Table 4.28: Performance indices of the designed controllers using MOPSO

Performance Index	**J_1**	**J_2**
Rise Time (sec.)	76.65	76.48
Settling Time (sec.)	126.41	140.31
Overshoot Percentage (%)	1.05	0.078
Gain Margin (dB)	4.82	4.098
Phase Margin (deg.)	180	180

Comparative Study for Performance Evaluation

Table 4.29**:** Comparison between MOGA and FPA based on Performance Indices

Method	**MOGA (GFCL)**		**Multi-Objective FPA (AOF)**		
Performance Index	**J_1**	J_2	**J_{S+T}**	**J_{ITAE+S}**	**J_{ITSE+S}**
Rise Time (sec.)	112.52	47.11	63.47	13.52	15.64
Settling Time (sec.)	202.39	95.70	107.1	259.78	198.7
Overshoot Percentage (%)	**≈ 0**	0	1.42	51.51	42.16
Gain Margin (dB)	5.31	2.77	4.07	0.47	0.70
Phase Margin (deg.)	180	180	180	-48.02	-27.96

The use of Multi-Objective Genetic Algorithm for optimizing the PID controller parameters as reported in this study offers advantages of decreased % overshoot, rise and settling time for the process resulting in better plant operations and robustness. Results when compared with the FPA as presented in this study, **the proposed Multi-Objective Genetic Algorithm** has proved superior in achieving the steady-state response and performance indices.

By results and discussions, it concluded that Soft Computing Techniques are fines to be used for PID Controller Tuning. The only main issue here is the precise problem formulation (selection of the cost function and appropriate weighting factors) which leads to a drawback of the local minima trap where the optimal solution not reached. On the other hand, for analytical tuning rules, the best result appears to have been obtained using a set of rules.

4.5 SUMMARY

In this chapter, different optimization techniques are carried out for better performance. First, in the design of controller using a single optimization different time domain performance indices have been used for formulating the objective function and have been solved using various optimization algorithms like GA, BA, PSO, FPA. But the results obtained are not satisfactory as in all the cases, the time-response of the controller is very oscillatory, and the minimum peak overshoot has obtained for GA (ITAE) tuned controller and also the frequency response there are peaks above the 0dB line. Thus these designs are not suitable for controller applications.

Second, the design of controller using multi-objective optimization has considered. The multi-objective optimization problem has expressed as a weighted sum of objectives and both the time and frequency domain performances have used to form the cost functions. The objectives of robust controller synthesis have used in conjunction with the time domain performances. The results obtained by the PSO, BA, and FPA when minimizing the infinity norm of sensitivity function and complementary sensitivity function (S+T) offers the best response both in the time domain and frequency domain, with no peaks above the 0 dB line on Bode plots. On comparing the time response, the flower pollination algorithm based controller offers the excellent response in comparison.

Lastly, a design controller using multi-objective optimization has considered. The problem has been expressed using Generate First Choose Later (GFCL) approach and both the time and frequency domain performances have used to form the cost functions. The objectives of robust controller synthesis have used in conjunction with the time domain performances. The results are obtained by the MOGA when minimizing the infinity norm of sensitivity function, and ITAE (equation J2) offers the best response both in the time domain with zero peaks above the 0 dB line on Bode plots. Thus, providing the most elegant controller for implementation purposes.

Chapter-5

ROBUST PID CONTROLLER TUNING

In this chapter, tuning is carried out to ensure robustness in the existence of typical problems in a process industry.

5.1 OVERVIEW

There are many tuning techniques available in the literature; however, none of them offer an ideal comprehensive solution to PID performance. There are some critical issues in the tuning of the controller for optimal process performance, an area that needs attention. Considering the facts that process models are rarely precise and accurate plus the existence of process disturbances requires that these issues need to be taken into account when PID controllers are tuned. This work aim evaluates and compare some well-known tuning rules and to suggested guidelines for robust tuning methods from a practical point of view. In this chapter, tuning is carried out to ensure robustness in the presence of abnormalities such as process changes, model- plant mismatch, valve stiction, saturation, sensor noise, and unmeasured disturbances.

The conventional methods seldom take real process abnormalities such as model plant mismatch and valve stiction into account. In this chapter, we attempt to view the issue of PID tuning from this perspective and look for a robust design against real problems in the process industry. Various well known PID techniques are evaluated and compared to a standard first-order plus time delay (FOPTD) processes. The ITAE (track), IMC and Villanova tuning rules are suggested for set-point tracking, while in the case of regulation, Z-N, ZNIMC and AMIGO tuning rule is verified to offer satisfactory results. For each category the best performing tuning rule gives the best results in nominal conditions, but as the uncertainty inside the system worsens, more robust tuning rules become superior in performance.

Extensive simulation results presented for a proposed model and afterward, an acceptable tuning is chosen and suggested. In the end, some concluding remarks and remedies suggested.

5.2 Objectives of a Robust PID Controller

In design and configuration of PID controller should elucidate to these objectives:

- Tracking of set points
- Regulation in the presence of Process Disturbances
- Robustness to Model uncertainties
- Attenuation of Sensor Noise
- Stability and Safety Consideration

The existence of such a trade-off between control objectives makes it necessary to prioritize the design for each application. The idea that there is no single solution for the tuning of an optimal controller.

In this work, we are more concerned about the robust design of system against structural model uncertainties and its trade-off against overall performance. However, problems of valve stiction and sensor noise are included in the design as well.

5.3 Choice of Process & Controller

In this study, we have focused on First-Order-Plus Time-Delay (FOPTD) systems with following dynamics

$$G_P(s) = \frac{K_P}{\tau s + 1}.e^{-\theta s} \tag{5.1}$$

FOPTD processes are a common type of systems given that such models can sufficiently well characterize the dynamics of most over damped operation. They are also known as three-parameter models; process gain, time constant and dead time being the varying parameters.

For the purpose of evaluation, we use the following standard ISA form of the PID controller as widely used in literature with a filter applied to the derivative part.

$$G_c = K_c(1 + \frac{1}{\tau_I.s} + \frac{\tau_D.s}{\tau_f.s+1}) \tag{5.2}$$

Based on the suggestion of Brosilow [157] to avoid noise amplification inside feedback loop the ratio of $\frac{\tau_f}{\tau_D}$ is selected to be 0.1. Ensures the system to have

$$\left|\frac{G(j\infty)}{G(0)}\right| < 20$$

5.4 Selection of Desired Closed Loop Time Constant

As a general rule, the closed loop time constant should be less than its open loop to ensure the minimum speed of response. There are a variety of suggestions in the literature to make the easy decision [4].

In some more recent tuning rules such as the IMC, formulation, a condition is set for the operator to specify the closed loop time constant. The selection of this user-defined quantity has a critical role in the final dynamic response.

As a general rule, the closed loop time constant should be less than its open loop to ensure the minimum speed of response $\left(\frac{\tau_c}{\tau}\right) < 1$. There are a variety of suggestions in the literature to make the decision easier [4].

Chien and Fruehauf, 1990) $\tau_c < \theta < \tau$ (5.3)

Skogestad, 2003 $\tau_c = \theta$ (5.4)

Rivera et al., 1986 $\frac{\tau_c}{\theta} < 0.8$ and $\tau_c > 0.1\tau$ (5.5)

It has also been a description in [158] that for a robust performance $\tau_c \geq \theta$ should be maintained. Changing τ_c would compromise between two challenging classes of parameters [158].

- Fast speed of tracking response and disturbance rejection corresponding to closed loop settling time
- Stability margins and robustness of the system in addition to the required control effort.

Keep in mind that increasing τ_c gives you less speed but more stability. In this sense, a previous rule could be fine-tuned according to the application of interest. Here the control engineer's experience comes into play for a better process performance.

In this thesis work, value around 1.02 times the dead time is appropriate for the desired closed loop time constant. That would correspond to a 15% overshoot in the presence of 10% MPM. In disturbance rejection mode with process abnormalities, select the rule $\tau_c = 2\theta$ for better result.

5.5 Defining FOPTD Process Domains

First-Order-Plus Time-Delay (FOPTD) models known as three parameter models. They commonly used for simplified analysis in process control. Process gains, time constant and dead time are the varying parameters in these models. According to the literature of controller design [8], process gain has the most straightforward effect on the calculation of controller parameters in the tuning. By deriving the closed loop transfer function of a system it is clear that the product of $k_p \times K_c$ should remain constant and therefore the controller gain is a function of inverse k_p $[K_c = \mathrm{f}(1/k_p)]$ [3].

We can exclude this parameter from our evaluation without destruction to the generality of the problem. Both τ and θ have the dimension of time (sec). It founded that the ratio of these parameters has an essential impact on the final response. We define alpha as the ratio of:

$$\alpha = \frac{\theta}{\tau} \tag{5.6}$$

Any process model may fall into five categories [2].

Process is Pseudo-Pure Lag if $\alpha < 0{:}2$

Lag Dominant if $0.2 < \alpha < 0.5$

Balanced Lag and Delay if $0.5 < \alpha < 1$

Delay Dominant if $1 < \alpha < 3$

Pseudo-Pure Delay if $\alpha > 3$

The boundaries set for this classifications are not sharp and may need slight changes relying on the specific situation.

Table 5.1: Selection of FOPTD Process model for different value of α [159]

Domain $\alpha = \frac{\theta}{\tau}$	P-Pure Lag	Lag Dom.	Balanced lag & Delay	Delay Dominant	P-Pure delay
α	0.1	0.4	0.7	1.5	3

To make validation simple, we matched the system for each situation to fit our practical model. In most cases the correct choice of the desired closed loop time constant (τ_c) is of great importance. A rule of thumb to select the desired closed loop time constant given in Table 5.2

In simulations, IMC [159] PI controller exhibited itself as a more robust controller compared with PID version considering the same τ_c .However PI controller is use in noise rich environments. The tuning rules with large derivative time constants caused a more significant variance in valve stem position. Although all of the techniques have derivative filters mounted inside the controller, using stronger derivative filter could also help.

A thumb rule to select the desired closed loop time constant given in Table 5.2, which is known as IMC Formulation thumb rule [158].

Table 5.2: Thumb Rule for determining Closed-Loop Time Constant (IMC Formulation)

FOPTD Modeling Zone	**Closed Loop time Constant**
Lag Dominant	$\tau_c = \max\left(\frac{\tau}{2}, 2\theta\right)$
Balanced lag and delay	$\tau_c = \gamma\theta$
Delay Dominant	Performances based $\tau_c = \theta$ Maximum Robustness $\tau_c = \gamma\theta$
Hint :Use γ =2 for PID and γ =1.5 for PI Controller	

From the comparison of tuning techniques, it has assumed that this IMC formulation thumb rule gives the best solution regarding performance and robustness.

5.6 Process Simulation

To compare and evaluate the quality of tuning rules, we have attempted to simulate the performance of controllers designed. We have the effort to simulate the performance of controllers designed for our proposed plant. Conventional step-tracking and disturbance rejection tests used for comparison.

For each case of servo and regulatory control, three different tuning rules selected. The selection of the best is well related to the testing situation and the considerations for a particular application. In each group, three tuning rules are deliberately chosen in this way: one with excellent performance, other with good robustness and a compromise tuning solution. We have chosen ITAE [20, 21], IMC [17, 23], and Vilanova [19] for set-point tracking and Ziegler- Nichols [2], ZNIMC [161], and AMIGO [18] for regulatory control.

In this chapter, we have emphasized the performance of the plant in nominal condition and the presence of all abnormalities.

Process Abnormalities

During the testing of different tuning method, there are various Process Abnormalities exist in the process industry like Model Plant Mismatch (MPM), valve stiction, saturation, disturbance and sensor noise.

In the case of uncertainty in systems, 10% MPM pronounced. That means that each FOPTD parameter was computed built on a 10% error in the gain, the time constant, and delay in the worst case direction. In the case of uncertain systems 10% MPM was imposed. That means that every FOPTD parameter was computed built on a 10% error in the gain, a time constant, and delay in the worst case direction. It is tantamount to higher than the normal estimated value of process gain and dead time and a reduced estimate of the time constant. The valve stiction introduced with the dead-band including stick-band of 2 and a slip jump of magnitude 1 [160]. The valve stiction block idea is adopted from the study of literature by Choudhury et al. [96]. Finally, measurement noise with variance of 0.01 and zero random seed was applied directly to the process.

5.7 Methodology

Various PID controller tuning techniques are available in the literature to achieve good performance and robustness characteristics for a feedback system, it is essential to differentiate between regulatory and tracking mechanisms. [161]. It means we have a need to design two sets of tuning parameters for our system.

Various evaluation techniques have to perform to achieve good performance and robustness characteristics for a feedback system [161]. Differentiate between step tracking and a Disturbance rejection mechanism is necessary. One way to address this problem is to use a controller with two degrees of freedom which is not the purview of this research.

Hence, we have to apply two optimal methods in our proposed problem which are step-tracking and disturbance rejection. The complete idea of controller design is based on a robust method which gives acceptable satisfactory control performance. One important point is that our endeavor aims to provide a handy and straightforward method useful to the sugar industry. Trial and error method applied to fine tuning so suitable controller parameters and evaluation is carried out by both qualitative and quantitative techniques. The main emphasis is given to the AMIGO due to its superior robustness characteristics.

5.7.1 Step Tracking

M. Morari et al. gives some result based on the industrial problem [162], according to that IMC technique shows good performance and robustness for step tracking and it comparatively tested in industry. The main confront for this method selection to determine the desired closed loop time constant.

In step tracking method, choose the different method of this category like IMC, ITAE (tracking) and Villanova to evaluate the performance and also compare the best approach to our proposed method AMIGO.

5.7.2 Disturbance Rejection

According to professionals, IMC tuning method does not get a good result in disturbance rejection in the process. In spite, classical Ziegler-Nichols tuning method can to rejected disturbances efficiently. Nonetheless, Ziegler-Nichols rule shows poor robustness but is a more aggressive tuning method than IMC rule.

For the IMC tuning rule has been fine tuned to obtain little or no undershoot for the second response peak in the presence of 10% MPM. However, that condition is not complete and therefore the final guidelines are needed for tracking are used as well for regulation. According to IMC rule, the desired closed-loop time constant is set to be equal or higher than the time delay.

5.8 Results & Discussion

In this chapter we want to study in to two categories. In the first category, choose step tracking and disturbance rejection PID tuning methods without any process abnormalities. Second category; choose step tracking and disturbance rejection PID tuning methods with all process abnormalities. The step tracking and disturbance rejection responses in the presence of the process abnormalities were drawn in

Figure 5.3, 5.4, 5.8 and 5.9 additionally, the sensitivity and complementary sensitivity plots were presented for each case.

Plant FOPTD $G(s) = \frac{1}{22.35s+1}e^{-15.7s}$

$K = 1$, $\tau = 22.35$, $\theta = 15.7$, $\alpha = \frac{\theta}{\tau} = \frac{15.7}{22.35} = 0.70$ (Balanced lag & Delay)

Step-Tracking

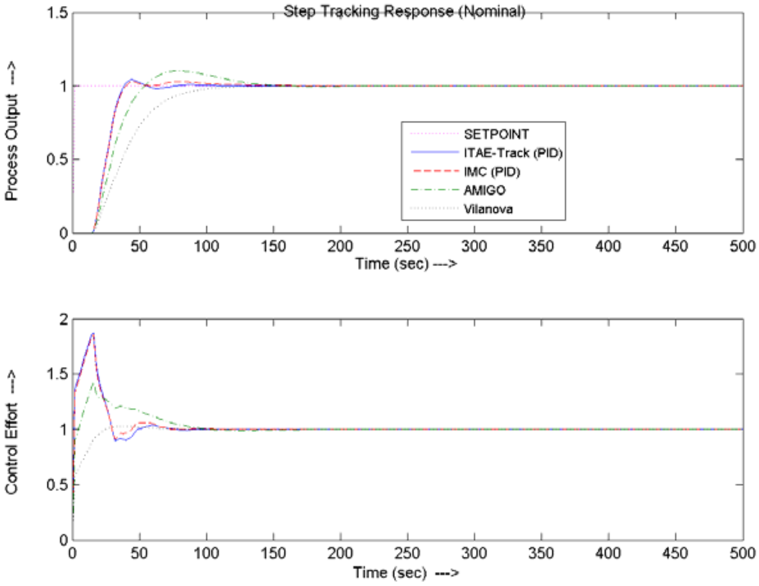


Figure 5.1: Step tracking response (Nominal)

Table 5.3: Controller parameters (Nominal)

Mode	Name of Tuning	K_c	τ_i	τ_d
Step-Tracking (τ_c = 16)	ITAE-track	1.30	32.25	4.96
	IMC	1.27	30.25	5.81
	Vilanova	0.55	22.84	-0.10
	AMIGO	0.84	21.15	6.48
Disturbance Rejection (τ_c =16)	Ziegler-Nichols	1.75	25.67	6.42
	ZNIMC	0.76	25.67	5.81
	AMIGO	0.84	21.15	6.48
	ITAE-(Regulation)	1.90	20.45	5.99

Table 5.4: Performance Indices of step tracking methods (Nominal)

Parameters	ITAE Track	IMC	AMIGO	Vilanova
GM	1.85	1.87	2.81	3.19
PM	61.41	63.16	59.31	66.14
MS	2.23	2.18	1.56	1.55
MT	1.29	1.22	1.04	1.00
IAE	59.01	60.55	60.07	57.03
ISE	43.64	45.01	45.67	46.74
ITAE	2340.83	2449.01	2375.04	1820.07
TV	105.66	107.59	112.38	87.94

Table 5.5: Performance Indices of step tracking methods (Abnormalities)

Parameters	ITAE Track	IMC	Vilanova	AMIGO
GM	1.85	1.87	3.19	2.81
PM	61.41	63.16	66.14	59.31
MS	2.23	2.18	1.55	1.56
MT	1.29	1.22	1.00	1.04
IAE	59.01	60.55	57.03	60.07
ISE	43.64	45.01	46.74	45.67
ITAE	2340.83	2449.01	1820.07	2375.04
TV	105.66	107.59	87.94	112.38

Table 5.6: Performance Indices of disturbance rejection methods (Nominal)

Parameters	AMIGO	ZN	ZNIMC	ITAE reg
GM	3.29	1.56	3.75	1.51
PM	62.31	55.00	71.72	41.70
MS	1.44	2.79	1.37	3.00
MT	1.02	1.79	1.00	2.03
Jsp	27.97	19.00	33.87	21.74
Jd	25.18	14.69	33.87	11.09
Ju	9.58	22.82	8.53	24.99
IAE	29.35	28.75	30.57	28.96
ISE	11.61	11.20	12.55	11.38
ITAE	1943.99	1911.79	2014.10	1925.84
TV	153.95	157.06	156.79	159.52

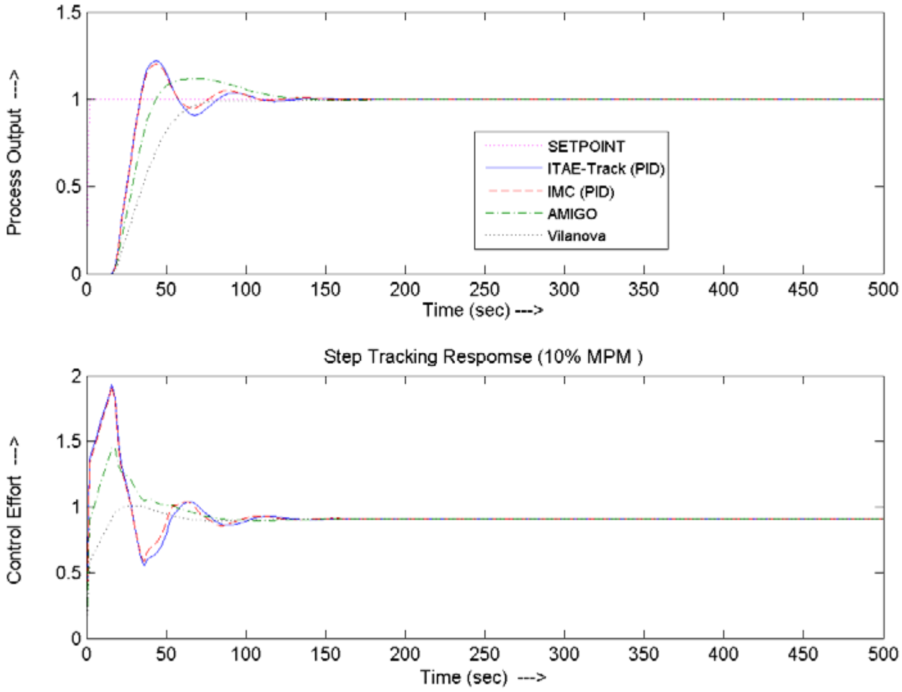


Figure 5.2: Step Tracking Response (10% MPM)

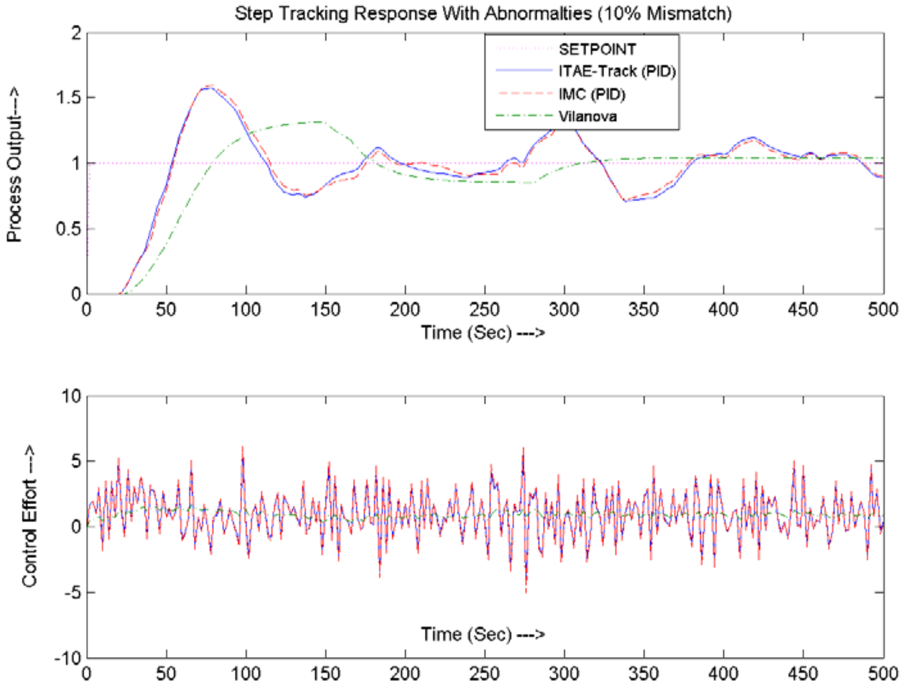


Figure 5.3: Step Tracking Response with abnormalities (10% MPM+ valve stiction +valve saturation +sensor noise)

