A Project Report

On

# Modified Smith Predictor Based Advanced Control Strategies for Purely Integrating Processes with Large Dead Time

A Project Report Submitted for Partial Fulfillment of the Requirement for 2 Year M.Tech. Degree in Instrumentation and Control Engineering from the Department of Applied Physics, University of Calcutta


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## Certificate of Approval

The Project entitled **'Modified Smith Predictor Based Advanced Control Strategies for Purely Integrating Processes with Large Dead Time'** prepared and submitted by **Aritra Bag** (Roll No.: 97/INM/201001) is hereby approved and certified as a credible study in technological subjects performed in a way sufficient for its acceptance for partial fulfillment of the degree of Master of Technology in Instrumentation and Control Engineering for which it is submitted.

It is to be understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed, or conclusion drawn therein, but approve the project only for the purpose for which it is submitted.

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# Recommendation

We hereby recommend that the project report titled '**Modified Smith Predictor Based Advanced Control Strategies for Purely Integrating Processes with Large Dead Time**' prepared and submitted by **Aritra Bag** (Roll No.: 97/INM/201001) may be accepted in the fulfilment of the requirements for the Degree of wo-year Master of Technology in Instrumentation and Control Engineering from the Department of Applied Physics, University of Calcutta.

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# Contents

# Chapter 1

# Introduction

## 1.1 Abstract

In this report, a Modified Smith Predictor based control strategy for purely integrating processes with large dead time is proposed. Dead times, or time delays, are found in many processes in the industry. Most tuning methods for PID controllers used in the industry consider dead times as an integral part of process dynamics models. Dead times are mainly caused by the time required to transport mass, energy, or information, but they can also be caused by processing time or by the accumulation of time lags in several simple dynamic systems connected in series. For processes exhibiting dead time, every action executed in the manipulated variable of the process will only affect the controlled variable after the process dead time.[1] This thesis presents control strategies that can reduce time delay found in processes while mitigating other model abnormalities and exhibiting satisfactory performance indices.

## 1.2 Motivation

Many processes in industry are controlled by the proportional + integral + derivative (PID) controllers. When the process exhibits a dead time, the tuning of the PID is difficult and the performance of the closed loop limited. Because of this, many efforts have been dedicated to the study and derivation of better tuning rules for PID controllers when controlling processes with dead time. The most popular tuning rules for processes with small dead times were proposed by Ziegler and Nichols. In general, for processes that can be modelled with simple transfer functions plus a dead time, a reasonable compromise between robustness and performance can be obtained by the correct tuning of PID controllers. However, when a high performance is desired and/or the relative dead time is very large, a predictive control strategy must be used [2]. This thesis presents one such strategy and justifies the application over dedicated single controller-based loops or other Smith Predictor based control loops, specific to the processes in consideration.

## 1.3 Interpretation of dead time

A time delay is defined as the time interval between the start of an event at one point in a system and its resulting action at another point in the system. Delays are also known as transport lags or dead times; they arise in physical, chemical, biological and economic systems, and measurement and computation (such as those required for making a chemical composition analysis).

Many processes in the industry exhibit time delays in their dynamic behavior. Delay time or dead time is caused by mass, energy or information transportation phenomena, but it can also arise due to processing time or the accumulation of time lags in several simple dynamic systems connected in series. In manufacturing applications, delays typically arise whenever there is physical transport of material, for example, in a pipe or on a conveyer belt; the delay can be determined as the ratio of distance to be travelled to the speed of the material. Delays arise in a wide variety of other manufacturing applications, often in combination with other process dynamics; examples of such applications range from plastic manufacturing and polymerization reactions , ventilation and air conditioning (HVAC) to industrial sewing machines.

Processes with significant dead times are difficult to control using standard feedback controllers because the effect of the perturbations is not felt until a considerable time has elapsed and the effect of the control action takes some time to affect the controlled variable. The control action that is applied based on a past error value which, though is correct for the past value, is not correlated with the present value. This is interpreted in the frequency domain as a reduction in the system’s phase which decreases stability, thus making it more difficult to control.

If a time delay is introduced into a well-tuned system, the gain must be reduced to maintain stability. The Smith Predictor Control scheme can help to overcome this limitation and allow the large gains, but it is critical that the model parameters exactly match the plant parameters. An adaptive control system can be added to the Smith Predictor to change the model parameters; so that they continually match the changing plant parameters, especially the addition of load disturbances.

# Chapter 2

# Literature Review

## 2.1 Overview

This chapter covers the findings concerning the different tuning strategies involving PI, PID and Smith Predictor Control techniques with their modifications. These are highly effective strategies that have been developed after extensive research and applied in favour of conventional PID Controller tuning techniques to meet a set of requirements that would have otherwise been extremely difficult to achieve. The one common objective of all these strategies is to compensate for the dead time or delay, leading to sluggish system response or instability. Thus, a survey has been prepared and presented in chronological order to explain the development through the reported works.

## 2.2 Survey report on advanced control techniques used in processes with large dead time

Any real-time process is evaluated using its mathematical model which can be then classified as stable, unstable or an integrating system with dead time. Controlling an unstable or integrating system to improve its time-domain performance while maintaining stability is considerably challenging. Conventional PID tuning rules are not applicable for such systems. A separate tuning technique for the integrating processes with dead time, capable of stabilizing the system for a nominal plant and under parameter variations (Perturbations) of the plant. Robust stability and robust performance are taken into consideration while designing a robust controller, and as they are inversely proportional, the optimization between these two becomes a challenge. Robust controller design involves more analytical calculations resulting in the higher-order controller designs which are difficult to implement in real-time. applications such as aerospace, chemical industries, space vehicles etc. Thus, the need for a lower order controller with the minimum tuning parameters, satisfying the robust principles has been put forth.

Predictor based control structures have been used as a solution to tackle the problem of dead time and improve the performance of the closed-loop system predictive strategy includes a model of the process in the structure of the controller. The first dead-time compensation algorithm appeared in 1957 in a paper by Smith [3]. This control algorithm, which became known as the Smith Predictor (SP), contained a dynamic model of the dead-time process and it can, in a certain sense, be considered the first model predictive control algorithm. The robust performance of Smith Predictors was investigated for the stable FOPDT case. After this, two other important predictors have proposed: The analytical predictor (AP) [5] and the optimal predictor (OP) [6]. Optimal predictors were used in model predictive control (MPC). While SPs are used to compensate for pure dead time, OPs are usually employed to predict the future behaviour of the plant in a multistep receding horizon. OPs do not explicitly appear in the resulting MPC structure, although it has been shown that the MPC structure is equivalent to an OP plus a primary controller [7]. Over the past 20 years, numerous extensions, and modifications of the SP (also called dead-time compensator, DTC) have been proposed to (a) improve the regulatory capabilities of the SP for measurable or unmeasurable disturbances, (b) allow its use with unstable plants or (c) to facilitate the tuning in industrial applications.

Matausek and Micic [8] tried to control higher-order processes with integral action and long dead-time using a modified Smith predictor. The model consists of an ideal integrator and dead-time and includes three tuning parameters. These are the dead-time, velocity gain of the model, and the desired time constant of the first order closed-loop set-point response. It had a good performance for the set-point tracking and load disturbance rejection.

Lee and Wang [9] have also obtained sufficient conditions for the practical stability, robust stability and the robust performance for the Smith predictor controller. A norm-bounded uncertainty is associated with the process model. Lee and Wang developed a two-step controller design approach based on the discovered conditions.

Lee *et al.* [10] have looked at robust PID tuning for the Smith predictor considering model uncertainty. The equivalent gain plus time delay (EGPTD) was used to approximate the tuning method. Using the EGPTD, it was possible to achieve a relatively good approximation over the required frequency range. This simple and easy tuning method also ensured robustness.Majhi and Atherton [11] proposed a modified Smith Predictor with a simple and effective controller design procedure, developed for time-delay processes. High performance for the controller was achieved, particularly for integrating and unstable processes using simple tuning formulas.
Julio E *et al.* [12] presented a unified approach for tuning PID controllers for stable, integrative, and unstable dead-time processes, based on a PID approximation of the Filtered Smith Predictor that allows controlling these processes by looking for a trade-off between performance and robustness.
T. Shiota *et al.* [13] proposed an adaptive I-PD controller using the augmented error method for SISO systems. A model reference adaptive control is used as one of the control schemes to overcome model uncertainty which is again re-designed according to the characteristic change of a controlled object. Based on this idea, the proposal for the application of the adaptive I-PD controller was made.
Mendes P. R. C. *et al.* [14] presented an SPC based on the filtered Smith predictor structure to improve the performance of SPC when applied to a stable or integrative dead-time process,

combining the robustness of subspace identification algorithms, the ability of predictive controllers to deal with multivariable processes and operational constraints and robustness of filtered Smith Predictor with model uncertainties.

Bruno M. Lima *et al.* [15] proposed an observer-predictor structure based on a steady-state Kalman filter, equivalent to the Filtered Smith Predictor (FSP) for linear systems. Thus, all the tools used to analyse the closed-loop properties of the FSP can also be used in the proposed predictor, especially the frequency domain ones.

Jan Cvejn *et al.* [16] proposed the design of the PID controller based on the MO criteria trying to keep maximum of the performance of the original MO settings but within stability margins. The paper proposes a way of removing the exogenous disturbance affecting the process which indirectly leads to slow disturbance rejection responses.