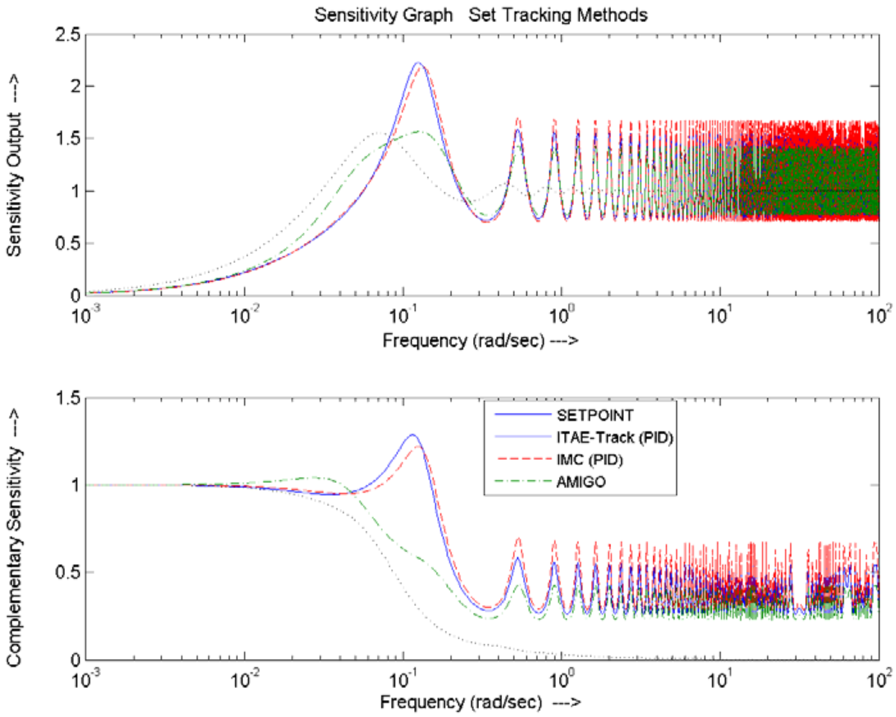


Figure 5.4: Sensitivity Graph of Step tracking Methods

Disturbance Rejection

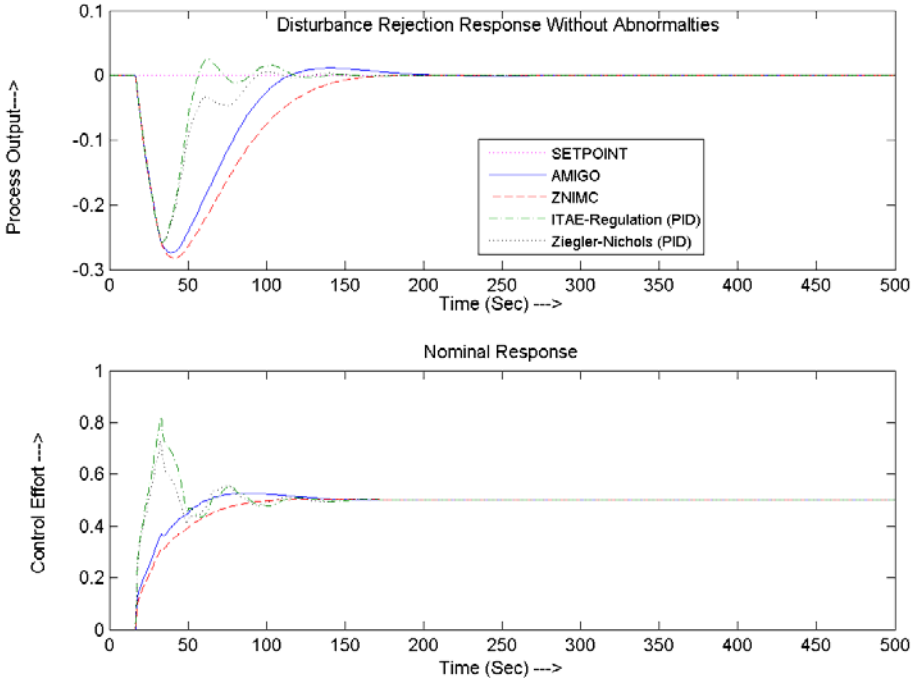


Figure 5.5: Disturbance Rejection Response (Nominal)

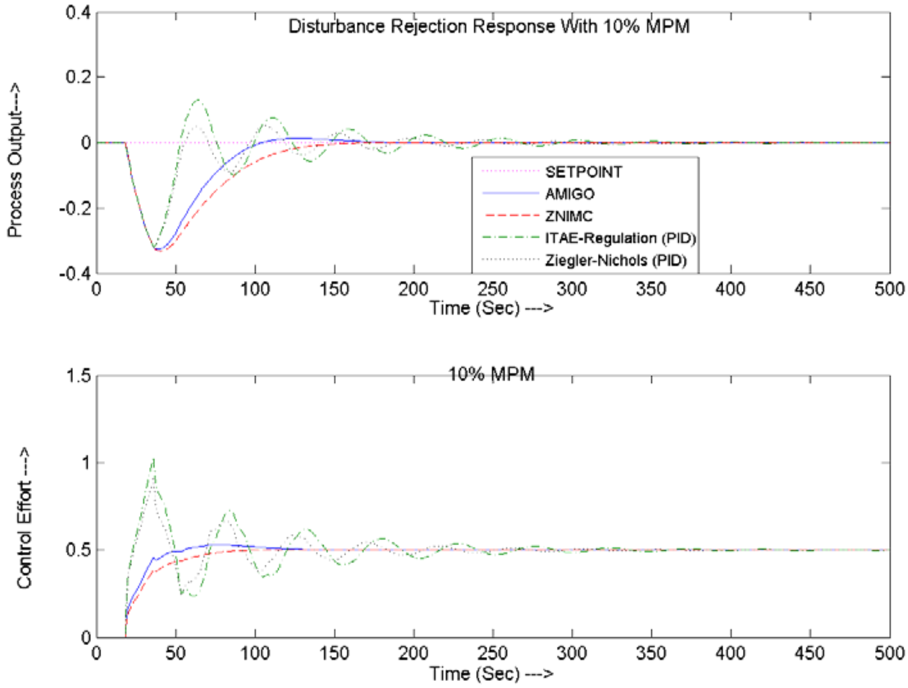


Figure 5.6: Disturbance Rejection Response (10% MPM)

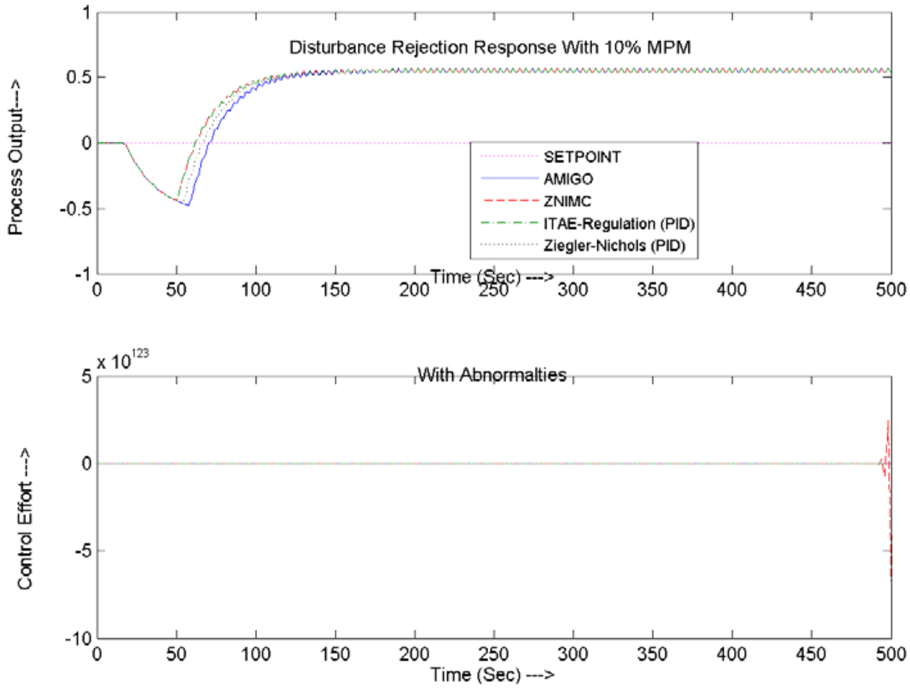


Figure 5.7: Disturbance Rejection Response (10%MPM+process abnormalities)

Table 5.7: Performance Indices of Disturbance Rejection methods with abnormalities

Parameters	AMIGO	ZNIMC	ITAE (Regulation)	Ziegler Nichols
GM	2.64	2.99	1.20	1.25
PM	59.42	69.61	26.56	40.74
MS	1.62	1.52	6.14	4.97
MT	1.04	1.00	5.18	4.00
IAE	23.52	25.58	25.58	23.80
ISE	8.36	10.15	10.15	8.61
ITAE	1577.00	1794.90	1794.90	1614.75
TV	76.00	86.00	86.00	78.00

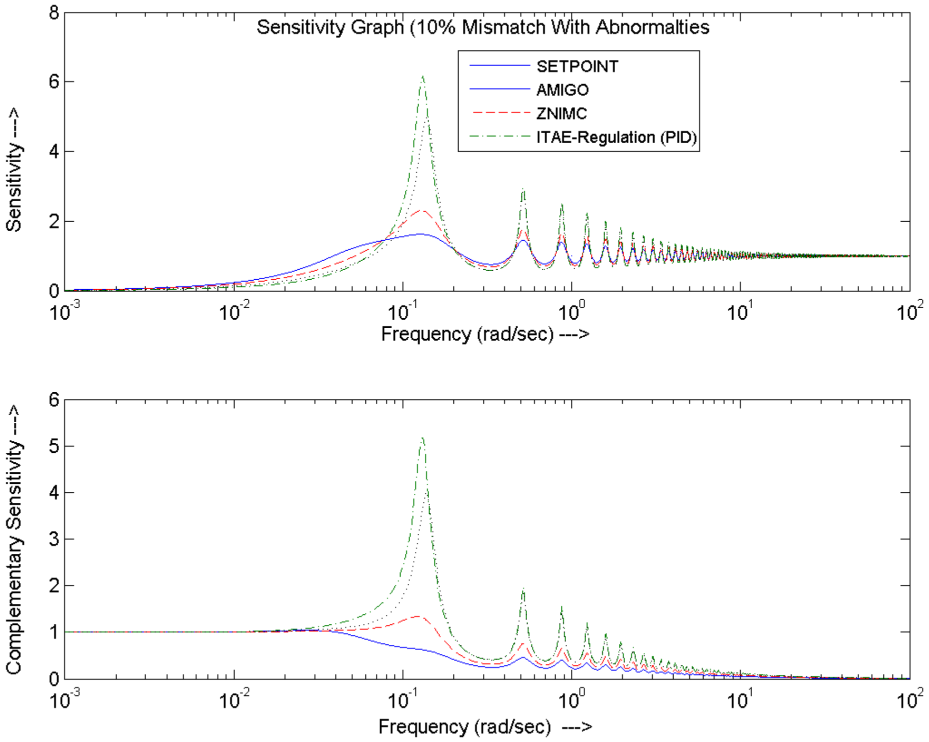


Figure 5.8: Sensitivity Graph of Disturbance Rejection Methods

The results from the simulation study show promising tuning algorithms. For each case of step-tracking and disturbance rejection control, three different tuning rules selected. As the response plots implicit, all of them were worthy of consideration and it is not a good idea to completely rule out any of them. The selection of the best is well related to the testing situation and the considerations for a specific application.

For the case of step tracking, the results are consistent and can use as rules of thumb for the controller design.

For the discussed degree of robustness, we recommend a gain margin in the range of 2-5, a phase margin in the range of 45^0-60^0, maximum sensitivity in the range of 1.2-2 and maximum complementary sensitivity in the range of 1-1.5. The suggested value for is to be found by the design formulation used by B. Kristiansson et al. [9]. The low value of the discrepancy between data points creates a wide scope of carrying out the recommendations highly reliable.

For the case of disturbance rejection control, it is not easy to draw meaningful patterns. The reason is that all of the indices are derived using the loop transfer function $L(s) = G(s)C(s)$ which is useful for describing the servo behavior. But in the case of disturbance rejection control, the dynamics are not exclusively determined by the loop transfer function, they are also a function of the process model. It means that performance indices cannot be defined based only on L(s), they should depend on the value of time constant (τ) and delay time (θ).

The result from simulation studies as depicted in table no 5.6 for performance indices of disturbance rejection method under nominal condition shows that AMIGO tuning method is best tuning method and from table no 5.7 which is under abnormalities/constrains the result are best again for AMIGO tuning method. In most cases, the exact selection of the desired closed loop time constant (τ_c) is of great importance.

The result from simulation studies as depicted in table no 5.4 for performance indices of step tracking method under nominal condition shows that Vilanova tuning method is best tuning method and from table no 5.5 which is under abnormalities/constrains the result are best again for Vilanova tuning method. However AMIGO tuning method gives comparable result. Comparative result showed in table 5.8.

Table 5.8: Comparison between best Step-tracking and Disturbance rejection Methods

Parameters	Step-Tracking		Disturbance Rejection		
	AMIGO	Vilanova	AMIGO	ZNIMC	Vilanova
GM	2.81	3.19	2.64	2.99	4.08
PM	59.31	66.14	59.42	69.61	68.80
MS	1.56	1.55	1.62	1.52	1.41
MT	1.04	1.00	1.04	1.00	1.0
IAE	60.07	57.03	23.52	25.58	26.13
ISE	45.67	46.74	8.36	10.15	9.09
ITAE	2375.04	1820.07	1577.00	1794.90	1604.67
TV	112.38	87.94	76.00	86.00	18.77

In this work, ranking of tuning rules based on performance and robustness is shown in table 5.9

Table 5.9: Ranking of tuning rules based on performance and robustness

Set-point Tracking	Performance	Disturbance Rejection	Robustness
Vilanova	1	AMIGO	1
IMC	2	ZNIMC	2
ITAE Track	3	Ziegler-Nichols	3

Responses for proposed system in presence of (a) 10% mismatch, (b) Valve stiction, (c) Valve saturation (d) Sensor noise (e) Sensitivity and complementary sensitivity behaviors obtained by various tuning rules results presented in the **Appendix-C**.

For Simulink models refer to **Appendix-D.**

For each category the best performing tuning rule gives the best results in nominal conditions, but as the uncertainty inside the system deteriorates, more robust tuning rules become superior in performance. These results validate that most of tuning methods show trade-off between performance and robustness for a given process. As it is almost impossible to have an exact model of the system, Model Plant Mismatch (MPM) is an essential consideration in PID tuning.

The presence of measurement noise proved to be challenging particularly in dealing with the required control effort. The tuning rules with large derivative time constants caused a more discrepancy in valve stem position. Although all of the techniques have derivative filters mounted inside the controller, using stronger derivative filter could also help.

5.9 Summary

This chapter discusses each category in performing of tuning and provides the best results in a real time environment. But as the process abnormalities like a model mismatch, valve stiction, saturation, sensor noise and disturbance inside the system deteriorate, more robust tuning rules become superior in performance. These results commit the trade-off between performance and robustness for a given process. However, in the design of tuning constant there is a significant, due to the tradeoff between robustness and performance. To avoid excessive sluggishness of response, we suggest using a two-degree of freedom controller, where ever possible.

“Robustness” is a common term and it has to be defined before the design as one of the control objective. In this thesis, I have investigated both with a mild degree of robustness and higher demands of robustness.

CHAPTER-6

CONCLUSION & FUTURE SCOPE

This chapter discusses all the preceding section briefly to examine the extent to which the objectives have achieved. Also, suggest some further enhancements to it.

6.1 Discussion on Reported Work

Chapter 1 discusses the various PID controller tuning techniques in time and frequency domains and some relevant fundamentals theory for this thesis have been studied. It presents the problem statements and scope which has been made in order to have a clear view of works to be done for the objective.

Chapter 2 discusses the literature review of PID control tuning methods for different applications by time and frequency domain performance indices.

In chapter 3, detailed study of centrifugal machine temperature control system in sugar plant has been carried out.

Short modeling time is essential to the process industry for fast controller design, and the goal is to find simple models that provide just enough process information for given tuning methods. This is probably the reason why more advanced system identification methods are typically not used in the industry.

In chapter 4, different optimization techniques have been used to design FOPTD and SOPTD transfer function of the system. It is run to investigate, analyze and compare the performance indices for controller tuning.

Concluding Remark

Indeed, intelligent technology is coming out with better and efficient design solutions. This technique based on probability and randomness. However, it can’t claim to attain the entire optimization domain, besides, also it can’t assure that the algorithm is not going to trapped in local optima. So, we conclude that in future we will get the best technologies which will sort out all the mentioned shortcomings of contemporary technologies. Finally, these techniques criticized for being computationally heavy, and convergence to the acceptable solution cannot promise. PID controller tuning took only a couple of seconds to solve the problem.

In chapter 5, some tuning rules ranked according to the robustness and performance. The best tuning rule in the context of this thesis was the one that gave a compromised behavior. The proposed AMIGO gave the best result for disturbance rejection. In step tracking, Vilanova gave the best result. However, compare Vilanova and AMIGO for set point tracking, AMIGO gave a compromised behavior by performance indices. The tuning rule for regulation (ZNIMC) also shows compromise behavior and provided a reliable tuning technique, when the desired closed-loop time constant selected appropriately. The results again confirmed the trade-off between those variables.

PID controllers do not provide the most optimal solutions to control problems. However, it seems that most of the potential of PID controllers can now be utilized using available tuning rules especially in the case of step tracking. For each category, the best performing tuning rule gives the best results in ideal conditions, but as the uncertainty inside the system worsens, more robust tuning rules become superior in performance. These results validate the trade-off between performance and robustness for a given process. It is almost impossible to have an exact model of the system. However, it seems that even if it succeeds as an alternative to PID controller, it will take a long time for it to be adopted.

6.2 Research Contributions

This study makes following contributions. The main contributions are:

1. To develop the mathematical modeling using input-output data by reaction curve method then step response identification performed by a Strejc method.

2. To determine an efficient mathematical model for a system and validate with actual measurement data using system identification.

3. Controller Design using Single Objective Optimization using GA, PSO, BAT, FPA using time domain performances indices.
4. Controller Design using Multi-Objective Optimization using GA, PSO, BAT, FPA using time domain specifications like rise time, settling time, overshoot percentage, etc. and frequency domain specifications like gain margin, phase margin, sensitivity, etc.
5. Controller Design using Multi-Objective Optimization using GA, PSO, BAT, FPA using time domain specifications like rise time, settling time, overshoot percentage, etc. and frequency domain specifications like gain margin, phase margin, sensitivity, etc.
6. Controller Design using Multi-Objective Genetic Algorithm and Multi-objective Particle Swarm Optimization using Generate First Choose Later Approach
7. Design Robust Controller against performance degradation in cases of model plant mismatch and in situations where process abnormalities encountered.

6.3 Scope for Future Work

In this thesis, it suggested that design and performance evaluation of PID controller tuning methods are the future of industrial applications. The future, however, does not exist yet, and the question is what is missing to fulfill the prediction. The most key which is still missing is a real-time implementation of the model that is tailor-made for optimal PID control. Some desired performance and robustness indices of a different method have suggested. It should ideally be as fast as possible and therefore provide just the process information that is indispensable control design.

Closed-loop identification methods, like a neural network, relay identification and fractional order calculus are preferred, since they are less sensitive to disturbances than their open-loop systems. In software, simulation work is just one suggestion of how such a tool could work in different process abnormalities, and some improvements are necessary before the proposed design can use in industry. It would be desirable to obtain faster solutions to the various optimization problems that way it would be possible to quickly determine a whole set of PID controllers, for performance and robustness with noise and disturbance sensitivity. A possible way to accelerate the solver is to simplify the optimization problem even further. What matters is that the software reliably provides PID controllers and low-pass filters that are decently close to optimal, with at least one robustness constraint (example M_S or M_T).

Experienced control engineers are probably able to use optimization based design techniques as stand-alone methods. But to attract a broader audience and to speed up controller tuning, they should ideally be part of future the auto-tuners together with the desired modeling method. One suggestion is to let modeling experiments be run by a PLC (Programmable Logic Controller) or DCS (Distributed Control System), while system identification and optimal PID design could be handled by an external unit, like a laptop or computer. Auto-tuning could then be scheduled to run either periodically by an operator or when changes have made to the process. This routine should preferably be reliable enough to use without the need for careful supervision.

It would be desirable to add optimization of other PID and filter forms; like the series form and derivative filter (Chapter 1). It should also be possible to change the cost function for minimizing ISE or ITAE, for input and output disturbances. In industrial applications, it is to design PID for set-point changes, and disturbance rejection includes the reference weights or a filter.