T Narayani *et al.* [17] presented a method to control double integrating processes with dead time. In the integrating process, a time delay is inevitable. The proposed tuning method presents some formulas, which consider the factors like time delay, mathematical model and feedback signals.

Ali Dokht Shakibjoo *et al.* [18] proposed a novel structure to design controllers for time-delay MIMO systems. A decoupled Smith predictor (SP) controller is developed using Internal Model Control structure (IMC) and step response model approximation is employed to approximate decoupled systems. The Smith predictor controller is combined with the PI+CI structure and a low pass filter to improve system performance and increase system robustness.

Sandeep Kumar Sunori *et al.* [19] proposed a control system with dead time compensation for a multivariable Lime Kiln Process.

Santhosh Kumar. P. *L et al.* [16] presented the design and implementation of a decentralized PI controller with a decoupler, based on the Smith Predictor for a Batch Distillation Column. The decoupler is used to minimize the interaction by combining it with a decentralized control algorithm. An ideal decoupling technique is implemented on a First Order Plus Dead Time (FOPDT) model.

Zichao Miao *et al.* [20] proposed compensation measures for the dead-time effect and zero-current clamping phenomenon in the Field Oriented Control (FOC) control strategy. The FOC strategy of a brushless motor is improved by utilizing this technique as a dead-time hysteresis loop is added near the current zero-crossing point to prevent current fluctuation and zero-point clamping from causing errors.

## 2.3 Outcome of literature review

Analysing the survey reveals that Smith Predictor Control techniques have some novel advantages over conventional PID controllers for the time-delay systems. For processes with larger dead times and disturbances, Modified Smith Predictor schemes have been proposed in recent years to improve the response even further. These modifications are made as per the requirements of the performance index parameters. Seeing the success and satisfaction rates of Modified Smith Predictors, it was decided to attain the objective of this project with this approach.

# Chapter 3

# Conventional Tuning Techniques

## 3.1 PID controller

The term PID stands for proportional integral derivative and it is one kind of device used to control different process variables like pressure, flow, temperature, and speed in industrial applications. In this controller, a control loop feedback device is used to regulate all the process variables. This type of control is used to drive a system in the direction of an objective location otherwise level. It is almost everywhere for temperature control and used in scientific processes, automation & myriad chemical. In this controller, closed-loop feedback is used to maintain the real output from a method like close to the objective otherwise output at the fixe point if possible.

The ideal continuous time domain PID controller for a SISO process is expressed in the Laplace domain as follows:

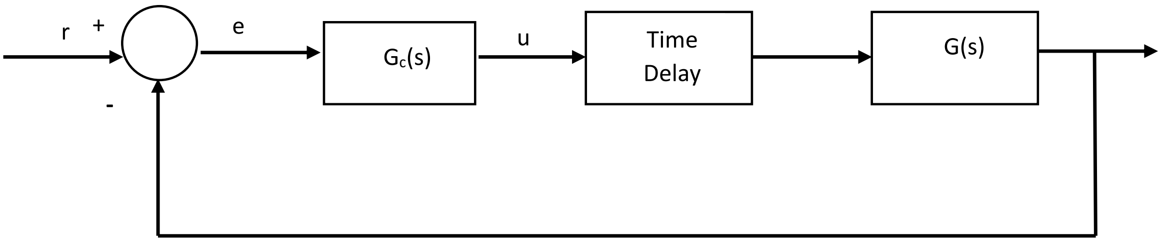



***Fig 3.1*** *Feedback control system using PID controller*

$$U(s) = G_c(s)E(s)$$

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{3.1}$$

And with $K_c$ =proportional gain, $T_i$ =integral time constant and $T_d$ =derivative time constant. If $T_i = \infty$ and $T_d = 0$(i.e., P control), then it is clear that the closed loop measured value y will always be less than the desired value r (for processes without an integrator term, as a positive error is necessary to keep the measured value constant, and less than the desired value). The introduction of integral action facilitates the achievement of equality between the measured value and the desired value, as a constant error produces an increasing controller output. The introduction of derivative action means that changes in the desired value may be anticipated, and thus an appropriate correction may be added prior to the actual change. Thus, in simplified terms, the PID controller allows contributions from present controller inputs, past controller inputs and future controller inputs.

Many variations of the PID controller structure have been proposed (indeed, the PI controller structure is itself a subset of the PID controller structure).

### 3.1.1 Ideal PI controller structure:

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right) \tag{3.2}$$

### 3.1.2 Ideal PID controller structure:

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{3.3}$$

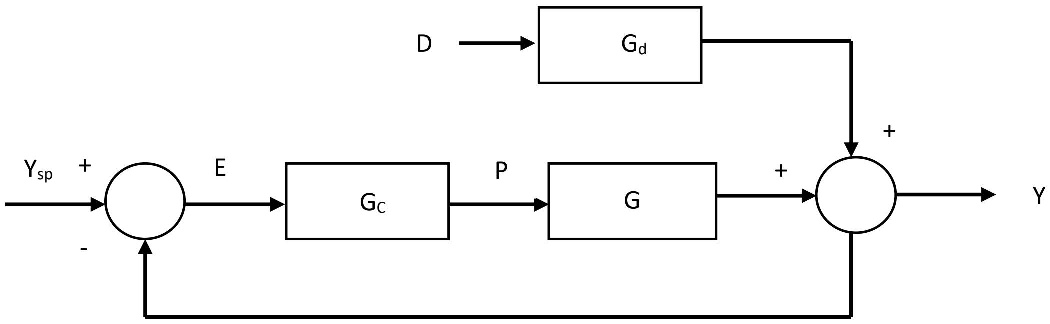



***Fig 3.2*** *Block diagram of a control system with a PI controller [30]*

**Table 3.1** Overview of the different notations in Fig. 3.2

| Parameter | Definition |
|---|---|
| $Y_{sp}$ | Set point of the process |
| E | Error between set-point and output of process |
| $G_c$ | Controller transfer function |
| P | Output of controller |
| G | Process transfer function |
| Y | Output of the process |
| D | Disturbance |
| $G_d$ | Disturbance transfer function |

For a PI controller, the controller output is given by equation (3.3) in the time domain [1]:

$$p(t) = \bar{p} + K_c\left(e(t) + \frac{1}{\tau_I}\int_0^t e\,(t^*)dt^*\right) \qquad (3.4)$$

The corresponding transfer function in the Laplace domain is given by:

$$\frac{P'(s)}{E(s)} = K_c\left(1 + \frac{1}{\tau_s}\right) = K_c\left(\frac{\tau_I s + 1}{\tau_I s}\right) \qquad (3.5)$$

The closed-loop set-point transfer function for the feedback control in figure 3.2 is obtained from the following derivation, where the disturbance is assumed to be zero:

$$Y = GP \qquad (3.6)$$

$$P = EG_c \qquad (3.7)$$

$$E = Y_{sp} - Y \qquad (3.8)$$

By inserting equation (3.7) and (3.8) into equation (3.6), the equation becomes

$$Y = G_c G\left(Y_{sp} - Y\right) \qquad (3.9)$$

Collecting terms with $Y$on the left side and terms with $Y_{sp}$ on the right side:

$$Y(1 + G_c G) = Y_{sp} G_c G \qquad (3.10)$$

This gives the closed-loop transfer function for set-point changes:

$$\frac{Y}{Y_{sp}} = \frac{G_c G}{1 + G_c G} \qquad (3.11)$$

When the process has a time delay, the process transfer function is given by

$$G = G_n e^{-\theta s} \qquad (3.12)$$

Finally, the closed-loop set-point transfer function is given as:

$$\frac{Y}{Y_{sp}} = \frac{G_c G_n e^{-\theta s}}{1 + G_c G_n e^{-\theta s}} \qquad (3.13)$$

## 3.2 Tuning rules for PI and PID controllers

**Table 3.2** PI tuning rules for controller $G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right)$

| **Rule**<br>**Ultimate cycle** | $\mathbf{K_c}$ | $\mathbf{T_i}$ | **Comment** |
|---|---|---|---|
| Ziegler and Nichols | $0.45K_u$ | $0.83T_u$ | Quarter decay ratio |
| Hwang and Chang [31] | $0.45K_u$ | $\frac{1}{p_1}\left(5.22 - \frac{5.22}{T_1}\right)$ | $p_1, T_1$ =decay rate, period measured under proportional control when $K_c = 0.5K_u$ |
| Hang *et al*. | $0.25K_u$ | $0.2546T_u$ | Dominant time delay process |
| McMillan [32] | $0.3571K_u$ | $T_u$ | |
| Astrom and Hagglund [33] | $0.4698K_u$ | $0.4373T_u$ | Gain margin = 2, Phase margin = 20° |
| Parr [34] | $0.1988K_u$ | $0.0882T_u$ | Gain margin = 2.44, Phase margin = 61° |
| Yu [35] | $0.2015K_u$ | $0.1537T_u$ | Gain margin = 3.45, |
| | $0.5K_u$ | $0.43T_u$ | Phase margin = 46° |
| | $0.33K_u$ | $2T_u$ | Quarter decay ratio |