The following may also include as future work in the area of PID controller:

1. Real-time implementation of the control system
2. For the system identification and controller design, fractional order calculus may be the better option. A fractional order calculus technique offers more degree of freedom for designing a controller from higher order system to lower order system.
3. Fractional order controllers tuning using multi-goal optimization helps in attaining the robust tradeoffs between sensitivity and complementary

sensitivity. This technique gives a better characterization of dynamics of the process.

4. Use of Pareto front analysis tools for selecting the ideal solution from the Pareto front using scatter matrices, PCA, level diagrams, etc.
5. The design of robust controller explored by Nelder-Mead optimization techniques.
6. LQR based algorithm can replace the conventional PID controller. It has incorporated two tuning parameters: Regulator and Estimator, and by using these, it claims higher performance and better robustness than current PID controllers.
7. Another interesting subject for future research would be to extend the autotuner to multivariable systems.

Finally, it is essential that different optimal PID design methods tested on more industrial applications and that their functions are discussed together with skillful control engineers. It will help facilitate the acceptance of such processes in the industry.

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Appendix-A

Overview of System Models

These models are described in discrete-time.

Auto-Regressive Model (ARX)

The mostly use model structure having a simple linear difference

$$y(t)+a_1y(t-1)+..+a_{nx}y(t-nx)=b_1u(t-1)+..+b_{ny}\left(t-ny\right) \tag{A.1}$$

Which relates to the current output y(t) in a finite number of past outputs y(t-k) and inputs u(t-k).

The structure is completely defined by the three integers n_a, n_b, and n_k. n_a which is equal to the number of poles and n_b–1 is the number of zeros, while nk is the pure dead-time delay (time delay) in the system.

For sampled-data control system, usually, n_k is equal to 1 if there is no time delay.

This model is describing input to output path in a linear difference equation. The model output is the summation of input and white noise, which go directly into the measurement noise system. When a model order is high, this model offers maximum model assessment and justification result [112,113].

This model structure is described by the equation as:

$$A(z)y(t)=B\left(z\right)u\left(t\right)+e(t) \tag{A.2}$$

Where A and B polynomials are output and input in that order, and e(t) is the white noise

$$A(z)=1+a_1z^{-1}+..........+a_{nx}z^{-nx} \tag{A.3}$$

$$B(z)=1+b_1z^{-1}+..........+b_{ny}z^{-ny} \tag{A.4}$$

$$y(t)+a_1y(t-1)+..+a_{nx}y(t-nx)=b_1u(t-1)+b_2u(t-2)+..+b_{ny}\left(t-ny\right)+e\left(t\right) \tag{A.5}$$

This model is usually used for identification because it has simplicity and linearity with respect to identified parameters.

Auto-Regressive Moving Average Exogenous Model (ARMAX)

This model has an advantage over the ARX model, due to that they not accurate in describing the property of dynamics disturbance. While this model consists of flexibility to model the disturbance separately other through adding numerator polynomial $C(z-1)$. This model can be beneficial to handle the disturbance, which enter in to the input [113].

This model structure is described by the equation as:

$$A(z)y(t) = B(z)u\left(t\right) + C(z)e(t) \tag{A.6}$$

Where A and B polynomials will be same as in ARX model, C polynomials can be written by the equation as

$$C(z) = 1 + c_1 z^{-1} + ...+ c_{nz} z^{-nz} \tag{A.7}$$

Box-Jenkins (BJ) model

This model structure provides additional development of the output error via filtering noise this through $\frac{C(z)}{D(z)}$ transfer function. It is use when noise enters delayed in the process, such as measurement noise [114].

An input-output linear model for a single-output system with input u and output y can be written by the equation as:

$A(z)y(t) = \sum_{i=1}^{nu}[\frac{B_i(z)}{F_i\left(z\right)}]u_i(t-nk_i) + [\frac{C(z)}{D(z)}]e(t)$ here u_i denotes input #i,

A, B, C, D and F_i are polynomials in the shift operators **(**z or q) (A.8)

The Box-Jenkins (BJ) structure is described by the equation as:

$$y(t) = \sum_{i=1}^{nu}[\frac{B_i(z)}{F_i\left(z\right)}]u_i(t-nk_i) + [\frac{C(z)}{D(z)}]e(t) \tag{A.9}$$

To assessment a BJ model, need to specify the parameters n_b, n_f, n_c, n_d and n_k.

Although, the ARX model structure does not discriminate among the poles for individual input/output paths, the BJ model offers flexibility in modeling the poles and zeros of the disturbance separately from the poles and zeros of the system dynamics.

Output-error (OE) model

Output-error (OE) model structure can be written by the equation as:

$$y(t) = \frac{B(z)}{F(z)} u(t - n_k) + e(t) \tag{10}$$

The white noise is brought to the measurement error that is output variable. Time and frequency-domain data can estimate directly by means of simplest Output-Error (OE) models. Frequency-domain data are not supported by other structures includes noise models [108,114].

For modeling the disturbance characteristics, no parameters are used only OE model structure depicts the system dynamics separately.

APPENDIX-B

Design of controllers using soft computing for FOPTD

Single- Objective Optimization

Controller Design for FOPTD using Genetic Algorithm (GA)

Table B.1**:** PID Controller Gains obtained using Genetic Algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	1.576	3.056	10.932	97.796
K_I	4.213	3.409	3.613	4.01
K_D	-3.499	-2.935	-2.339	6.621

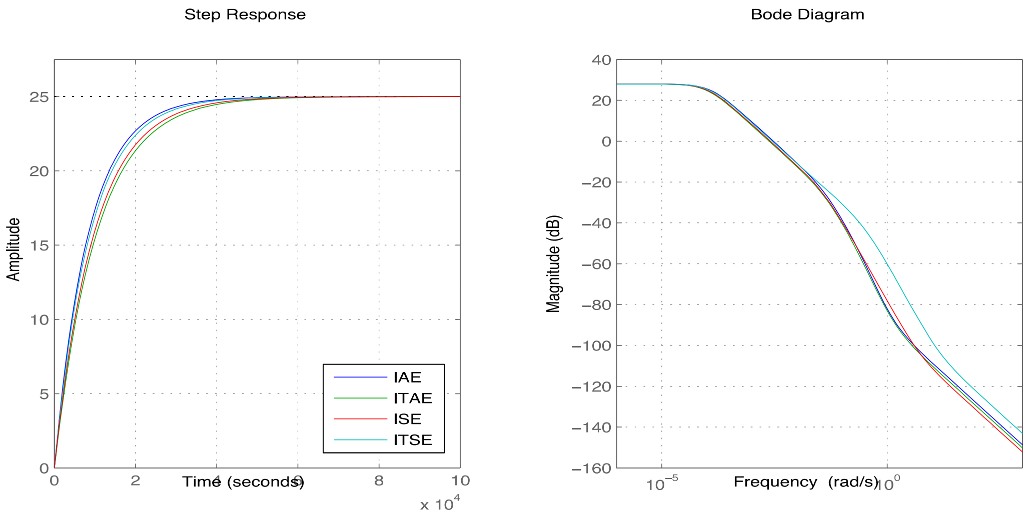


Figure B.1: Time & Frequency Response using GA for optimized PID Controller

Table B.2: Performance Indices of the designed controllers using GA

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (sec.)	18406	22769	21483	19395
Settling Time (sec.)	32814	40583	38291	34551
Overshoot Percentage (%)	0	0	0	0
Gain Margin (dB)	21.24	26.99	28.7	33.94
Phase Margin (deg.)	85.35	86.75	86.73	89.59

Controller Design for FOPTD using Bat Algorithm (BA)

Table B.3: PID Controller Gains Obtained using Bat Algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	169.257	207.506	234.986	204.616
K_I	4.271	6.213	7.939	7.38
K_D	591.823	1055.7	550.647	1262.7

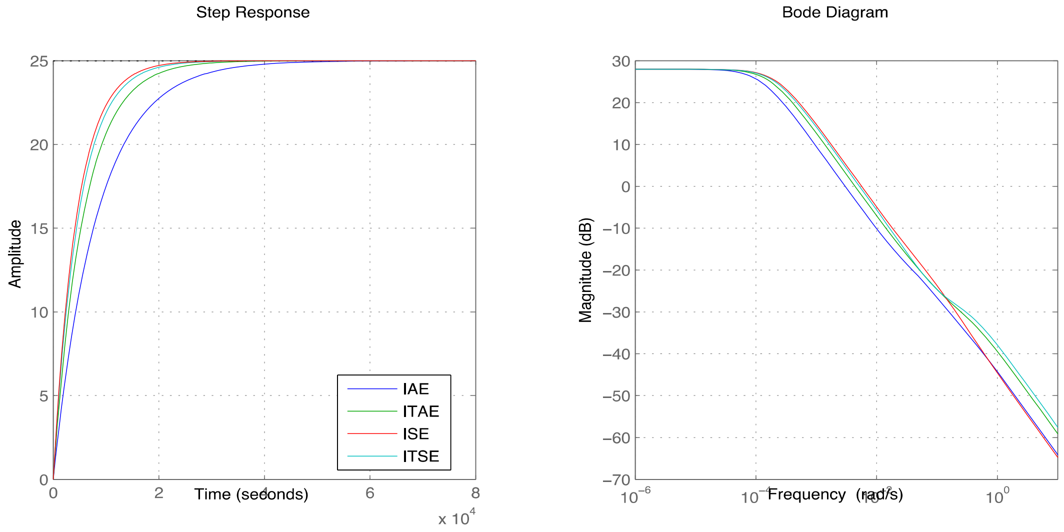


Figure B.2. Time and frequency Response with BA

Table B.4: Performance Indices of the designed controllers using Bat Algorithm

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (secs.)	18241	12525	9788	10529
Settling Time (secs.)	32481	22309	17441	18761
Overshoot Percentage (%)	0	0	0	0
Gain Margin (dB.)	31.48	26.72	19.56	26.27
Phase Margin (deg.)	92.03	90.35	88.57	88.33

Controller Design for FOPTD using Particle Swarm Optimization Algorithm

Table B.5: PID Controller Gains Obtained using PSO

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	0.475	-1.71	-2.107	-1.0399
K_I	4.3621	3.403	5.1995	0.4552
K_D	0.176	-2.408	-4.134	4.0506

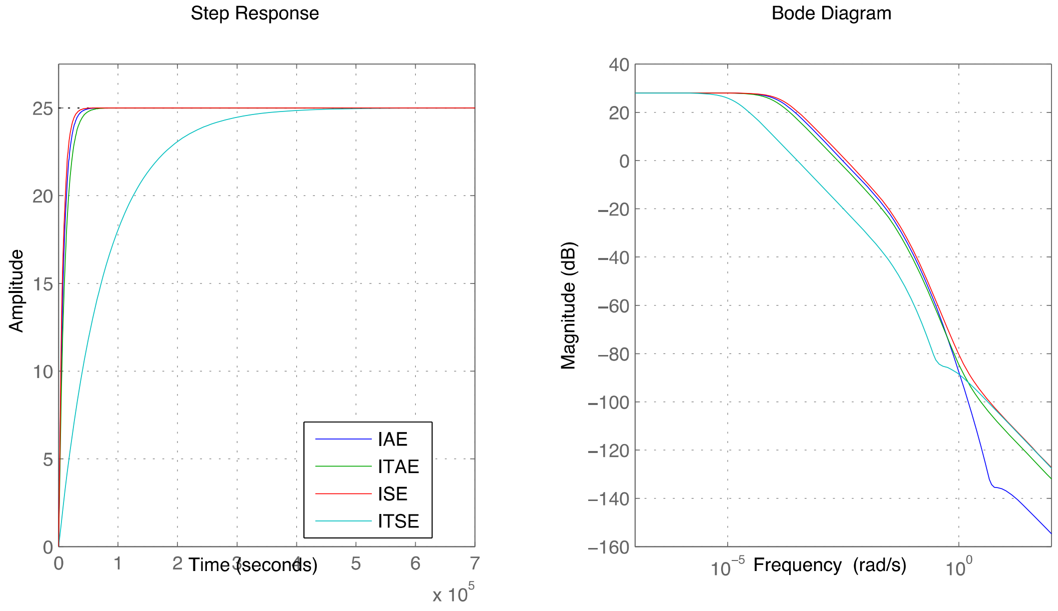


Figure B.3: Time and Frequency Response with PSO

Table B.6: Performance Indices of the designed controllers using PSO

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (secs.)	17773	22806	14894	17108
Settling Time (secs.)	31688	40650	26561	30467
Overshoot Percentage (%)	0	0	0	0
Gain Margin (dB.)	20.26	25.12	16.5	174.23
Phase Margin (deg.)	85.06	86.56	83.55	91.5

Controller Design for FOPTD using Flower Pollination Algorithm

Table B.7: PID Controller Gains Obtained using FPA

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
K_P	244.525	203.371	219.962	223.148
K_I	5.23	4.751	8.264	5.642
K_D	135.268	329.233	648.199	336.106

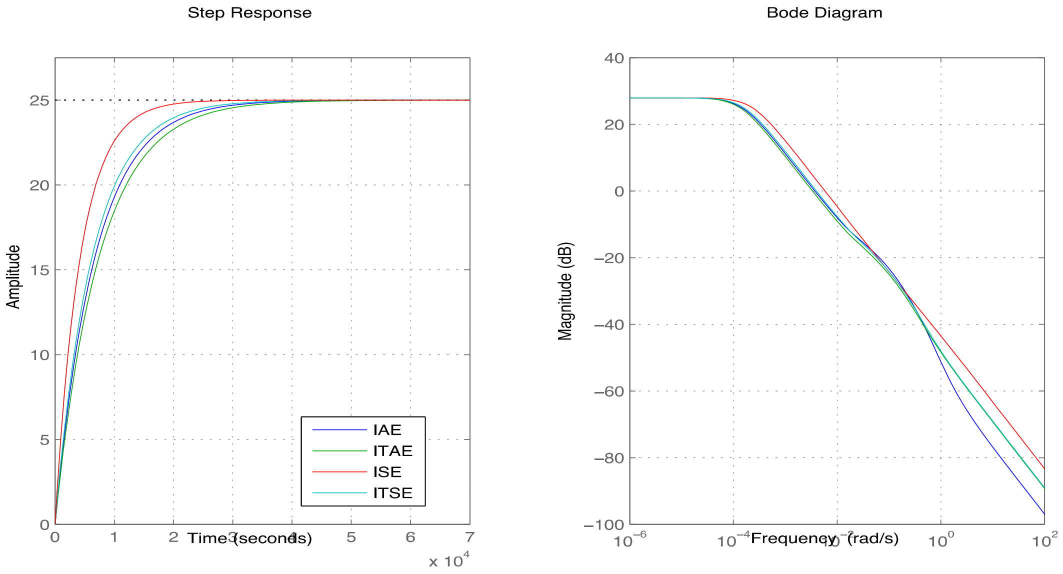


Figure B.4: Time and Frequency Response with FPA

Table B.8: Performance Indices of the designed controllers using FPA

Controller Parameter	**IAE**	**ITAE**	**ISE**	**ITSE**
Rise Time (sec.)	14911	16405	9397	13807
Settling Time (sec.)	26546	29209	16747	24587
Overshoot Percentage (%)	0	0	0	0
Gain Margin (dB)	16.99	22.41	21.84	19.94
Phase Margin (deg.)	93.42	92.59	87.45	91.9

(B) Multi Objective Optimization Design of the Controller

Controller Design for FOPTD using GA(AOF)

Table B.9: PID Controller Gains Obtained using GA (AOF)

Controller Parameter	**J_{ITAE+S}**	**J_{ITSE+S}**	**J_{S+T}**
K_P	17.177	6.826	10.05
K_I	3.665	2.718	2.953
K_D	-4.094	-2.09	3.452

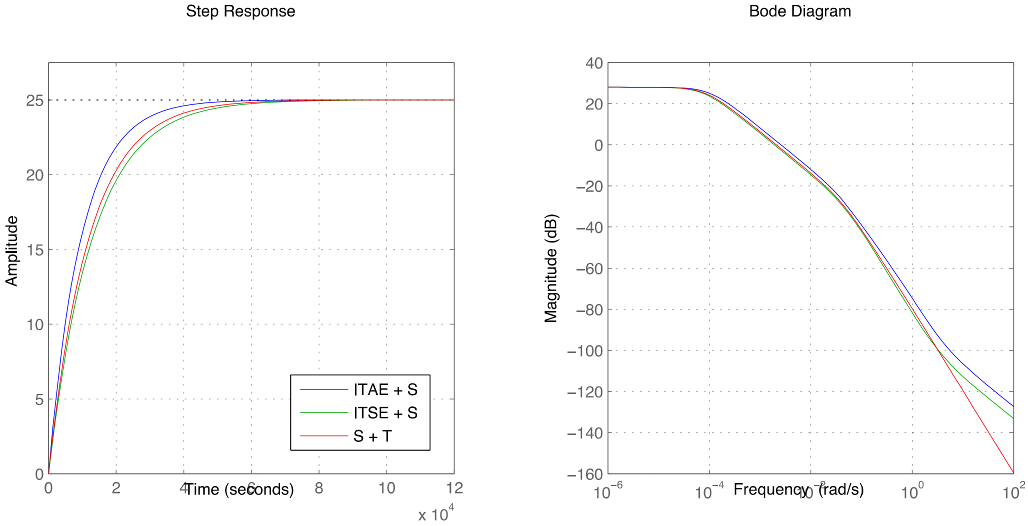


Figure B.5: Time and frequency Response with GA

Table B.10: Performance Indices of the designed controllers using GA (AOF)

Performance Index	**J_{ITAE+S}**	**J_{ITSE+S}**	**J_{S+T}**
Rise Time (sec.)	21181	28583	26304
Settling Time (sec.)	37751	50934	46874
Overshoot Percentage (%)	0	0	0
Gain Margin (dB)	31.02	37.05	35.94
Phase Margin (deg.)	86.9	88.06	87.7

Controller Design for FOPTD using BA (AOF)

Table B.11: PID Controller Gains obtained using BA (AOF)

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	202.8	202.9	40.1
K_I	7.218	5.919	8.81
K_D	1467.5	1042.5	1022.7

Table B.12: Performance Indices of the designed controllers using BA (AOF)

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	10767	13149	8764
Settling Time (sec.)	19181	23421	15642
Overshoot Percentage (%)	0	0	0
Gain Margin (dB)	24.71	27.31	29.42
Phase Margin (deg.)	88.53	90.65	79.38

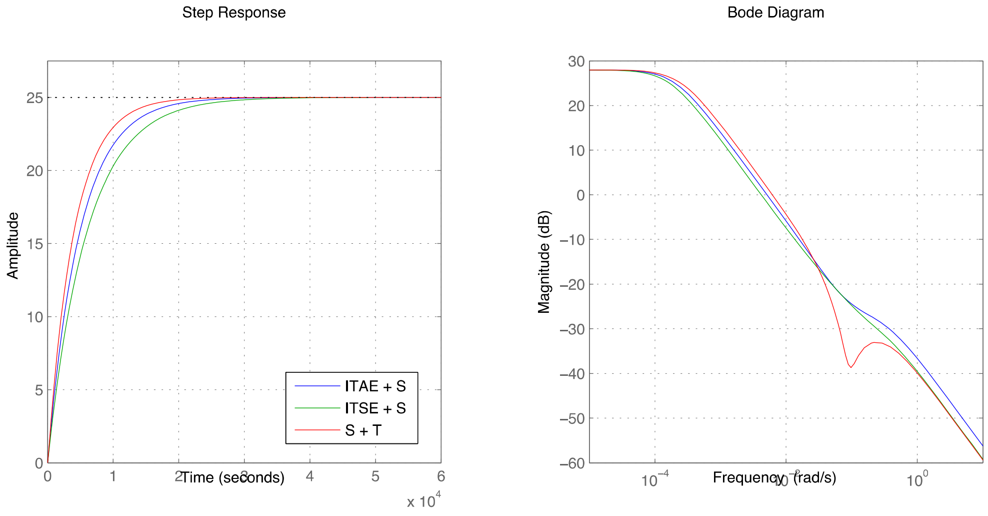


Figure B.6: Time and frequency response with BA

Controller Design for FOPTD using PSO (AOF)

Table B.13: PID Controller Gains Obtained using PSO

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	2.341	35.313	3.612
K_I	2.296	3.769	1.354
K_D	2.809	-8.209	6.801

Table B.14: Performance Indices of the designed controllers using PSO (AOF)

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	33849	20604	57463
Settling Time (sec.)	60312	36720	102369
Overshoot Percentage (%)	0	0	0
Gain Margin (dB)	40.55	37.76	76.28
Phase Margin (deg.)	88.57	87.46	90.2

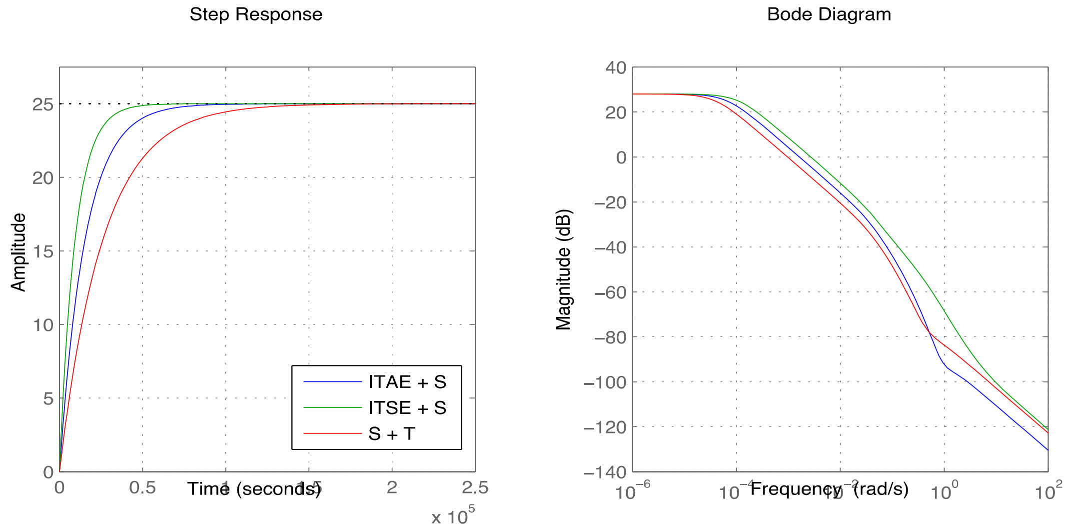


Figure B.7: Time and frequency response with PSO

Controller Design for FOPTD using FPA (AOF)