**Table 3.3** PID tuning rules for controller $G_c(s) = K_c\left(1 + \frac{1}{T_i} + T_d s\right)$

| Rule Ultimate Cycle | $K_c$ | $T_i$ | $T_d$ | Comments |
|---|---|---|---|---|
| Ziegler and Nichols | $[0.6K_u, K_u]$ | $0.5T_u$ | $0.125T_u$ | Quarter decay ratio |
| Blickley[36] | $0.5K_u$ | $T_u$ | $[0.125T_u, 0.167T_u]$ | Quarter decay ratio |
| Parr | $0.5K_u$ | $T_u$ | $0.2T_u$ | Overshoot to servo Parr – response ≈ 20% |
| De Paor | $0.5K_u$ | $0.34T_u$ | $0.08T_u$ | Quarter decay ratio |
| | $0.866K_u$ | $0.5T_u$ | $0.125T_u$ | phase margin = $30^{\circ}$ |
| Corripio[37] | $0.75K_u$ | $0.63T_u$ | $0.1T_u$ | Quarter decay ratio |
| Mantzand Tacconi[38] | $0.906K_u$ | $0.5T_u$ | $0.125T_u$ | phase margin = $25^{\circ}$ |
| Astrom and Hagglund | $0.4698K_u$ | $0.4546T_u$ | $0.1136T_u$ | Gain margin = 2, phase Margin = $20^{\circ}$ |
| Astrom and Hagglund | $0.1988K_u$ | $1.2308T_u$ | $0.3077T_u$ | Gain margin = 2.44, phase Margin = $61^{\circ}$ |
| Atkinson and Davey [39] | $0.2015K_u$ | $0.7878T_u$ | $0.1970T_u$ | Gain margin = 3.45, phase margin = $46^{\circ}$ |
| Perry and Chilton [40] | $0.35K_u$ | $0.77T_u$ | $0.19T_u$ | Gain margin ≥ 2, phase margin ≥ $45^{\circ}$ |

| Rule<br>Ultimate Cycle | $K_c$ | $T_i$ | $T_d$ | Comments |
|---|---|---|---|---|
| | $0.25K_u$ | $0.75T_u$ | $0.25T_u$ | 20% overshoot Servo response |
| | $0.33K_u$ | $0.5T_u$ | $0.33T_u$ | 'Some' overshoot |
| Yu | $0.2K_u$ | $0.5T_u$ | $0.33T_u$ | 'No' overshoot |
| Luo*et al*. | $0.33K_u$ | $0.5T_u$ | $0.125T_u$ | 'Some' overshoot |
| | $0.48K_u$ | $0.5T_u$ | $0.125T_u$ | |
| McMillan | $0.2K_u$ | $0.5T_u$ | $0.125T_u$ | 'No' overshoot |
| Mc Avoy and Johnson | $0.5K_u$ | $0.5T_u$ | $0.125T_u$ | |
| | $0.54K_u$ | $T_u$ | $0.2T_u$ | |
| Karaboga and Kalinli [41] | $[0.32K_u, 0.6K_u]$ | $\left[\frac{0.4267K_u}{T_u}, \frac{1.5K_u}{T_u}\right]$ | $[0.08K_uT_u, 0.125K_uT_u]$ | |
| St. Clair [42] | $0.5K_u$ | $1.2T_u$ | $0.125T_u$ | 'aggressive' tuning |
| | $0.25K_u$ | $1.2T_u$ | $0.125T_u$ | 'conservative' tuning |

## 3.3 Closed-loop performance indices

Before thinking about how to tune a controller (i.e., adjust the controller parameters to produce an optimal controlled response) it is required to be decided what constitutes a good response. There are many different measures which can be used to compare the quality of controlled responses. The control measures describe in this section are very precise and give exact comparisons between different control schemes, or different sets of tuning parameters, and are widely used in academic journal papers and simulation studies. They are also completely useful for measuring the performance of real control systems.

The three commonly used measures are Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE) [43-45]. All the measures require a fixed experiment to be performed on the system (i.e., a fixed set-point or disturbance change) and the integrals are evaluated over a fixed time period (in theory to infinity, but usually until a time long enough for the responses to settle).

### 3.3.1 Integral Squared Error (ISE)

ISE integrates the square of the error over time. Mathematically,

$$ISE = \int \varepsilon^2 \, dt$$

ISE will penalise large errors more than smaller ones (since the square of a large error will be much bigger). Control systems specified to minimise ISE will tend to eliminate large errors quickly, but will tolerate small errors persisting for a long period of time. Often this leads to fast responses, but with considerable, low amplitude, oscillation.

### 3.3.2 Integral Absolute Error (IAE)

IAE integrates the absolute error over time. Mathematically,

$$IAE = \int |\varepsilon| \, dt$$

It doesn’t add weight to any of the errors in a systems response. It tends to produce slower response than ISE optimal systems, but usually with less sustained oscillation.

### 3.3.3. Integral Time-Weighted Absolute Error (ITAE)

ITAE integrates the absolute error multiplied by the time over time. Mathematically,

$$ITAE = \int t|\varepsilon| \, dt$$

What this does is to weight errors which exist after a long time much more heavily than those at the start of the response. ITAE tuning produces systems which settle much more quickly than the other two tuning methods. The downside of this is that ITAE tuning also produces systems with sluggish initial response (necessary to avoid sustained oscillation).

## 3.4 IMC controller designing

Internal Model Control system is framed on the Internal Model Principle. It states that if any control system encloses within it, implicitly or explicitly, some illustration of the process tobe controlled then a perfect control is readily achieved. IMC have most powerful advantages as; it allows model uncertainty and trade-offs between performance and robustness which can be contemplated in a more efficient tone. It also provides time-delay compensation. Generally, the result of IMC formulation is only one tuning parameter $\lambda$. It is general design method, but results in PID controllers for low order process models.

### 3.4.1 IMC structure

In further part the feedback equivalence to IMC is obtained by using block diagram. manipulation. In practice, variance of process model is common. Also, it cannot be invertible due to system is often get affected by unknown disturbances. Hence open loop control is unable to maintain output at set- point. The IMC structure is shown in *Figure 3.3*. r(s) – y(s) is simply the error term used by a standard feedback controller. Therefore, it is clearly seen that the IMC structure can be rearranged to the feedback control structure [46].

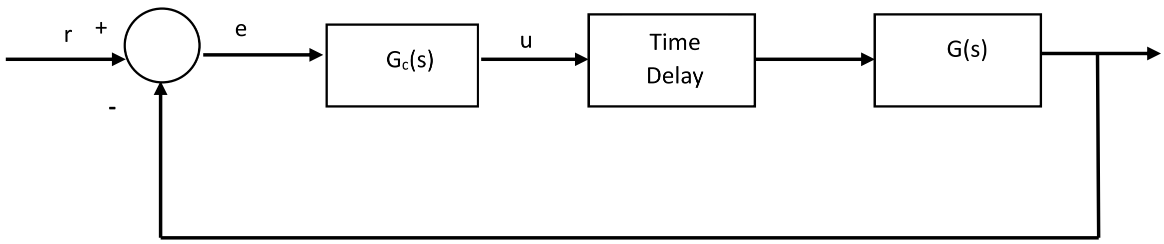



***Fig 3.3*** *IMC structure*

The advantage of reformulation is that when the IMC design procedure is used a PIDcontroller often results. Also, the standard IMC block diagram is not deal with unstable systems, so this feedback form must be used for those cases.

The various parameters used in the IMC basic structure shown above are as follows:

**Table 3.4** Parameters and annotations

| Parameter | Annotation |
|---|---|
| Disturbance | q(s) |
| Set Point | r(s) |
| Modified Set-Point | i(s) |
| Manipulated Output | u(s) |
| Process | g(s) |
| Process Model | ĝ(s) |
| Disturbance | d(s) |
| Measured Process Output | y(s) |
| Model Output | $\tilde{y}$(s) |

Unknown disturbance d(s) is affecting to the system. The process and the model are introduced by the manipulated input u(s). y(s) is the process output get compared with the output of the model, as a result signal estimate disturbance. The obtained feedback signal is:

$$\widetilde{\mathrm{d}}(\mathrm{s}) = (\mathrm{g_p}(\mathrm{s}) - \widetilde{\mathrm{g_p}}(\mathrm{s}) + \mathrm{d}(\mathrm{s}) \tag{3.14}$$

### 3.4.2 IMC design procedure

IMC controller designing is relatively easy. The very first step is factoring the process modelinto “invertible” and “noninvertible” components to make controller stable [15].

$$\hat{g}_p(s) = \hat{g}_{p+}(s)g_{p-}(s) \tag{3.15}$$

To obtain idealized IMC controller the inverse of the invertible part of the model was made:

$$\tilde{q}(s) = \hat{g}_{p^{-1}}{}^{-1}(s) \tag{3.16}$$

To make controller, proper filter will be added:

$$q(s) = \hat{g}_{p^{-1}}{}^{-1}(s)f(s) \tag{3.17}$$

Where the filter factor f(s) is:

$$f(s) = \frac{1}{(\lambda s + 1)^n} \tag{3.18}$$

n should be chosen to make the controller proper or semi-proper. Filter factor $\lambda$ should be adjusted. System performs fast for small value of $\lambda$ and if the value is large then closed loop become more robust.

## 3.5 Design procedure of an IMC-based PID controller for a first order system with time-delay

According to the procedure the result is obtained in PID equivalent form, so approximations are first made to the dead time. Some control system design techniques require a rational transfer function in such cases Padé approximation for dead time is mostly used. The Padé approximation frequently gives better approximation of the function.