Table B.15: PID Controller Gains obtained using FPA (AOF)

Controller Parameter	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
K_P	242.588	230.751	120.674
K_I	4.888	6.515	3.401
K_D	264.444	689.694	569.726

Table B.16: Performance Indices of the designed controllers using FPA (AOF)

Performance Index	J_{ITAE+S}	J_{ITSE+S}	J_{S+T}
Rise Time (sec.)	15906	11948	22899
Settling Time (sec.)	28410	21280	40779
Overshoot Percentage (%)	0	0	0
Gain Margin (dB)	18.2	21.96	46.03
Phase Margin (deg.)	93.92	90.76	91.52

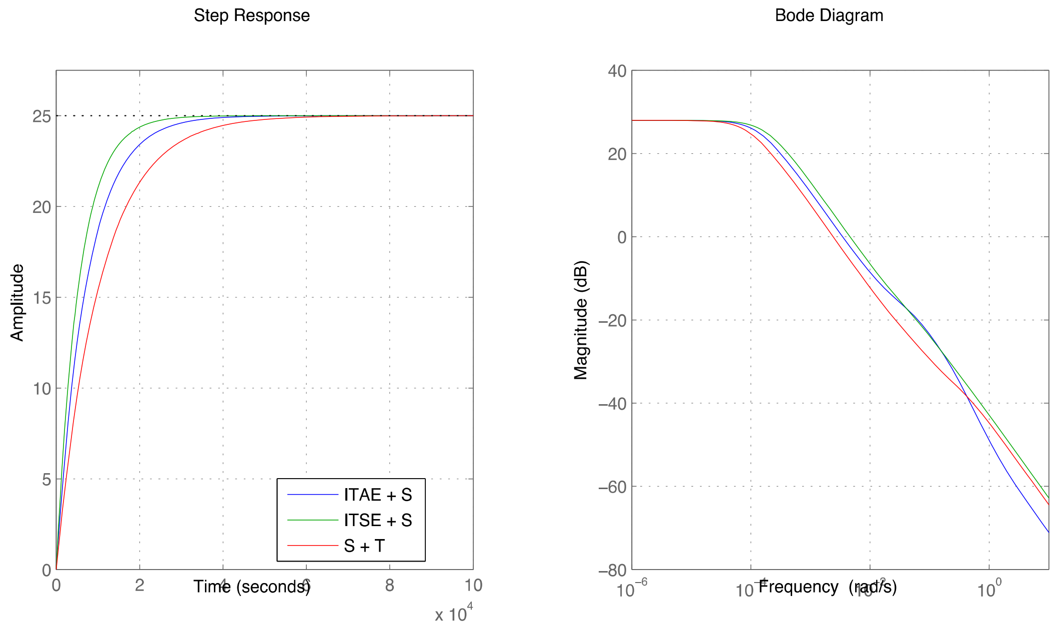


Figure B.8: Time and frequency response with FPA

(C) Multi-Objective Optimization using (GFCL)

Controller Design using Multi-objective Genetic Algorithm

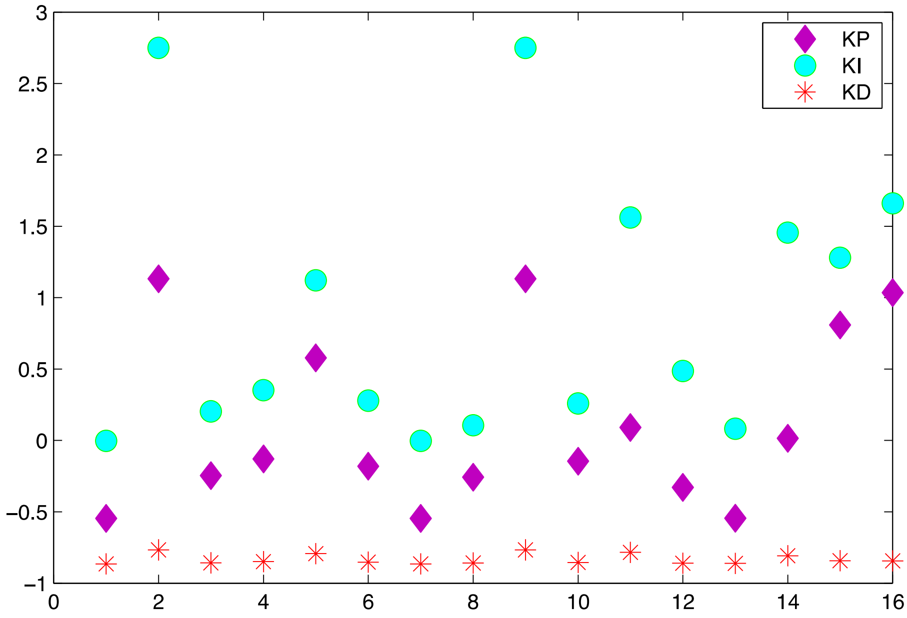


Figure B.9: Plot for the Pareto Optimal Set of Solutions (Design Objectives and Controller Gains)

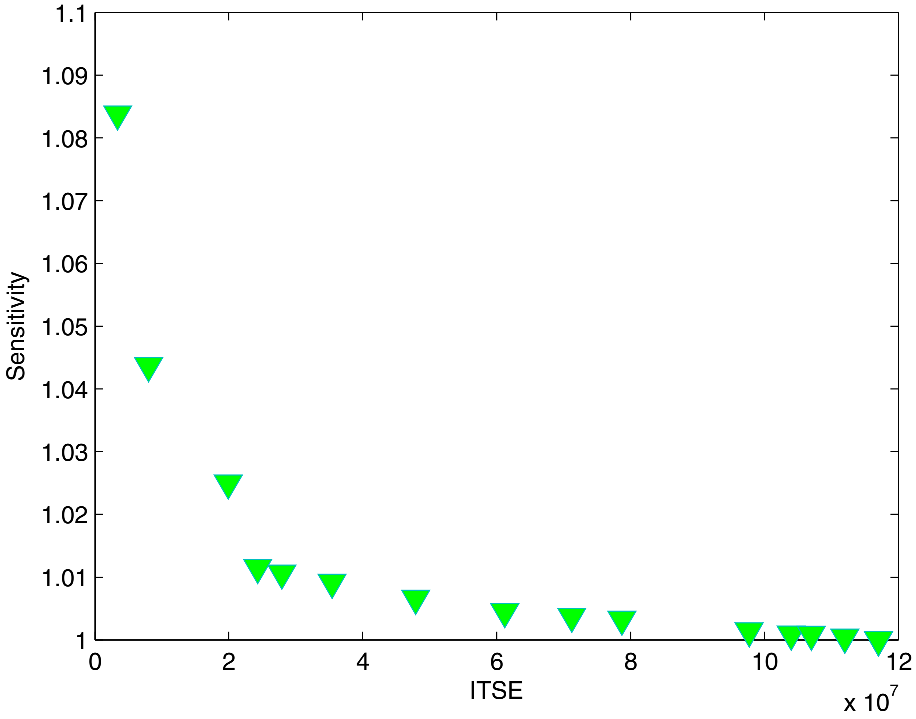


Figure B.10: Pareto Front Visualization of Controller Design Objectives

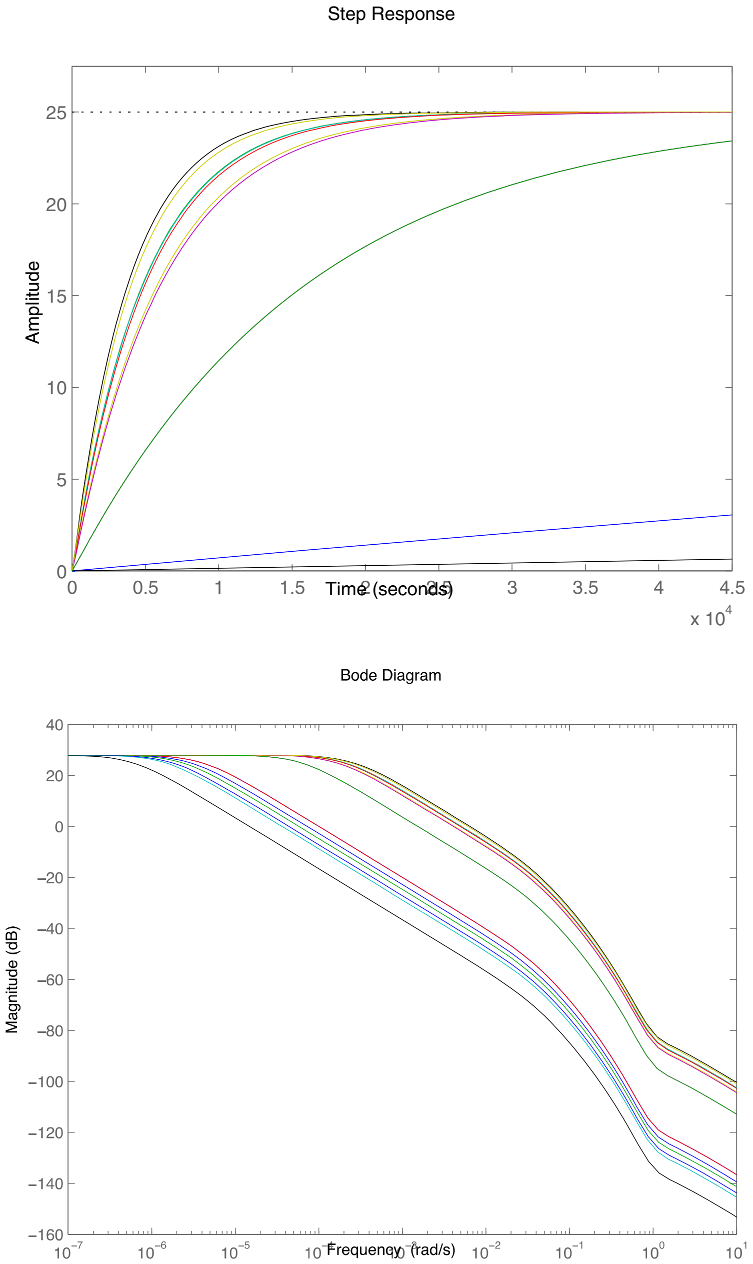
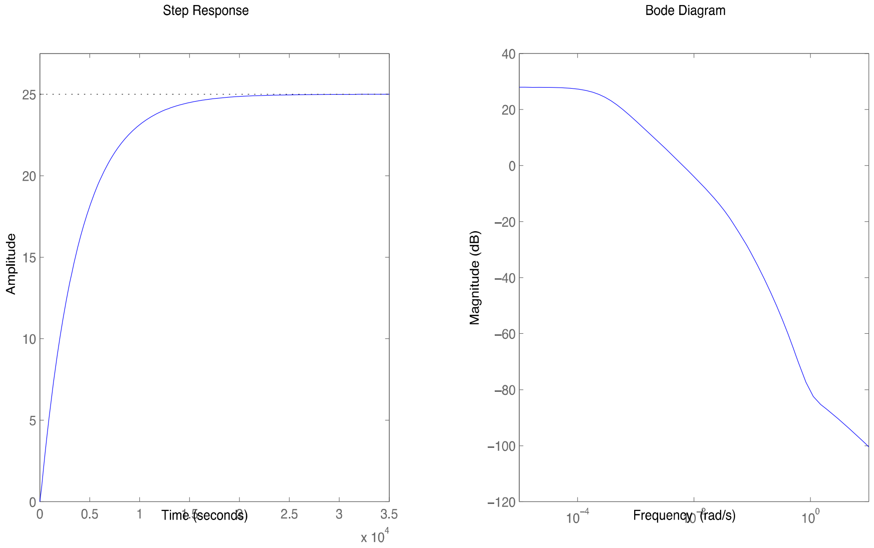


Figure B.11: Step and Frequency Response with Pareto Optimal Set of Solutions.

Table B.17: PID Controller Gains Obtained using MOGA by Minimizing *J_1*

Controller Parameter	**K_P**	**K_I**	**K_D**
J_1	0.5784	1.121	-0.79



FigureB.12: Step and Frequency Response with best controller parameters chosen from POS

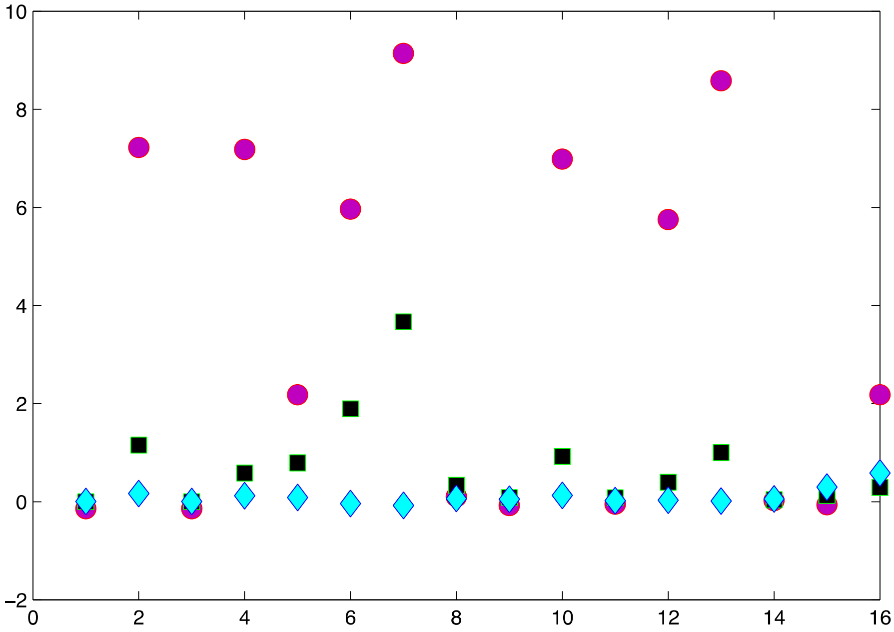


Figure 13: Plot for the Pareto Optimal Set of Solutions (Design Objectives and Controller Gains)

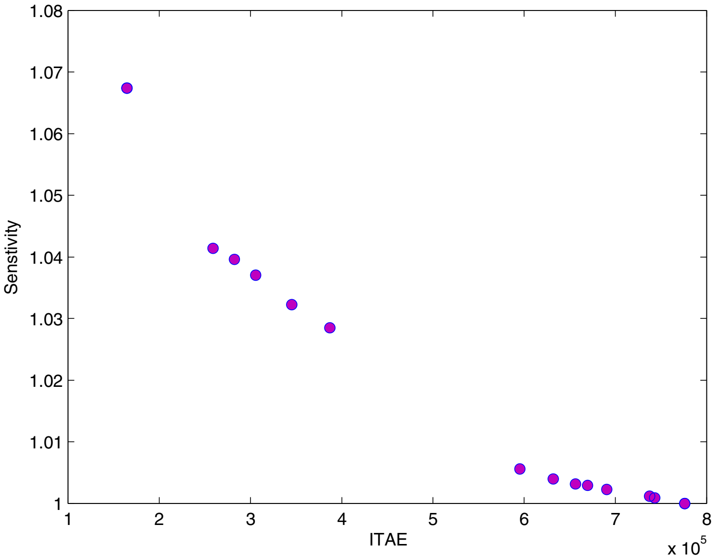


Figure 14: Pareto Front Visualization of Controller Design Objectives.

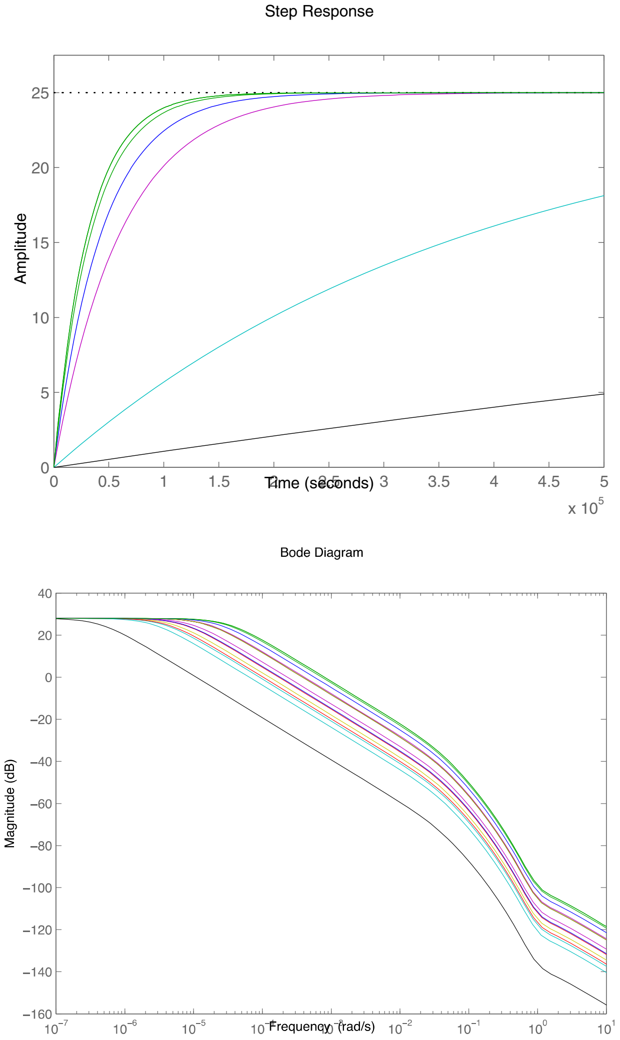


Figure 15: Step and Frequency Response with Pareto Optimal Set of Solutions.

Table B.18: PID Controller Gains Obtained using MOGA by Minimizing J_2

Controller Parameter	**K_P**	**K_I**	**K_D**
J_2	0.103	0.334	0.0647

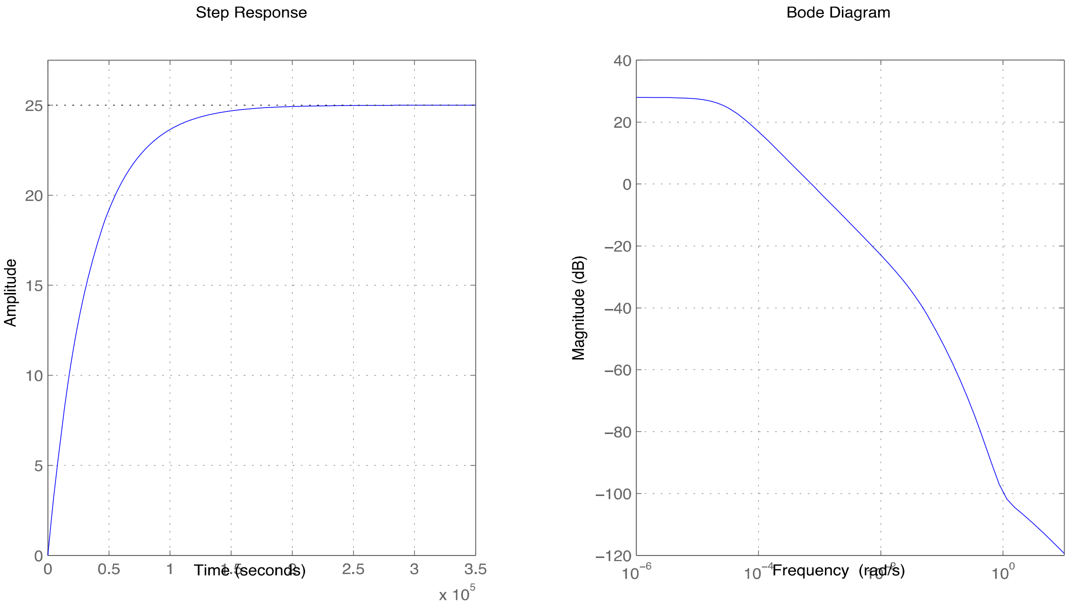


Figure B.16: Step and Frequency Response with best controller parameters chosen from POS

Table B.19: Performance Indices of the designed controllers using MOGA

Performance Index	**J_1**	**J_2**
Rise Time (sec.)	75210	8437
Settling Time (sec.)	133964	15064
Overshoot Percentage (%)	0	0
Gain Margin (dB)	89.88	10.14
Phase Margin (deg.)	90.62	77.51

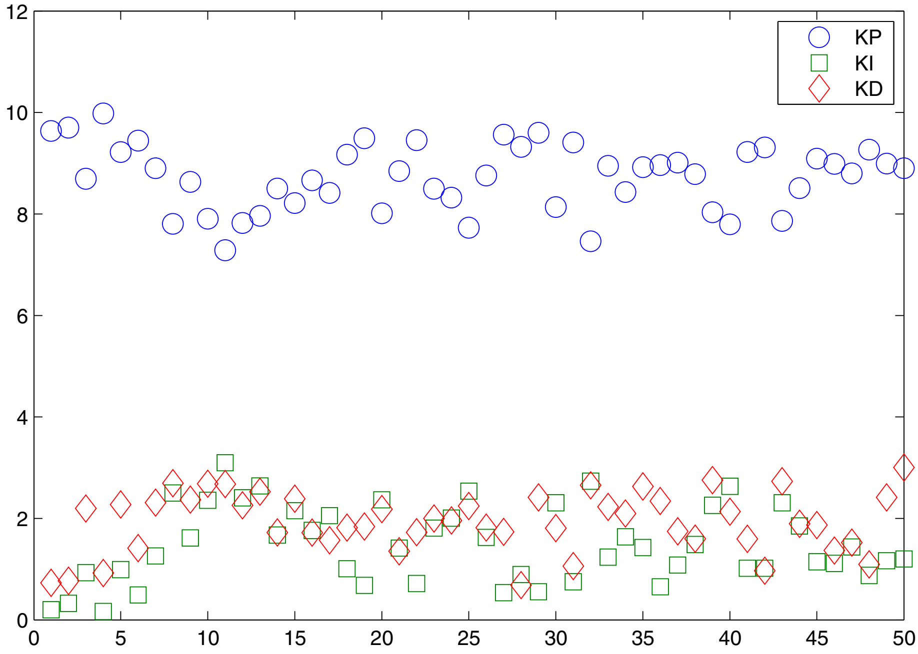


Figure B.17: Plot for the Pareto Optimal Set of Solutions (Design Objectives and Controller Gains)

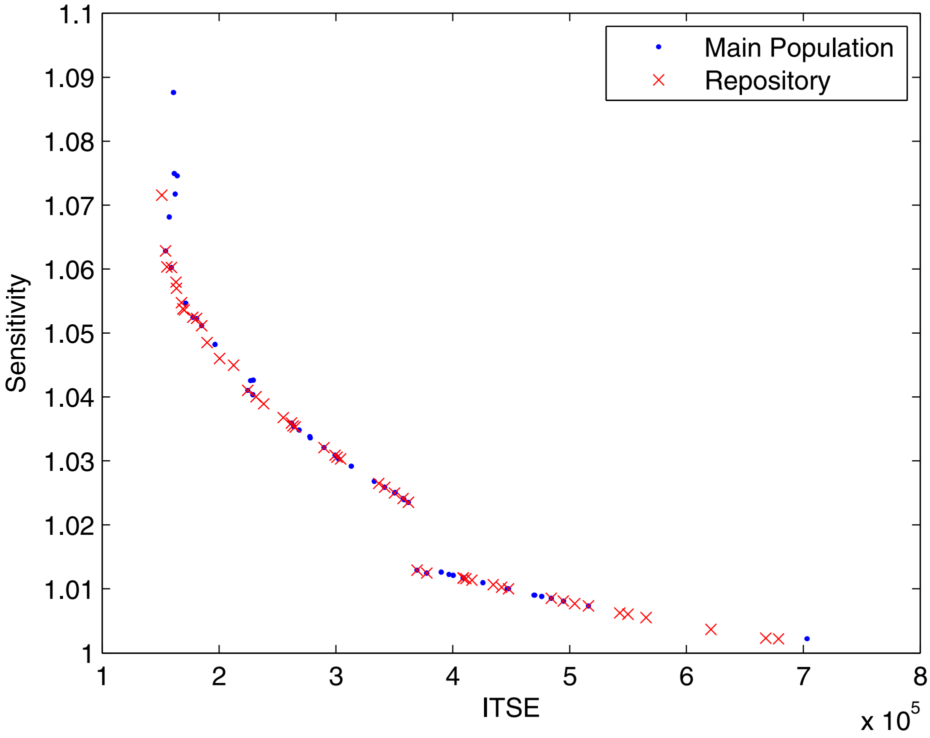


Figure B.18: Pareto Front Visualization of Controller Design Objectives.

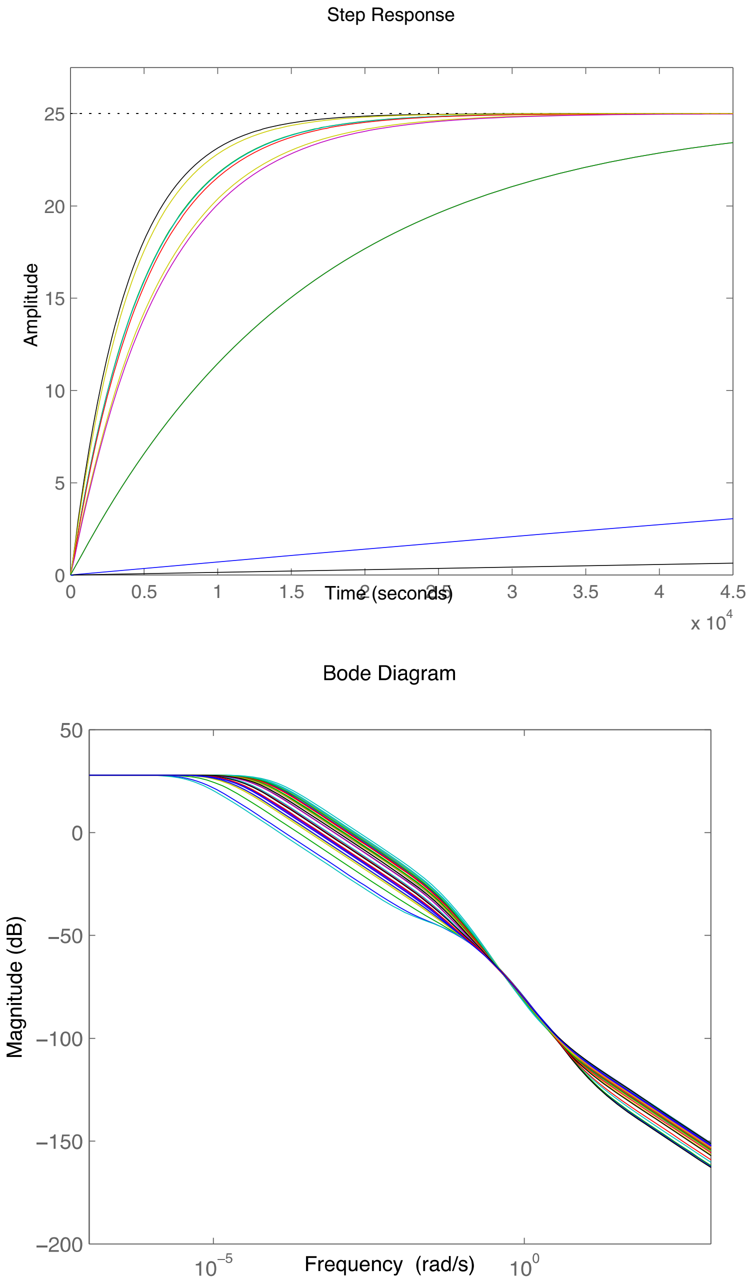


Figure B.19: Step and Frequency Response with Pareto Optimal Set of Solutions.

Table B.20: PID Controller Gains Obtained using MOPSO by Minimizing J_1

Controller Parameter	**K_P**	**K_I**	**K_D**
J_1	7.804	2.498	2.695

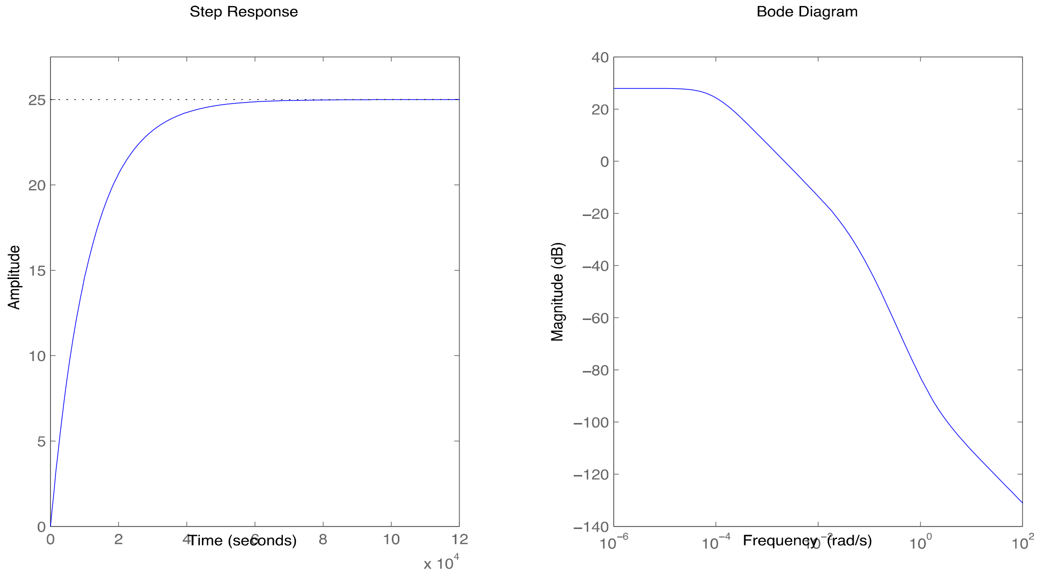


Figure B.20: Step & Frequency Response with Best Controller Parameters chosen from POS.

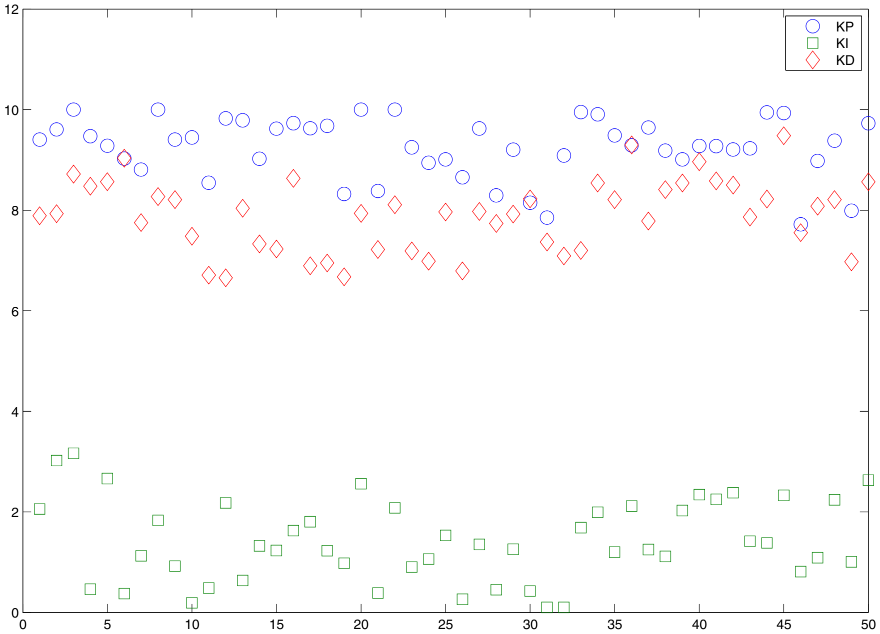


Figure B.21: Plot for the Pareto Optimal Set of Solutions (Design Objectives and Controller Gains)

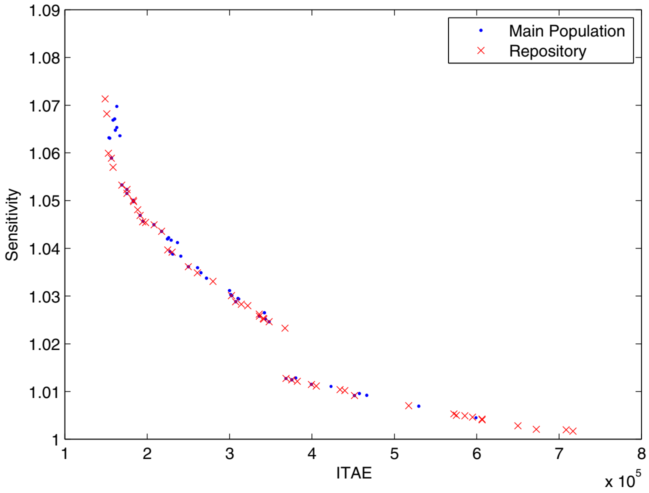


Figure B.22: Pareto Front Visualization of Controller Design Objectives.

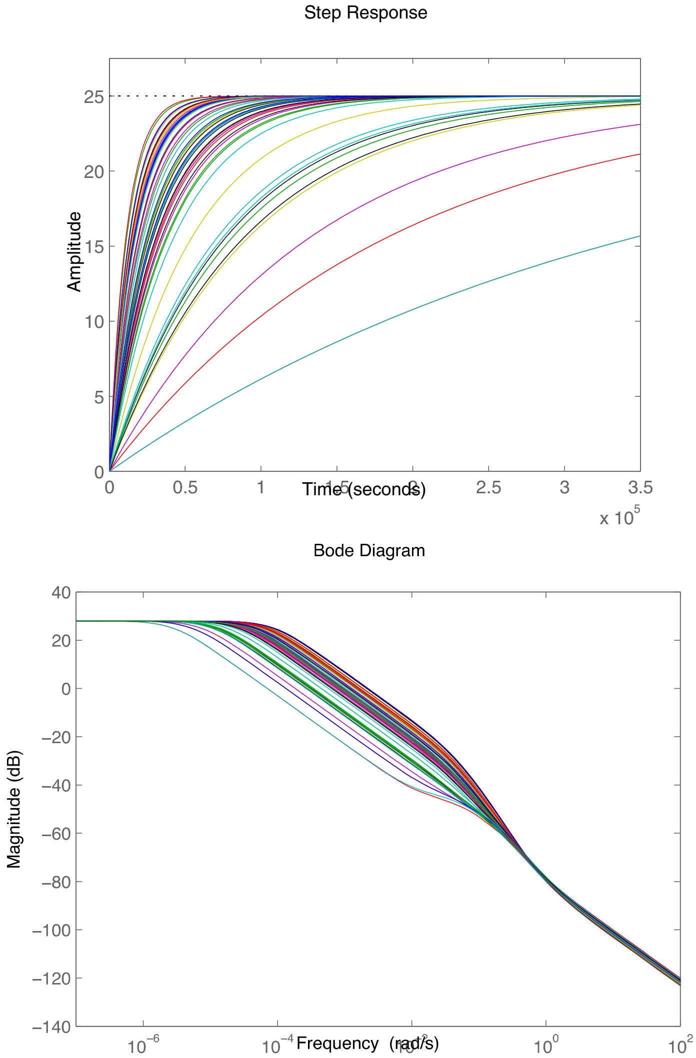


Figure B.23: Step and Frequency Response with Pareto Optimal Set of Solutions.

Table B.21: PID Controller Gains Obtained using MOPSO by Minimizing J_2

Controller Parameter	$\mathbf{K_P}$	$\mathbf{K_I}$	$\mathbf{K_D}$
$\mathbf{J_2}$	9.403	0.923	8.211

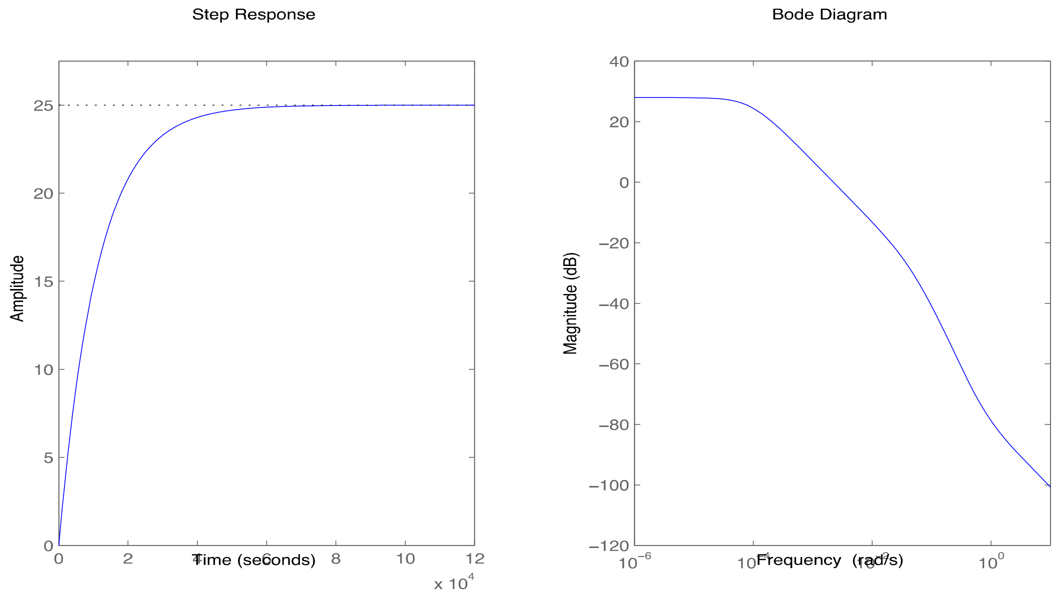


Figure B.24: Step and Frequency Response with best controller parameters Chosen from POS.

Table B.22: Performance Indices of the designed controllers using MOPSO

Performance Index	$\mathbf{J_1}$	$\mathbf{J_2}$
Rise Time (secs.)	24540	25073
Settling Time (secs.)	43773	44684
Overshoot Percentage (%)	0	0
Gain Margin (dB.)	33.35	32.36
Phase Margin (deg.)	87.44	87.44

APPENDIX-C

Step- Tracking

Case 1- Process Abnormalties-10 % MPM

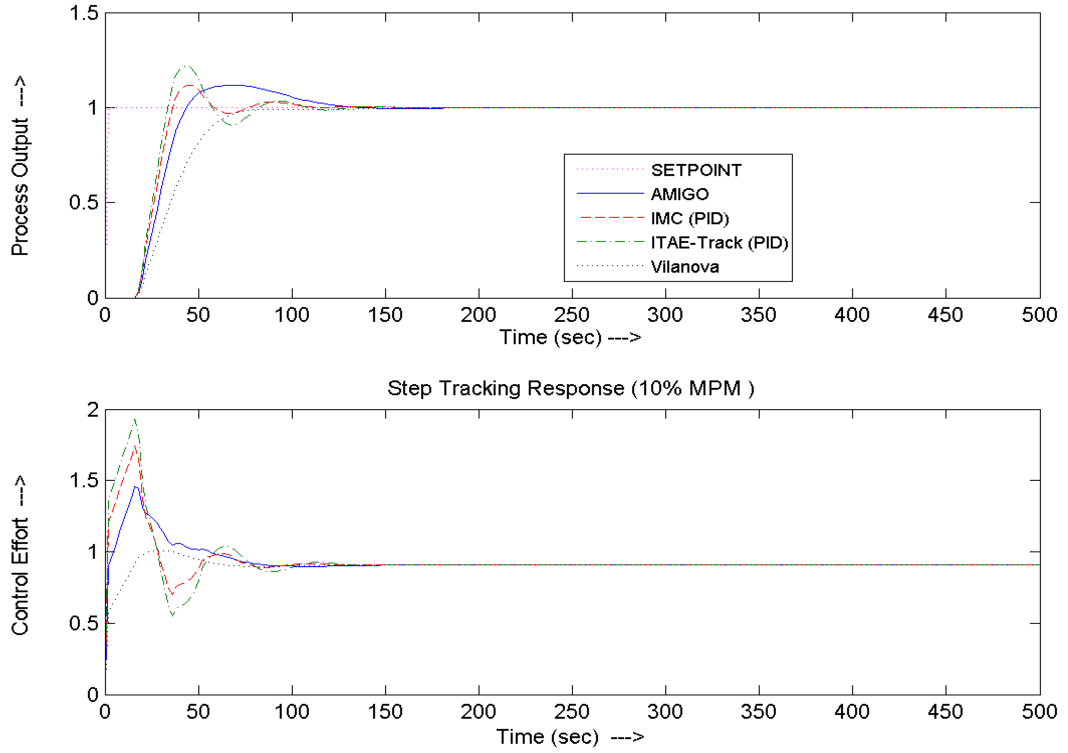


Figure C.1: Step Tracking Response with abnormalities (10% MPM)

Table C.1: Performance Indices of step tracking methods with abnormalities (10% MPM)

Parameters	AMIGO	IMC	ITAE Track	Vilanova
GM	2.81	2.05	1.85	3.19
PM	59.31	66.71	61.41	66.14
MS	1.56	1.97	2.23	1.55
MT	1.04	1.01	1.29	1.00
Jsp	25.85	23.86	22.50	37.92
Jd	25.20	26.25	24.75	41.71
Ju	51500.89	67023.60	63646.90	561.80
IAE	34.18	28.83	30.58	37.75
ISE	25.55	23.48	23.35	29.68
ITAE	816.09	504.77	622.10	823.68
TV	103.64	102.04	103.13	89.87

Case 2- Process Abnormalities (Valve Stiction)

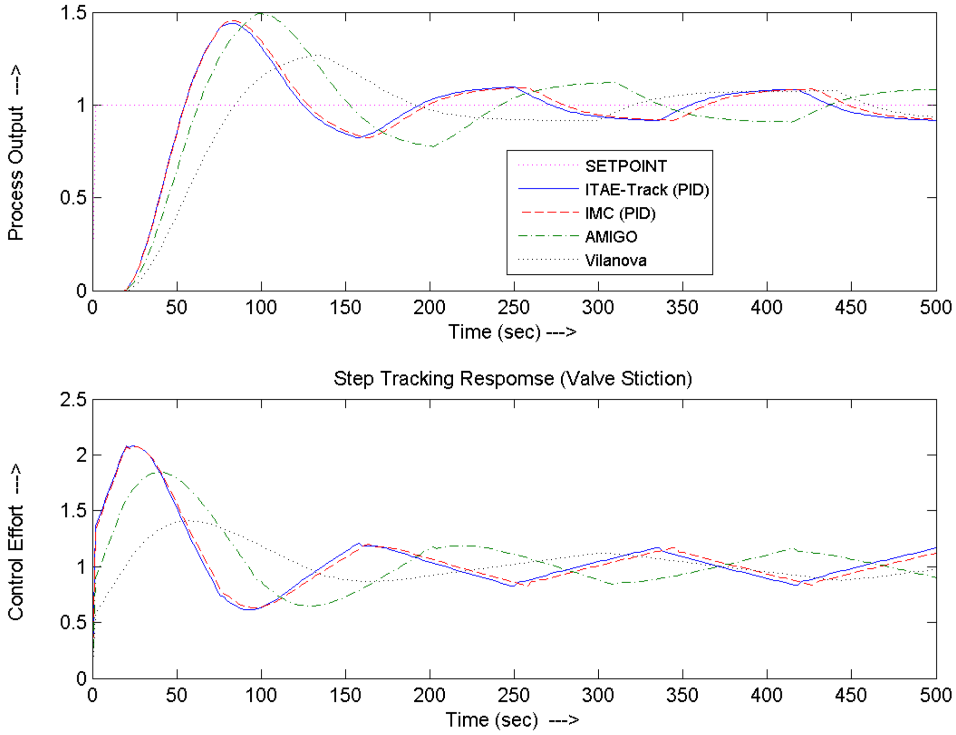


Figure C.2: Step Tracking Response with abnormalities (Valve Stiction)