If the given process model is:

$$\widetilde{g_p}(s) = \frac{k_p e^{-\theta_s}}{\tau_p s + 1} \tag{3.19}$$

First, order Padé approximation is used for dead time:

$$e^{-\theta_s} = \frac{-0.5\theta_s + 1}{0.5\theta_s + 1} \tag{3.20}$$

By using Padé approximation:

$$\widetilde{g_p} = \frac{k_p e^{-\theta_s}}{\tau_p(s) + 1} \tag{3.21}$$

$$\widetilde{g_p}(s) = \frac{k_p(-0.5s+1)}{(\tau_p s+1)(0.5s+)} \tag{3.22}$$

By factoring invertible and noninvertible element :

$$\widetilde{g_p} = \frac{k_p}{(\tau_p s + 1)(0.5s + 1)}$$

$$\widetilde{g_p}(-0.5s + 1) \tag{3.23}$$

From the idealized controller:

$$q(s) = \frac{k_p}{(\tau_p s + 1)(0.5s + 1)} \tag{3.23}$$

Adding filter factor:

$$q(s) = \frac{k_p}{(\tau_p s + 1)(0.5s + 1)} \frac{1}{\lambda s + 1} \tag{3.24}$$

The following PID parameters are found by solving above equation:

$$k_c = \frac{(\tau_p + 0.5\theta)}{k_p(\lambda + 0.5\theta)} \tag{3.25}$$

$$\tau_I = \tau_p + 0.5\theta \tag{3.26}$$

$$\tau_D = \frac{\tau_p \theta}{2\tau_p + \theta} \tag{3.27}$$

The IMC-based PID controller design procedure has resulted in a PID controller.

# Chapter 4

# Smith Predictor & Modified Smith Predictor

## 4.1 Introduction

Plants with long time-delays can sometimes not be controlled effectively using a PID controller in the conventional single feedback loop structure. The main reason for this is that the additional phase lag contributed by the time delay tends to destabilize the closed loop system. The stability problem can be solved by decreasing the controller gain. However, in this case the response obtained is very sluggish. O. J. M. Smith [47] proposed a controller structure shown in Fig. 4.1, which is a well-known effective dead-time compensator for stable processes with long time-delays. The closed loop transfer function for the system of Fig.4.1 is given by

$$T(s) = \frac{C(s)}{R(s)} = \frac{G_C(s)G(s)e^{-\theta s}}{1 + G_C(s)[G_m(s) + G_e(s)]} \tag{4.1}$$

Where,

$$G_e(s) = G(s)e^{-\theta s} - G_m(s)e^{-\theta_m s}$$

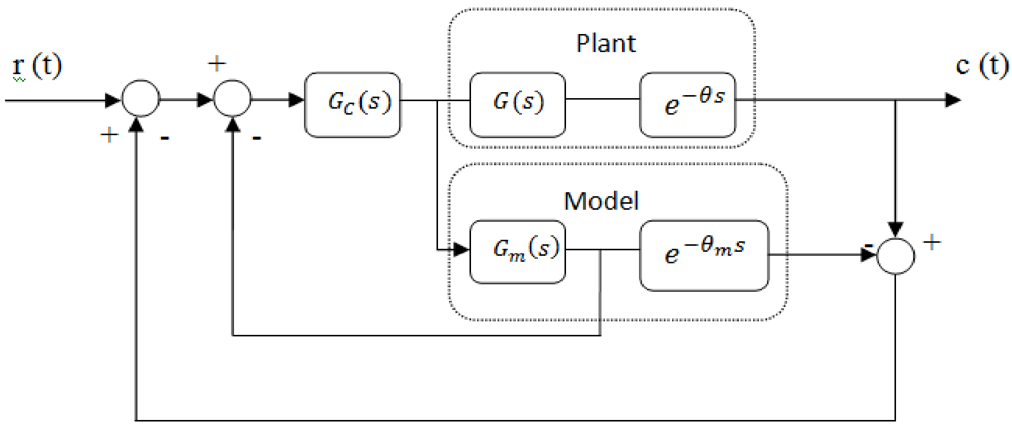



***Fig 4.1*** *Smith Predictor configuration*

$G_m(s)e^{-\theta_m s}$,$G(s)e^{-\theta s}$ and $G_c(s)$are respectively the plant's dynamic model, and the transfer functions of the plant and the controller, which is usually a PI or a PID controller. The stability of the Smith predictor is affected by the accuracy with which the model represents the plant. Based on the assumption that the model used matches perfectly the plant dynamics,$G_e(s) = 0$ and the closed loop transfer function of Eqn.4.1 reduces to

$$T_o(s) = \frac{G_c(s)G_m(s)e^{-\theta_m s}}{1 + G_c(s)G_m(s)} \tag{4.2}$$

According to Eqn. 4.2, the parameters of the primary controller, $G_c(s)$ which is typically taken as PI or PID, may be determined using a model of the delay free part of the plant. Here in Fig. 4.1 the Smith Predictor contains two feedback loops; a positive loop containing the dead time and a negative loop without it. The positive feedback loop cancels out the effect of the negative feedback loop through the process, leaving the negative feedback loop in the predictor with only the lag and gain of the model in it. This arrangement makes the predictor input identical to that which would exist if there were no dead time in the process resulting in better control. The compensation technique involves the prediction of the process output through the use of a process model which does not contain the dead time. The output of this predictor element is also delayed with a time delay element which constitutes a separate model of the process dead time. With model dead time, lag and the controller gain matched to the process, the smith predictor reproduces a step change exactly one dead time later.