Table C.2: Performance Indices of step tracking methods with abnormalities (Valve Stiction)

Parameters	AMIGO	IMC	ITAE Track	Vilanova
GM	2.36	2.36	3.53	4.08
PM	68.95	69.27	62.21	68.80
MS	1.77	1.75	1.40	1.41
MT	1.00	1.00	1.02	1.00
Jsp	24.75	23.85	28.03	41.71
Jd	24.75	23.85	25.18	41.71
Ju	74209.40	86637.62	60794.22	559.55
IAE	54.10	54.69	55.81	55.85
ISE	39.49	40.00	42.17	45.27
ITAE	2012.52	2059.02	2040.59	1743.92
TV	120.22	121.79	123.09	94.24

Case 3- Process Abnormalities (Valve Saturation)

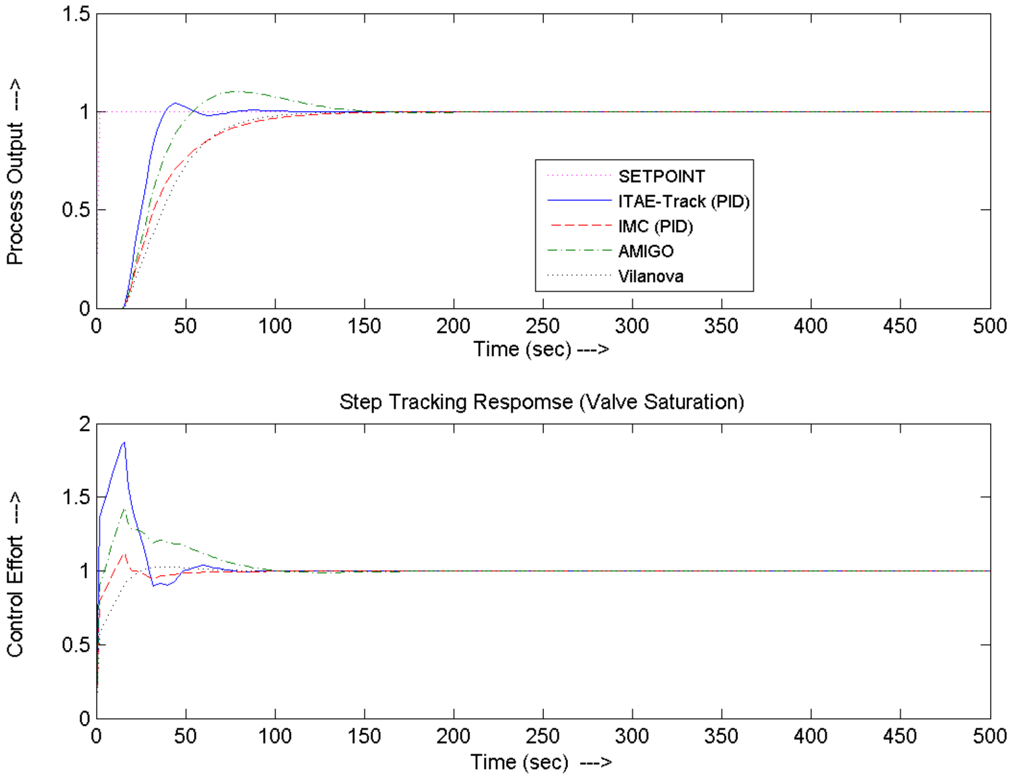


Figure C.3: Step Tracking Response with abnormalities (Valve Saturation)

Table C.3: Performance Indices of step tracking methods with abnormalities (Valve Stiction)

Parameters	AMIGO	IMC	ITAE Track	Vilanova
GM	2.36	3.94	3.53	4.08
PM	68.95	78.34	62.21	68.80
MS	1.77	1.35	1.40	1.41
MT	1.00	1.00	1.02	1.00
Jsp	24.75	39.85	28.03	41.71
Jd	24.75	39.85	25.18	41.71
Ju	74209.40	47580.96	60794.22	559.55
IAE	26.32	39.40	34.29	41.66
ISE	22.20	28.23	25.48	30.89
ITAE	388.39	1003.48	806.62	1064.31
TV	112.10	97.42	112.50	95.62

Case 4- Process Abnormalities (Sensor Noise)

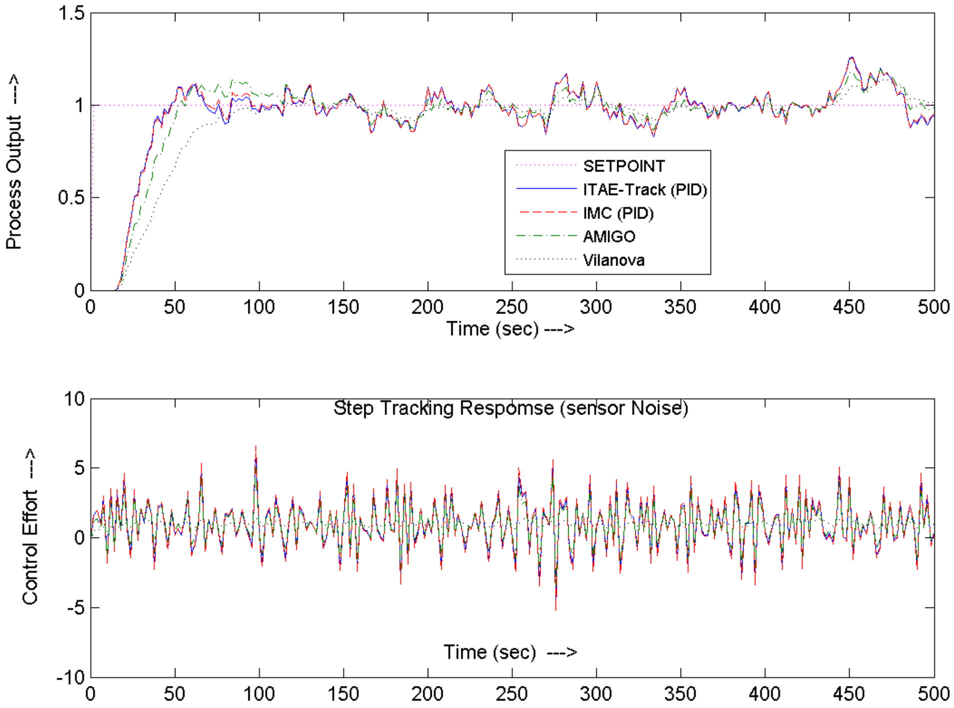


Figure C.4: Step Tracking Response with abnormalities (Sensor Noise)

Table C.4: Performance Indices of step tracking methods with abnormalities (Sensor Noise)

Parameters	AMIGO	IMC	ITAE Track	Vilanova
GM	2.36	2.36	3.53	4.08
PM	68.95	69.27	62.21	68.80
MS	1.77	1.75	1.40	1.41
MT	1.00	1.00	1.02	1.00
Jsp	24.75	23.85	28.03	41.71
Jd	24.75	23.85	25.18	41.71
Ju	74209.40	86637.62	60794.22	559.55
IAE	54.10	54.69	55.81	55.85
ISE	39.49	40.00	42.17	45.27
ITAE	2012.52	2059.02	2040.59	1743.92
TV	120.22	121.79	123.09	94.24

Disturbance-Rejection

Case 1- Process Abnormalities (10 % MPM)

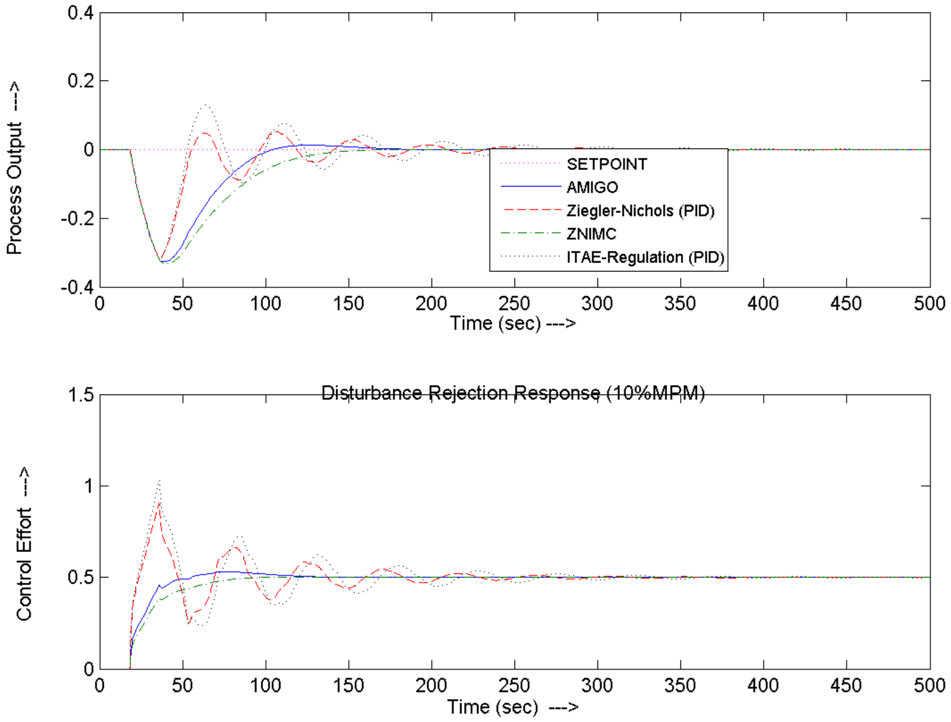


Figure C.5: Disturbance Rejection Response with abnormalities (10% MPM)

Table C.5: Performance Indices of disturbance rejection methods with abnormalities (10% MPM)

Parameters	AMIGO	ZN	ZNIMC	ITAE reg
GM	2.64	1.25	2.99	1.20
PM	59.42	40.74	69.61	26.56
MS	1.62	4.97	1.52	6.14
MT	1.04	4.00	1.00	5.18
Jsp	25.76	36.13	30.80	46.60
Jd	25.20	14.69	33.87	18.69
Ju	9.75	26.09	8.58	28.54
IAE	13.13	8.81	15.77	9.89
ISE	3.02	1.72	3.74	1.85
ITAE	641.33	404.15	839.21	482.16
TV	37.82	43.27	34.01	45.85

Case 2- Process Abnormalities-Valve Stiction

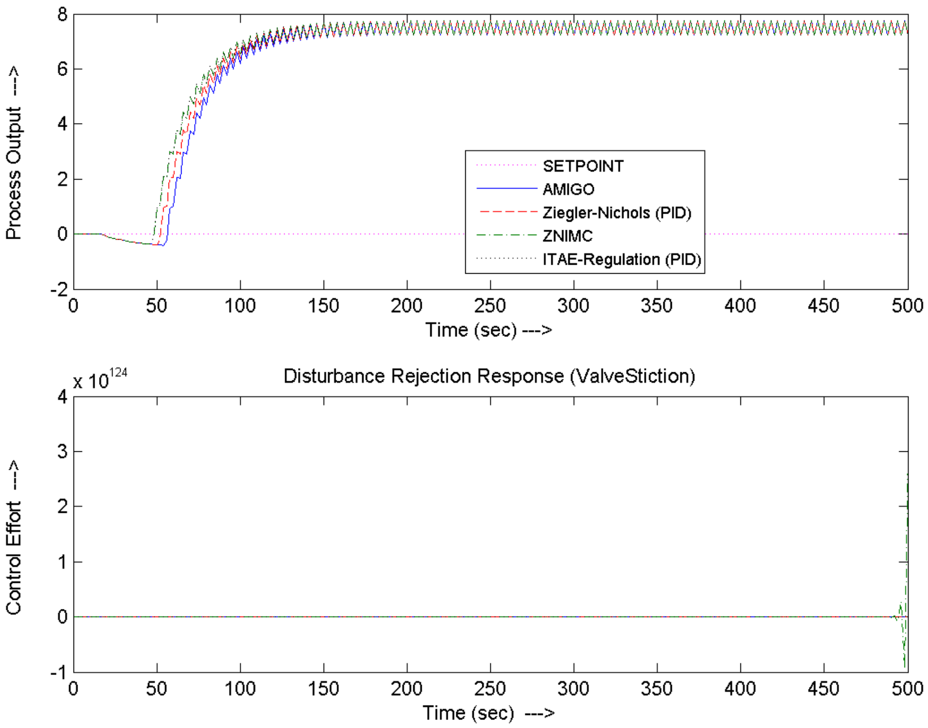


Figure C.6: Disturbance Rejection Response with abnormalities (Valve Stiction)

Table C.6: Performance Indices of disturbance rejection methods with abnormalities (Valve Stiction)

Parameters	AMIGO	IMC	ITAE Track	Vilanova
GM	2.36	3.94	3.53	4.08
PM	68.95	78.34	62.21	68.80
MS	1.77	1.35	1.40	1.41
MT	1.00	1.00	1.02	1.00
Jsp	24.75	39.85	28.03	41.71
Jd	24.75	39.85	25.18	41.71
Ju	74209.40	47580.96	60794.22	559.55
IAE	26.32	39.40	34.29	41.66
ISE	22.20	28.23	25.48	30.89
ITAE	388.39	1003.48	806.62	1064.31
TV	112.10	97.42	112.50	95.62

Case 3- Process Abnormalities-Valve Saturation

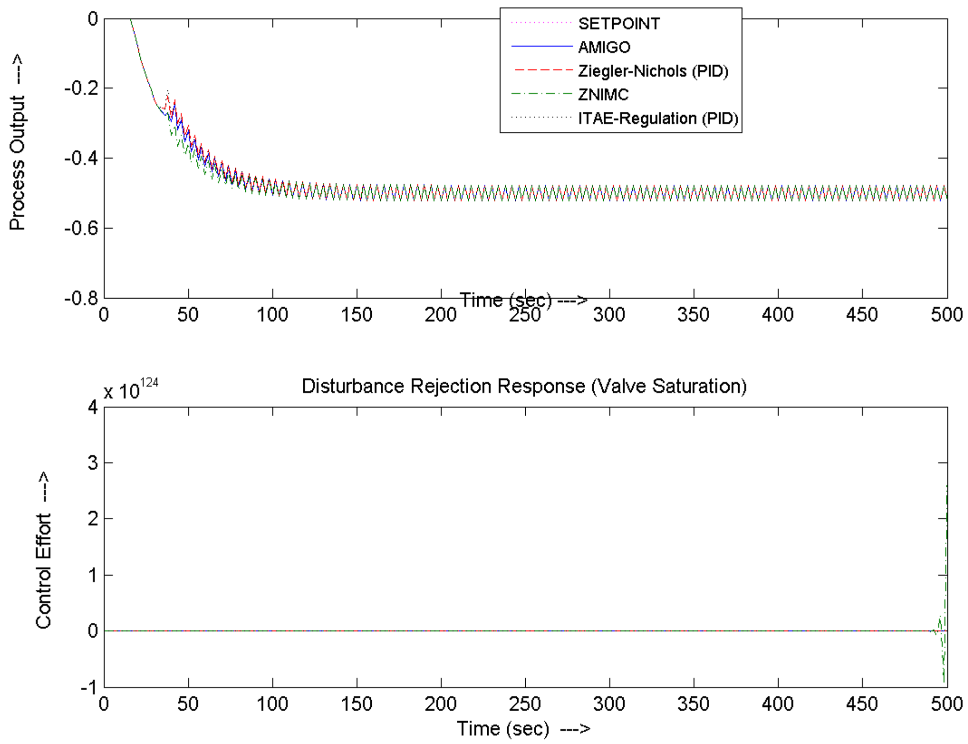


Figure C.7: Disturbance Rejection Response with abnormalities (Valve Saturation)

Table C.7: Performance Indices of disturbance rejection methods with abnormalities (Valve Saturation)

Parameters	AMIGO	ZN	ZNIMC	ITAE reg
GM	3.29	1.56	3.75	1.51
PM	62.31	55.00	71.72	41.70
MS	1.44	2.79	1.37	3.00
MT	1.02	1.79	1.00	2.03
Jsp	27.97	19.00	33.87	21.74
Jd	25.18	14.69	33.87	11.09
Ju	9.58	22.82	8.53	24.99
IAE	29.35	28.75	30.57	28.96
ISE	11.61	11.20	12.55	11.38
ITAE	1943.99	1911.79	2014.10	1925.84
TV	153.95	157.06	156.79	159.52

Case 4- Process Abnormalities-Sensor Noise

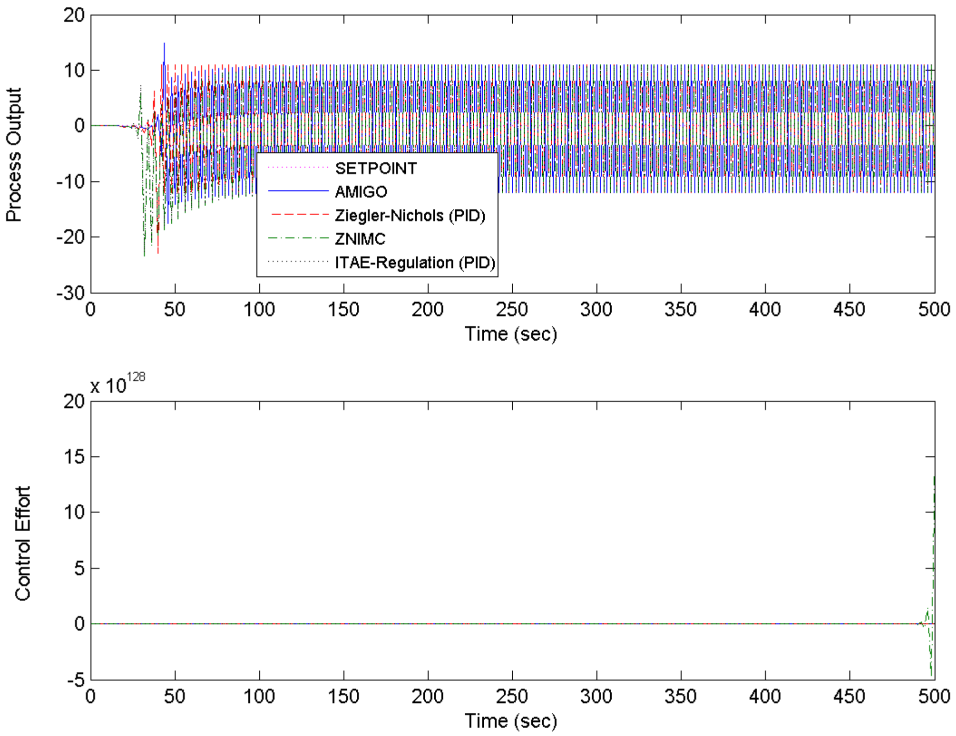


Figure C.8: Disturbance Rejection Response with abnormalities (Sensor Noise)

Table C.8: Performance Indices of disturbance rejection methods with abnormalities (Sensor Noise)

Parameters	AMIGO	ZN	ZNIMC	ITAE reg
GM	3.29	1.56	3.75	1.51
PM	62.31	55.00	71.72	41.70
MS	1.44	2.79	1.37	3.00
MT	1.02	1.79	1.00	2.03
Jsp	27.97	19.00	33.87	21.74
Jd	25.18	14.69	33.87	11.09
Ju	9.58	22.82	8.53	24.99
IAE	29.35	28.75	30.57	28.96
ISE	11.61	11.20	12.55	11.38
ITAE	1943.99	1911.79	2014.10	1925.84
TV	153.95	157.06	156.79	159.52

Sensitivity Graph (Disturbance Rejection)

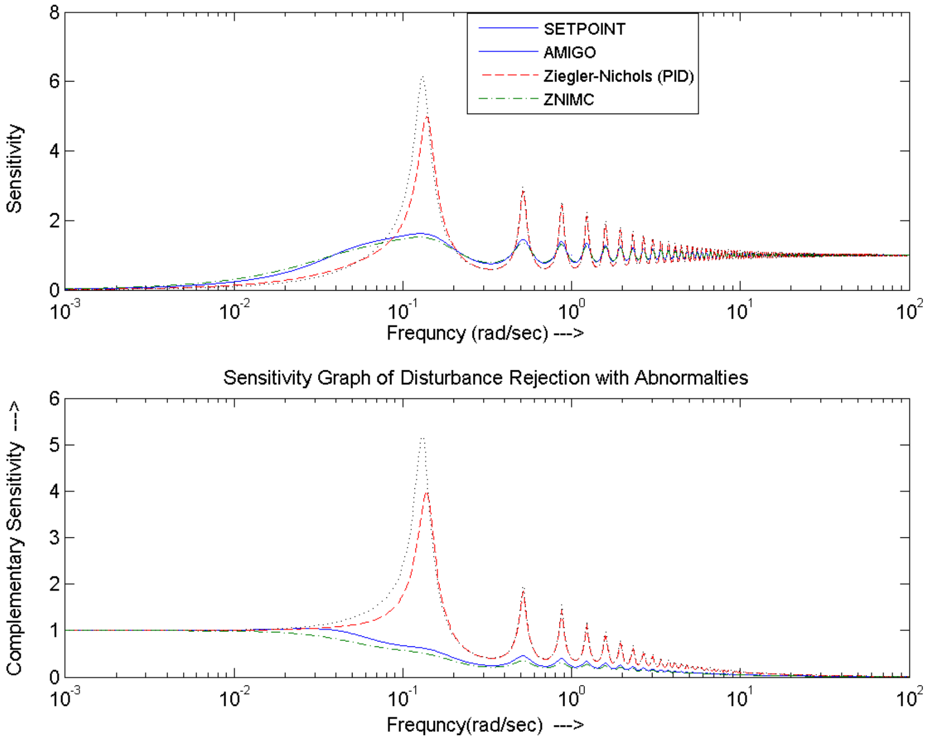


Figure C.9: Sensitivity Graph of Disturbance Rejection Methods

Appendix-D

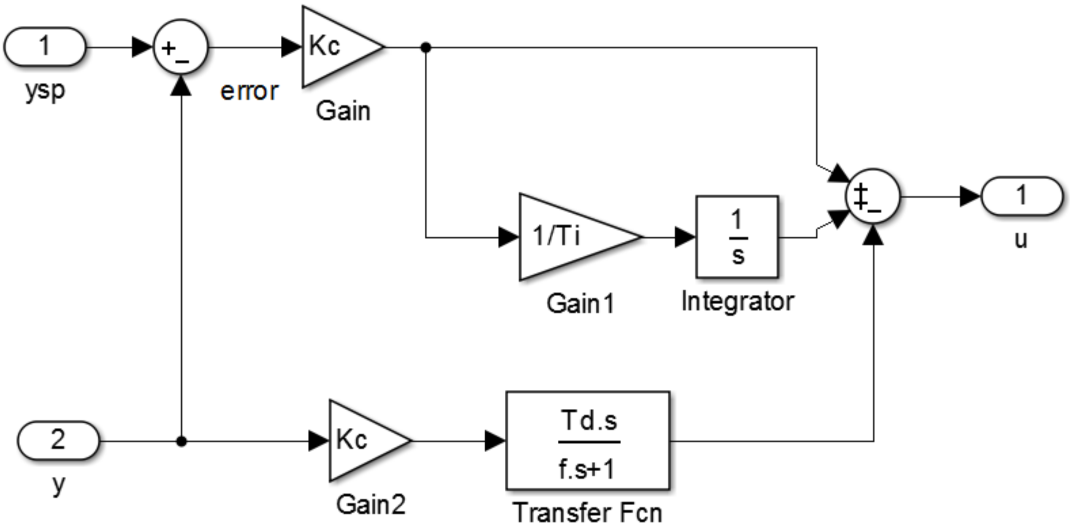


Figure D.1: No Kick PID with Derivative Filter

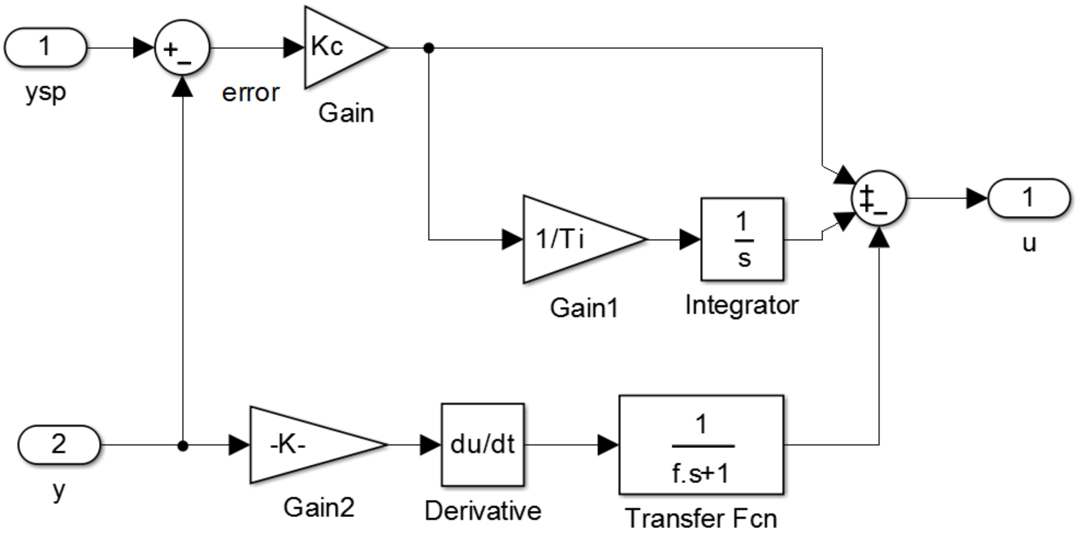


Figure D.2: No Kick PID with Explicit Derivative Filter

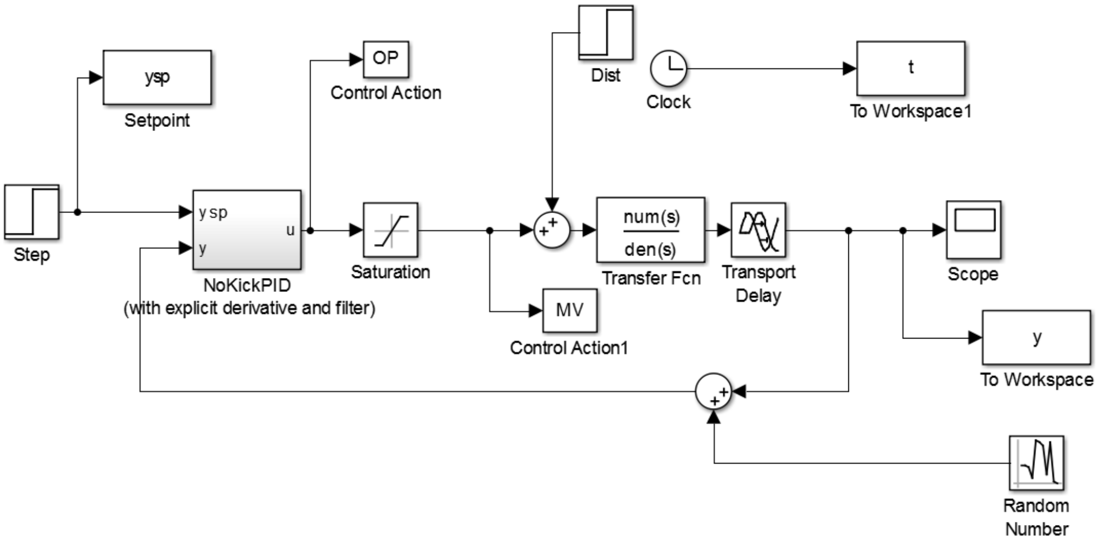


Figure D.3: PID Combined Response with No Stiction

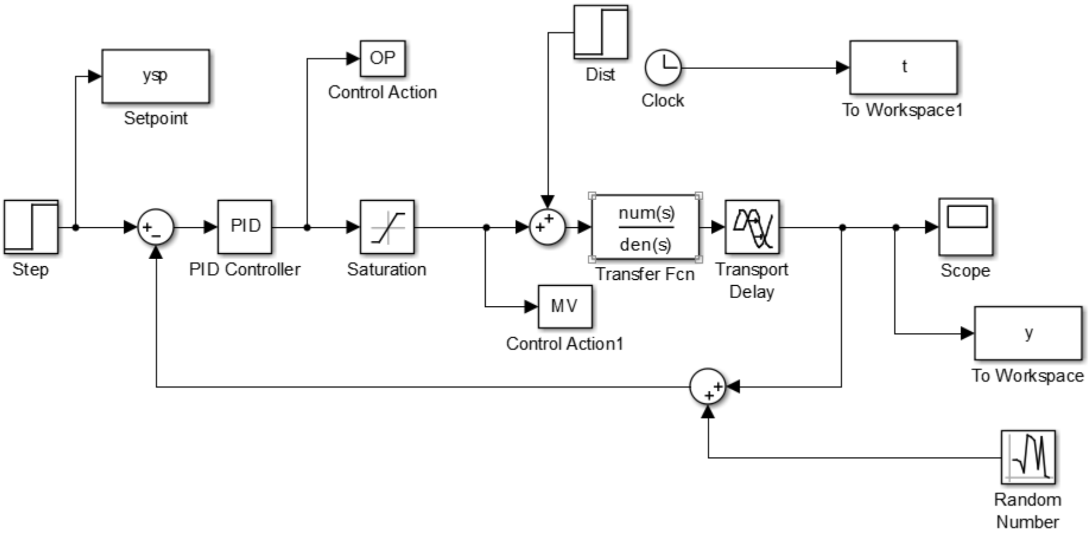


Figure D.3: PID Combined Response with PID at No Stiction

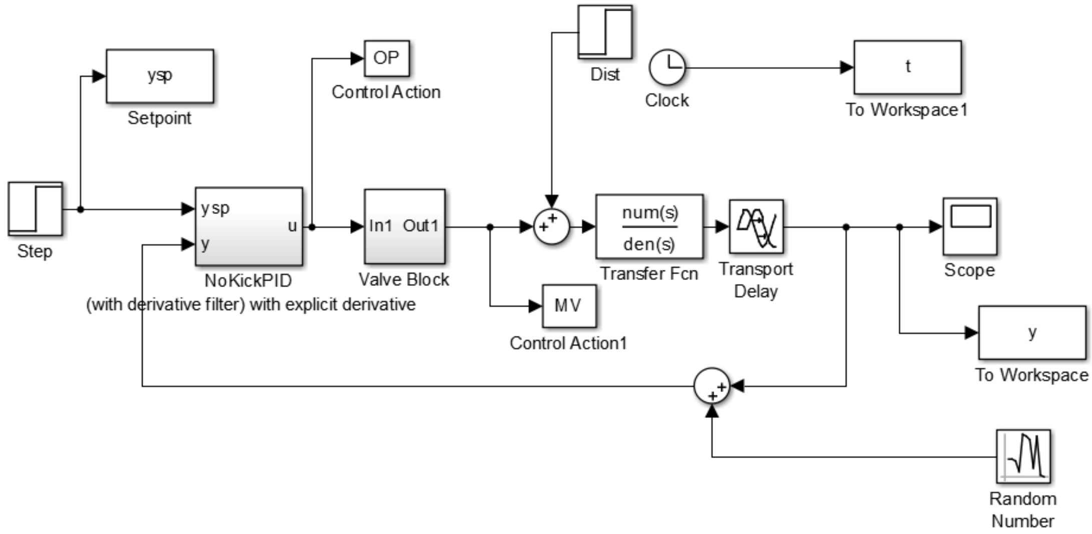


Figure D.5: PID Combined Response with Stiction

Appendix-E

Data Sheet of Centrifugal Machine Temperature control System

V=input Voltage (Volts) T= Temperature (deg.C)

Sampling Interval: 2 seconds Total Number of Samples: 800

S.N.	Time	V	T
1	0.00	9.000	129.320
2	2.00	9.000	129.320
3	4.00	9.000	129.564
4	6.00	9.000	131.516
5	8.00	9.000	134.200
6	10.00	9.000	136.640
7	12.00	9.000	139.324
8	14.00	9.000	141.764
9	16.00	9.000	144.204
10	18.00	9.000	146.156
11	20.00	9.000	148.596
12	22.00	9.000	150.548
13	24.00	9.000	152.256
14	26.00	9.000	154.208
15	28.00	9.000	155.428
16	30.00	9.000	156.648
17	32.00	9.000	157.624
18	34.00	9.000	158.600
19	36.00	9.000	159.576
20	38.00	9.000	160.796
21	40.00	9.000	161.772
22	42.00	9.000	162.260
23	44.00	9.000	162.748
24	46.00	9.000	163.724
25	48.00	9.000	164.212
26	50.00	9.000	165.188
27	52.00	9.000	166.164
28	54.00	9.000	167.140
29	56.00	9.000	167.872
30	58.00	9.000	168.604
31	60.00	9.000	169.092
32	62.00	9.000	169.336
33	64.00	9.000	169.824
34	66.00	9.000	170.312
35	68.00	9.000	170.556
36	70.00	9.000	171.044
37	72.00	9.000	171.532
38	74.00	9.000	172.020
39	76.00	9.000	172.508
40	78.00	9.000	172.752
41	80.00	9.000	172.996
42	82.00	9.000	173.240
43	84.00	9.000	173.484
44	86.00	9.000	173.972
45	88.00	9.000	173.728
46	90.00	9.000	173.728

S.N.	Time	V	T
47	92.00	9.000	174.216
48	94.00	9.000	174.948
49	96.00	9.000	175.680
50	98.00	9.000	175.924
51	100.00	9.000	175.924
52	102.00	9.000	176.168
53	104.00	9.000	176.900
54	106.00	9.000	177.144
55	108.00	9.000	177.632
56	110.00	9.000	178.120
57	112.00	9.000	177.876
58	114.00	9.000	178.364
59	116.00	9.000	178.364
60	118.00	9.000	178.364
61	120.00	9.000	178.852
62	122.00	9.000	179.096
63	124.00	9.000	179.584
64	126.00	9.000	179.828
65	128.00	9.000	180.072
66	130.00	9.000	180.316
67	132.00	9.000	180.316
68	134.00	9.000	180.804
69	136.00	9.000	180.804
70	138.00	9.000	181.292
71	140.00	9.000	181.536
72	142.00	9.000	182.024
73	144.00	9.000	182.024
74	146.00	9.000	182.024
75	148.00	9.000	182.024
76	150.00	9.000	182.268
77	152.00	9.000	182.512
78	154.00	9.000	182.756
79	156.00	9.000	183.000
80	158.00	9.000	183.000
81	160.00	9.000	183.000
82	162.00	9.000	183.488
83	164.00	9.000	183.732
84	166.00	9.000	183.976
85	168.00	9.000	184.220
86	170.00	9.000	184.220
87	172.00	9.000	184.464
88	174.00	9.000	184.708
89	176.00	9.000	184.952
90	178.00	9.000	184.464
91	180.00	9.000	184.220
92	182.00	9.000	184.464
93	184.00	9.000	184.708
94	186.00	9.000	185.196
95	188.00	9.000	185.440
96	190.00	9.000	185.684
97	192.00	9.000	185.440
98	194.00	9.000	185.684
99	196.00	9.000	185.928
100	198.00	9.000	186.172

S.N.	Time	V	T
101	200.00	9.000	186.172
102	202.00	9.000	186.416
103	204.00	9.000	186.416
104	206.00	9.000	186.416
105	208.00	9.000	186.416
106	210.00	9.000	186.172
107	212.00	9.000	186.172
108	214.00	9.000	186.416
109	216.00	9.000	186.904
110	218.00	9.000	187.392
111	220.00	9.000	187.636
112	222.00	9.000	187.636
113	224.00	9.000	187.880
114	226.00	9.000	187.880
115	228.00	9.000	187.880
116	230.00	9.000	187.880
117	232.00	9.000	187.880
118	234.00	9.000	187.636
119	236.00	9.000	187.880
120	238.00	9.000	187.880
121	240.00	9.000	187.880
122	242.00	9.000	187.880
123	244.00	9.000	188.124
124	246.00	9.000	188.368
125	248.00	9.000	188.368
126	250.00	9.000	188.368
127	252.00	9.000	188.612
128	254.00	9.000	187.880
129	256.00	9.000	187.880
130	258.00	9.000	187.880
131	260.00	9.000	188.124

S.N.	Time	V	T
132	262.00	9.000	188.124
133	264.00	9.000	188.368
134	266.00	9.000	189.100
135	268.00	9.000	189.344
136	270.00	9.000	189.344
137	272.00	9.000	189.344
138	274.00	9.000	189.588
139	276.00	9.000	189.100
140	278.00	9.000	189.344
141	280.00	9.000	189.832
142	282.00	9.000	190.320
143	284.00	9.000	190.076
144	286.00	9.000	189.832
145	288.00	9.000	189.832
146	290.00	9.000	190.320
147	292.00	9.000	190.564
148	294.00	9.000	190.564
149	296.00	9.000	190.320
150	298.00	9.000	189.588
151	300.00	9.000	189.588
152	302.00	9.000	190.076
153	304.00	9.000	190.076
154	306.00	9.000	190.076
155	308.00	9.000	190.076
156	310.00	9.000	190.320
157	312.00	9.000	190.076
158	314.00	9.000	190.320
159	316.00	9.000	190.320
160	318.00	9.000	190.564
161	320.00	9.000	190.564
162	322.00	9.000	190.564

S.N.	Time	V	T
163	324.00	9.000	190.320
164	326.00	9.000	190.320
165	328.00	9.000	190.320
166	330.00	9.000	190.320
167	332.00	9.000	190.564
168	334.00	9.000	191.052
169	336.00	9.000	191.540
170	338.00	9.000	191.296
171	340.00	9.000	191.296
172	342.00	9.000	191.296
173	344.00	9.000	191.296
174	346.00	9.000	191.296
175	348.00	9.000	191.784
176	350.00	9.000	191.296
177	352.00	9.000	191.296
178	354.00	9.000	191.540
179	356.00	9.000	192.028
180	358.00	9.000	191.540
181	360.00	9.000	191.784

S.N.	Time	V	T
182	362.00	9.000	191.784
183	364.00	9.000	191.540
184	366.00	9.000	191.052
185	368.00	9.000	191.052
186	370.00	9.000	191.052
187	372.00	9.000	190.808
188	374.00	9.000	190.808
189	376.00	9.000	191.052
190	378.00	9.000	191.052
191	380.00	9.000	191.052
192	382.00	9.000	191.296
193	384.00	9.000	191.540
194	386.00	9.000	191.540
195	388.00	9.000	191.540
196	390.00	9.000	191.784
197	392.00	9.000	192.028
198	394.00	9.000	192.028
199	396.00	9.000	192.028
200	398.00	9.000	192.028

S.N.	Time	V	T
201	400.00	4.000	192.028
202	402.00	4.000	191.540
203	404.00	4.000	189.588
204	406.00	4.000	186.172
205	408.00	4.000	181.780
206	410.00	4.000	177.632
207	412.00	4.000	173.972
208	414.00	4.000	170.068
209	416.00	4.000	166.164
210	418.00	4.000	162.992
211	420.00	4.000	160.064
212	422.00	4.000	157.624
213	424.00	4.000	155.184
214	426.00	4.000	153.232
215	428.00	4.000	151.036
216	430.00	4.000	149.328
217	432.00	4.000	147.132
218	434.00	4.000	145.180
219	436.00	4.000	143.228
220	438.00	4.000	142.008
221	440.00	4.000	140.544
222	442.00	4.000	139.324
223	444.00	4.000	138.348
224	446.00	4.000	137.128
225	448.00	4.000	136.152
226	450.00	4.000	135.420
227	452.00	4.000	134.444
228	454.00	4.000	133.468

S.N.	Time	V	T
229	456.00	4.000	132.736
230	458.00	4.000	131.516
231	460.00	4.000	130.296
232	462.00	4.000	129.320
233	464.00	4.000	128.588
234	466.00	4.000	127.856
235	468.00	4.000	127.124
236	470.00	4.000	126.392
237	472.00	4.000	125.416
238	474.00	4.000	124.684
239	476.00	4.000	123.952
240	478.00	4.000	123.464
241	480.00	4.000	122.732
242	482.00	4.000	122.000
243	484.00	4.000	121.512
244	486.00	4.000	120.780
245	488.00	4.000	120.536
246	490.00	4.000	119.804
247	492.00	4.000	119.316
248	494.00	4.000	118.584
249	496.00	4.000	117.852
250	498.00	4.000	117.364
251	500.00	4.000	116.876
252	502.00	4.000	116.388
253	504.00	4.000	116.144
254	506.00	4.000	115.656
255	508.00	4.000	115.412
256	510.00	4.000	114.680

S.N.	Time	V	T
257	512.00	4.000	114.436
258	514.00	4.000	113.948
259	516.00	4.000	113.704
260	518.00	4.000	112.972
261	520.00	4.000	112.728
262	522.00	4.000	112.240
263	524.00	4.000	111.996
264	526.00	4.000	111.752
265	528.00	4.000	111.752
266	530.00	4.000	111.752
267	532.00	4.000	111.508
268	534.00	4.000	111.264
269	536.00	4.000	111.020
270	538.00	4.000	111.264
271	540.00	4.000	110.776
272	542.00	4.000	110.288
273	544.00	4.000	110.044
274	546.00	4.000	109.800
275	548.00	4.000	109.312
276	550.00	4.000	109.556
277	552.00	4.000	109.556
278	554.00	4.000	109.556

S.N.	Time	V	T
279	556.00	4.000	109.312
280	558.00	4.000	108.824
281	560.00	4.000	108.092
282	562.00	4.000	107.360
283	564.00	4.000	106.872
284	566.00	4.000	106.628
285	568.00	4.000	106.140
286	570.00	4.000	105.896
287	572.00	4.000	105.652
288	574.00	4.000	105.408
289	576.00	4.000	104.920
290	578.00	4.000	104.676
291	580.00	4.000	104.188
292	582.00	4.000	103.700
293	584.00	4.000	103.456
294	586.00	4.000	103.212
295	588.00	4.000	102.968
296	590.00	4.000	102.480
297	592.00	4.000	102.236
298	594.00	4.000	101.748
299	596.00	4.000	101.504
300	598.00	4.000	101.260

S.N.	Time	V	T
301	600.00	4.000	101.260
302	602.00	4.000	101.016
303	604.00	4.000	100.772
304	606.00	4.000	100.528
305	608.00	4.000	100.528
306	610.00	4.000	100.284
307	612.00	4.000	99.796
308	614.00	4.000	99.308
309	616.00	4.000	99.308
310	618.00	4.000	99.308
311	620.00	4.000	99.064
312	622.00	4.000	98.820
313	624.00	4.000	98.576
314	626.00	4.000	98.576
315	628.00	4.000	98.088
316	630.00	4.000	97.844
317	632.00	4.000	97.600
318	634.00	4.000	97.112
319	636.00	4.000	96.868
320	638.00	4.000	96.624
321	640.00	4.000	96.868
322	642.00	4.000	96.624
323	644.00	4.000	96.624
324	646.00	4.000	96.380
325	648.00	4.000	95.892
326	650.00	4.000	95.892
327	652.00	4.000	95.892
328	654.00	4.000	95.404

S.N.	Time	V	T
329	656.00	4.000	95.648
330	658.00	4.000	95.404
331	660.00	4.000	95.160
332	662.00	4.000	94.916
333	664.00	4.000	94.672
334	666.00	4.000	94.672
335	668.00	4.000	94.428
336	670.00	4.000	94.428
337	672.00	4.000	94.184
338	674.00	4.000	93.940
339	676.00	4.000	93.696
340	678.00	4.000	93.696
341	680.00	4.000	93.696
342	682.00	4.000	93.208
343	684.00	4.000	92.964
344	686.00	4.000	92.720
345	688.00	4.000	92.720
346	690.00	4.000	92.476
347	692.00	4.000	92.476
348	694.00	4.000	92.476
349	696.00	4.000	92.476
350	698.00	4.000	92.476
351	700.00	4.000	92.476
352	702.00	4.000	91.988
353	704.00	4.000	91.988
354	706.00	4.000	91.744
355	708.00	4.000	91.744
356	710.00	4.000	91.500

S.N.	Time	V	T
357	712.00	4.000	91.012
358	714.00	4.000	91.012
359	716.00	4.000	90.768
360	718.00	4.000	90.768
361	720.00	4.000	90.768
362	722.00	4.000	90.768
363	724.00	4.000	91.012
364	726.00	4.000	90.768
365	728.00	4.000	90.524
366	730.00	4.000	90.280
367	732.00	4.000	90.280
368	734.00	4.000	90.036
369	736.00	4.000	89.792
370	738.00	4.000	89.548
371	740.00	4.000	89.548
372	742.00	4.000	89.548
373	744.00	4.000	89.304
374	746.00	4.000	89.304
375	748.00	4.000	89.060
376	750.00	4.000	89.060
377	752.00	4.000	88.816
378	754.00	4.000	88.572

S.N.	Time	V	T
379	756.00	4.000	88.572
380	758.00	4.000	88.816
381	760.00	4.000	88.572
382	762.00	4.000	88.328
383	764.00	4.000	88.084
384	766.00	4.000	87.840
385	768.00	4.000	87.352
386	770.00	4.000	87.596
387	772.00	4.000	87.352
388	774.00	4.000	87.352
389	776.00	4.000	87.352
390	778.00	4.000	87.108
391	780.00	4.000	87.108
392	782.00	4.000	87.108
393	784.00	4.000	87.108
394	786.00	4.000	86.864
395	788.00	4.000	87.108
396	790.00	4.000	86.864
397	792.00	4.000	86.620
398	794.00	4.000	86.620
399	796.00	4.000	86.620
400	798.00	4.000	86.376

S.N.	Time	V	T
401	800.00	8.000	86.132
402	802.00	8.000	85.888
403	804.00	8.000	86.864
404	806.00	8.000	89.548
405	808.00	8.000	93.208
406	810.00	8.000	97.356
407	812.00	8.000	101.504
408	814.00	8.000	105.164
409	816.00	8.000	108.824
410	818.00	8.000	111.996
411	820.00	8.000	114.924
412	822.00	8.000	117.364
413	824.00	8.000	119.316
414	826.00	8.000	121.512
415	828.00	8.000	123.464
416	830.00	8.000	124.928
417	832.00	8.000	126.636
418	834.00	8.000	128.100
419	836.00	8.000	129.564
420	838.00	8.000	130.784
421	840.00	8.000	132.004
422	842.00	8.000	133.224
423	844.00	8.000	134.200
424	846.00	8.000	135.176
425	848.00	8.000	136.152
426	850.00	8.000	136.884
427	852.00	8.000	138.104
428	854.00	8.000	138.836

S.N.	Time	V	T
429	856.00	8.000	139.324
430	858.00	8.000	140.300
431	860.00	8.000	141.276
432	862.00	8.000	141.764
433	864.00	8.000	142.008
434	866.00	8.000	142.740
435	868.00	8.000	143.960
436	870.00	8.000	144.448
437	872.00	8.000	145.180
438	874.00	8.000	145.912
439	876.00	8.000	146.644
440	878.00	8.000	147.376
441	880.00	8.000	147.620
442	882.00	8.000	148.352
443	884.00	8.000	148.840
444	886.00	8.000	149.084
445	888.00	8.000	149.572
446	890.00	8.000	150.060
447	892.00	8.000	150.304
448	894.00	8.000	150.548
449	896.00	8.000	151.036
450	898.00	8.000	151.524
451	900.00	8.000	152.500
452	902.00	8.000	152.988
453	904.00	8.000	153.232
454	906.00	8.000	153.720
455	908.00	8.000	154.208
456	910.00	8.000	154.696

S.N.	Time	V	T
457	912.00	8.000	155.184
458	914.00	8.000	155.672
459	916.00	8.000	155.672
460	918.00	8.000	155.672
461	920.00	8.000	155.916
462	922.00	8.000	156.160
463	924.00	8.000	156.404
464	926.00	8.000	156.404
465	928.00	8.000	156.892
466	930.00	8.000	157.380
467	932.00	8.000	157.624
468	934.00	8.000	158.112
469	936.00	8.000	158.600
470	938.00	8.000	158.600
471	940.00	8.000	159.088
472	942.00	8.000	159.576
473	944.00	8.000	159.332
474	946.00	8.000	159.332
475	948.00	8.000	159.576
476	950.00	8.000	159.820
477	952.00	8.000	159.820
478	954.00	8.000	159.820
479	956.00	8.000	160.064
480	958.00	8.000	160.308
481	960.00	8.000	160.552
482	962.00	8.000	160.796
483	964.00	8.000	160.796
484	966.00	8.000	160.796
485	968.00	8.000	161.040
486	970.00	8.000	161.528
487	972.00	8.000	161.772
488	974.00	8.000	161.772
489	976.00	8.000	162.016
490	978.00	8.000	162.504
491	980.00	8.000	162.504
492	982.00	8.000	162.748
493	984.00	8.000	162.748
494	986.00	8.000	162.748
495	988.00	8.000	162.992
496	990.00	8.000	163.236
497	992.00	8.000	163.236
498	994.00	8.000	162.992
499	996.00	8.000	163.236
500	998.00	8.000	163.480

S.N.	Time	V	T
501	1000.00	3.000	163.724
502	1002.00	3.000	163.968
503	1004.00	3.000	162.992
504	1006.00	3.000	160.308
505	1008.00	3.000	155.916
506	1010.00	3.000	151.280
507	1012.00	3.000	146.644
508	1014.00	3.000	142.740
509	1016.00	3.000	139.080
510	1018.00	3.000	136.152
511	1020.00	3.000	133.224
512	1022.00	3.000	130.784
513	1024.00	3.000	128.588
514	1026.00	3.000	126.636
515	1028.00	3.000	125.172
516	1030.00	3.000	123.220
517	1032.00	3.000	121.756
518	1034.00	3.000	120.292
519	1036.00	3.000	118.828
520	1038.00	3.000	117.364
521	1040.00	3.000	115.900
522	1042.00	3.000	114.680
523	1044.00	3.000	113.460
524	1046.00	3.000	112.240
525	1048.00	3.000	111.264
526	1050.00	3.000	110.288
527	1052.00	3.000	109.068
528	1054.00	3.000	107.604

S.N.	Time	V	T
529	1056.00	3.000	106.628
530	1058.00	3.000	105.652
531	1060.00	3.000	104.676
532	1062.00	3.000	103.944
533	1064.00	3.000	102.968
534	1066.00	3.000	102.236
535	1068.00	3.000	101.504
536	1070.00	3.000	100.284
537	1072.00	3.000	99.796
538	1074.00	3.000	99.308
539	1076.00	3.000	98.332
540	1078.00	3.000	97.844
541	1080.00	3.000	97.356
542	1082.00	3.000	96.868
543	1084.00	3.000	96.380
544	1086.00	3.000	95.892
545	1088.00	3.000	95.160
546	1090.00	3.000	94.672
547	1092.00	3.000	94.184
548	1094.00	3.000	93.696
549	1096.00	3.000	93.208
550	1098.00	3.000	92.964
551	1100.00	3.000	92.476
552	1102.00	3.000	91.988
553	1104.00	3.000	91.256
554	1106.00	3.000	90.768
555	1108.00	3.000	90.280
556	1110.00	3.000	89.792

S.N.	Time	V	T
557	1112.00	3.000	89.548
558	1114.00	3.000	89.060
559	1116.00	3.000	88.084
560	1118.00	3.000	87.596
561	1120.00	3.000	87.352
562	1122.00	3.000	87.108
563	1124.00	3.000	86.864
564	1126.00	3.000	86.864
565	1128.00	3.000	86.376
566	1130.00	3.000	85.888
567	1132.00	3.000	85.888
568	1134.00	3.000	85.644
569	1136.00	3.000	84.912
570	1138.00	3.000	84.180
571	1140.00	3.000	84.180
572	1142.00	3.000	83.936
573	1144.00	3.000	83.692
574	1146.00	3.000	83.448
575	1148.00	3.000	83.204
576	1150.00	3.000	82.716
577	1152.00	3.000	82.228
578	1154.00	3.000	81.984

S.N.	Time	V	T
579	1156.00	3.000	81.984
580	1158.00	3.000	81.740
581	1160.00	3.000	81.740
582	1162.00	3.000	81.496
583	1164.00	3.000	81.008
584	1166.00	3.000	80.764
585	1168.00	3.000	80.276
586	1170.00	3.000	80.032
587	1172.00	3.000	79.788
588	1174.00	3.000	79.544
589	1176.00	3.000	79.300
590	1178.00	3.000	79.056
591	1180.00	3.000	78.568
592	1182.00	3.000	78.568
593	1184.00	3.000	78.324
594	1186.00	3.000	78.324
595	1188.00	3.000	78.080
596	1190.00	3.000	77.836
597	1192.00	3.000	77.836
598	1194.00	3.000	77.592
599	1196.00	3.000	77.104
600	1198.00	3.000	76.860

S.N.	Time	V	T
601	1200.00	7.000	76.372
602	1202.00	7.000	76.372
603	1204.00	7.000	77.104
604	1206.00	7.000	79.300
605	1208.00	7.000	82.472
606	1210.00	7.000	85.888
607	1212.00	7.000	89.060
608	1214.00	7.000	92.232
609	1216.00	7.000	95.160
610	1218.00	7.000	97.600
611	1220.00	7.000	99.552
612	1222.00	7.000	101.260
613	1224.00	7.000	103.212
614	1226.00	7.000	105.164
615	1228.00	7.000	106.628
616	1230.00	7.000	107.604
617	1232.00	7.000	108.580
618	1234.00	7.000	109.800
619	1236.00	7.000	110.776
620	1238.00	7.000	111.996
621	1240.00	7.000	112.972
622	1242.00	7.000	113.948
623	1244.00	7.000	114.680
624	1246.00	7.000	115.656
625	1248.00	7.000	116.144
626	1250.00	7.000	117.120
627	1252.00	7.000	117.608
628	1254.00	7.000	118.340

S.N.	Time	V	T
629	1256.00	7.000	118.828
630	1258.00	7.000	119.804
631	1260.00	7.000	120.292
632	1262.00	7.000	121.024
633	1264.00	7.000	121.512
634	1266.00	7.000	122.000
635	1268.00	7.000	122.244
636	1270.00	7.000	122.976
637	1272.00	7.000	123.464
638	1274.00	7.000	123.952
639	1276.00	7.000	124.440
640	1278.00	7.000	124.928
641	1280.00	7.000	125.660
642	1282.00	7.000	125.904
643	1284.00	7.000	126.148
644	1286.00	7.000	126.636
645	1288.00	7.000	126.636
646	1290.00	7.000	127.124
647	1292.00	7.000	127.368
648	1294.00	7.000	127.368
649	1296.00	7.000	127.368
650	1298.00	7.000	127.368
651	1300.00	7.000	127.856
652	1302.00	7.000	128.344
653	1304.00	7.000	128.588
654	1306.00	7.000	129.076
655	1308.00	7.000	129.320
656	1310.00	7.000	129.564

S.N.	Time	V	T
657	1312.00	7.000	130.052
658	1314.00	7.000	130.296
659	1316.00	7.000	130.296
660	1318.00	7.000	130.540
661	1320.00	7.000	130.784
662	1322.00	7.000	131.272
663	1324.00	7.000	131.516
664	1326.00	7.000	131.760
665	1328.00	7.000	131.760
666	1330.00	7.000	132.004
667	1332.00	7.000	132.004
668	1334.00	7.000	132.492
669	1336.00	7.000	132.492
670	1338.00	7.000	132.492
671	1340.00	7.000	132.248
672	1342.00	7.000	132.492
673	1344.00	7.000	132.980
674	1346.00	7.000	132.980
675	1348.00	7.000	132.980
676	1350.00	7.000	133.468
677	1352.00	7.000	133.956
678	1354.00	7.000	133.956

S.N.	Time	V	T
679	1356.00	7.000	133.956
680	1358.00	7.000	133.956
681	1360.00	7.000	134.200
682	1362.00	7.000	134.444
683	1364.00	7.000	134.932
684	1366.00	7.000	135.176
685	1368.00	7.000	135.176
686	1370.00	7.000	135.176
687	1372.00	7.000	135.176
688	1374.00	7.000	135.420
689	1376.00	7.000	135.664
690	1378.00	7.000	135.908
691	1380.00	7.000	136.396
692	1382.00	7.000	136.396
693	1384.00	7.000	136.396
694	1386.00	7.000	136.640
695	1388.00	7.000	136.396
696	1390.00	7.000	136.884
697	1392.00	7.000	136.640
698	1394.00	7.000	136.884
699	1396.00	7.000	136.640
700	1398.00	7.000	136.640

S.N.	Time	V	T
701	1400.00	6.000	136.884
702	1402.00	6.000	136.884
703	1404.00	6.000	136.884
704	1406.00	6.000	136.396
705	1408.00	6.000	135.664
706	1410.00	6.000	134.932
707	1412.00	6.000	133.956
708	1414.00	6.000	132.980
709	1416.00	6.000	132.248
710	1418.00	6.000	131.760
711	1420.00	6.000	131.028
712	1422.00	6.000	130.784
713	1424.00	6.000	130.296
714	1426.00	6.000	130.052
715	1428.00	6.000	129.320
716	1430.00	6.000	128.588
717	1432.00	6.000	128.100
718	1434.00	6.000	127.612
719	1436.00	6.000	127.368
720	1438.00	6.000	127.368
721	1440.00	6.000	127.368
722	1442.00	6.000	127.368
723	1444.00	6.000	127.124
724	1446.00	6.000	127.124
725	1448.00	6.000	126.636
726	1450.00	6.000	126.636
727	1452.00	6.000	126.392
728	1454.00	6.000	126.148

S.N.	Time	V	T
729	1456.00	6.000	126.148
730	1458.00	6.000	126.148
731	1460.00	6.000	125.904
732	1462.00	6.000	125.904
733	1464.00	6.000	125.416
734	1466.00	6.000	125.172
735	1468.00	6.000	124.928
736	1470.00	6.000	124.928
737	1472.00	6.000	124.928
738	1474.00	6.000	125.172
739	1476.00	6.000	125.660
740	1478.00	6.000	126.148
741	1480.00	6.000	126.636
742	1482.00	6.000	126.636
743	1484.00	6.000	126.636
744	1486.00	6.000	126.392
745	1488.00	6.000	126.636
746	1490.00	6.000	126.880
747	1492.00	6.000	126.636
748	1494.00	6.000	125.904
749	1496.00	6.000	125.416
750	1498.00	6.000	125.416
751	1500.00	6.000	126.148
752	1502.00	6.000	126.880
753	1504.00	6.000	126.880
754	1506.00	6.000	126.880
755	1508.00	6.000	126.880
756	1510.00	6.000	126.636

S.N.	Time	V	T
757	1512.00	6.000	126.392
758	1514.00	6.000	126.148
759	1516.00	6.000	125.904
760	1518.00	6.000	125.660
761	1520.00	6.000	125.416
762	1522.00	6.000	125.172
763	1524.00	6.000	124.928
764	1526.00	6.000	124.440
765	1528.00	6.000	123.952
766	1530.00	6.000	123.708
767	1532.00	6.000	123.220
768	1534.00	6.000	122.976
769	1536.00	6.000	122.244
770	1538.00	6.000	122.000
771	1540.00	6.000	122.488
772	1542.00	6.000	122.732
773	1544.00	6.000	122.732
774	1546.00	6.000	122.732
775	1548.00	6.000	122.732
776	1550.00	6.000	122.244
777	1552.00	6.000	122.244
778	1554.00	6.000	122.000

S.N.	Time	V	T
779	1556.00	6.000	121.756
780	1558.00	6.000	121.756
781	1560.00	6.000	121.756
782	1562.00	6.000	121.756
783	1564.00	6.000	121.756
784	1566.00	6.000	121.268
785	1568.00	6.000	121.268
786	1570.00	6.000	121.268
787	1572.00	6.000	121.024
788	1574.00	6.000	120.780
789	1576.00	6.000	120.780
790	1578.00	6.000	120.536
791	1580.00	6.000	120.780
792	1582.00	6.000	120.780
793	1584.00	6.000	121.024
794	1586.00	6.000	121.024
795	1588.00	6.000	121.268
796	1590.00	6.000	121.268
797	1592.00	6.000	120.780
798	1594.00	6.000	120.780
799	1596.00	6.000	120.536
800	1598.00	6.000	120.536

List of Publications

Published & Communicated Research Papers

1. **Sanjay Kumar Singh**, D. Boolchandani, S.G. Modani "Optimal Tuning of PID Controller for Centrifugal Temperature Control System in Sugar Industry using Genetic Algorithm" at Fifth International Conference on soft Computing for Problem Solving 2015 (Socpros 2015) 18-20 Dec 2015**)** **(Indexed In: : SCOPUS)**
2. **Sanjay Kr Singh**, D Boolchandani, S.G. Modani, Nitish Katal, "Multi-objective Optimization of PID Controller for Temperature Control in Centrifugal Machines using Genetic Algorithm" at Research Journal of Applied Sciences, Engineering and Technology **ISSN:** 2040-7467 (Online) **(Indexed In: SCOPUS) Publish in: 7(9) March 2014.**
3. **Sanjay Kr Singh**, D. Boolchandani, S.G. Modani, Nitish Katal, "Optimal Tuning of PID controller for Centrifugal Machine Temperature control system using Bat Algorithm" is to be communicated in International Journal of Engineering Intelligent Systems, CRL Publishing Ltd ISSN: 1472-8915 **(Indexed In: SCOPUS)**
4. **Sanjay Kr Singh**, D. Boolchandani, S.G. Modani, "Optimal Tuning of PID controller for Centrifugal Machine Temperature control system using Particle Swarm Optimization" is to be submitted to the First International Conference on Smart Technologies in Computer and Communication (Smart Tech-2017) 27-29 March, 2017, Amity University Rajasthan (AUR), India

Other Published Research Papers

1. Nitish Katal, **Sanjay Kr. Singh**, "Multi-objective Optimization of PID Controller for DC Servo Motor using Genetic Algorithm", in International Journal of Engineering Intelligent Systems, CRL Publishing Ltd ISSN: 1472-8915 Vol 23 no 1 Mach 2015 **(Indexed In: SCOPUS)**
2. **Sanjay Kr Singh**, D. Boolchandani, S.G. Modani, Nitish Katal, "Multi Objective PID Optimization for Speed Control of an Isolated Steam Turbine using Genetic Algorithms" at Research Journal of Applied Sciences, Engineering and Technology **ISSN:** 2040-7467(Online) **(Indexed In: SCOPUS) Publish in: 7(17) May 2014.**

3. **Sanjay Kr Singh**, Nitish Katal, S.G. Modani, Optimization of PID Controller for Brushless DC Motor by using Bio-Inspired Algorithms at Research Journal of Applied Sciences, Engineering and Technology **ISSN:** 2040-7467 (Online) **(Indexed In: SCOPUS)**
4. Nitish Katal, **Sanjay Kr Singh,** Manmohan Agrawal, Optimizing Response of PID Controller for Servo DC Motor by Genetic Algorithm" in "International Journal of Applied Engineering Research (IJAER)" Vol 7, number 11(2012) special Issues (ISSN:09734562) **(Indexed In: SCOPUS)**
5. **Sanjay Kr Singh**, Nitish Katal, S.G. Modani, Multi-objective Optimization of PID Controller for Coupled Tank Liquid Level Control System using Genetic Algorithm "2nd International Conference on 'Soft Computing for Problem Solving"JKLU Jaipur. December 28-30, 2012. Paper published in proceeding of second international conference on soft computing for problem solving (SOCPROS 2012) pp-57-66 ISBN:978-81-322-1601-8 published in journal Advances in Intelligent Systems and Computing Volume 236, 2014, pp 59-66 (Springer) **(Indexed In: SCOPUS)**
6. Nitish Katal, **Sanjay Kr. Singh**, Ashutosh Tripathi, S.G. Modani, Optimizing the Response of a PID Controller for Three Tank Liquid Level System using Multi objective Genetic Algorithm", in UACEE International Journal of Advances in Engineering Volume 2: Issue 3 ISSN 2278-215X (online)
7. Nitish Katal, **Sanjay Kr Singh**, Optimal Tuning of PID Controller for DC Motor using Bio-Inspired Algorithms" in "International Journal of Computer Applications - IJCA", October Edition, 2012. (ISSN: 0975 - 8887)

About Author

Sanjay Kumar Singh has 22 years of teaching & Industrial experience and is currently an Assistant Professor in the Department of Electronics & Communication Engineering at Amity University Rajasthan Jaipur, India. He obtained Bachelor's degree in Instrumentation Engineering from D.N Patel college of Engineering affiliated with Poona University, Master's degree in Instrumentation from School of Instrumentation Devi Ahilya Vishwavidyalaya Indore (M.P.) India. He is currently pursuing Ph.D. at Malaviya National Institute of Technology Jaipur, India, in the field of Intelligent Control & Automation. He has guided two Master's thesis and several undergraduate projects. He is currently a member of IET UK, ICSES Iran, and IAENG and Lifetime member of ISTE India.