A smith predictor achieves some form of derivative action required for compensating dead time in first order processes by a lag in its feedback path. By matching the lag in the smith predictor to the lag (inertia) in a dead time process, the input manipulated variable follows the process lag exactly but delayed by the dead time. The delayed predictor output is compared to the measured process output and the resulting model error quantity is added to the current predictor output to correct for predictor deficiencies, provided that the model is a true representation of the process and there are no further disturbances to the process during the dead time period. It is observed that the optimal predictor part of the controller algorithm changes also with the time delay. The smith predictor is an optimal dead time compensator for only those systems having disturbances for which the optimal prediction is a constant over the period of the dead time.

## 4.2 Mathematical model of a smith predictor

As we discussed Smith's strategy [28] is shown in Fig. 4.2. It consists of an ordinary feedback loop plus an inner loop that introduces two extra terms directly into the feedback path. The first term is an estimate of what the process variable would look like in the absence of any disturbances. It is generated by running the controller output through a process model that intentionally ignores the effects of load disturbances. If the model is otherwise accurate in representing the behaviour of the process, its output will be a disturbance-free version of the actual process variable.

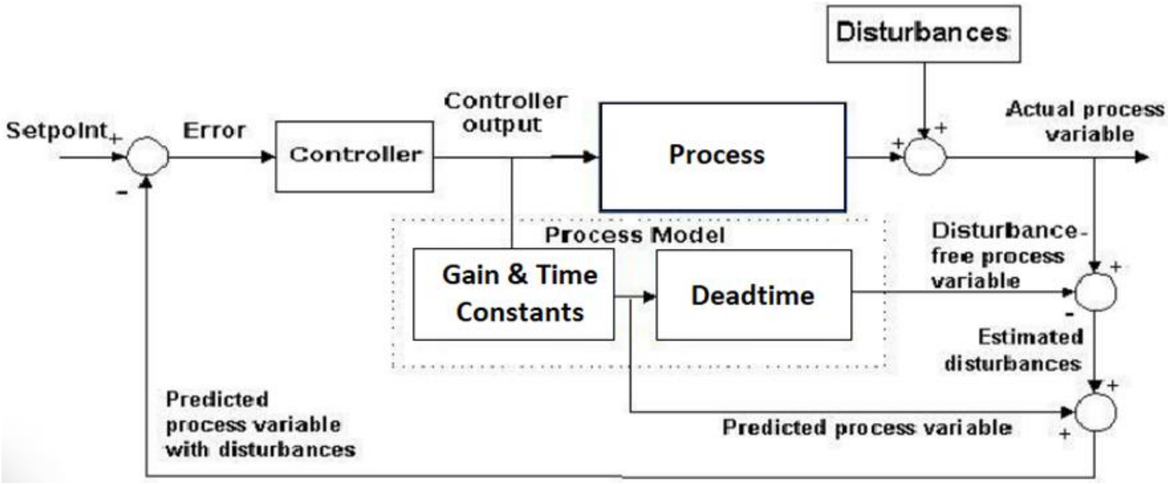



***Fig 4.2*** *The mathematical model of a Smith Predictor*

The mathematical model used to generate the disturbance-free process variable has two elements connected in series. The first represents all of the process behaviour not attributable to dead time. The second represents nothing but the dead time. The dead time-free element is generally implemented as an ordinary differential or difference equation that includes estimates of all the process gains and time constants. The second element is simply a time delay. The signal that goes into it comes out delayed, but otherwise unchanged.

The second term that Smith's strategy introduces into the feedback path is an estimate of what the process variable would look like in the absence of both disturbances and dead time. It is generated by running the controller output through the first element of the process model (the gains and time constants), but not through the time delay element. It thus predicts what the disturbance-free process variable will be once the dead time has elapsed (hence the expression Smith Predictor). Subtracting the disturbance-free process variable from the actual process variable yields an estimate of the disturbances. By adding this difference to the predicted process variable, Smith created a feedback variable that includes the disturbances, but not the dead time.

The purpose of all these mathematical manipulations is best illustrated by Fig. 4.3. It shows the Smith Predictor of Figure 1 with the blocks rearranged. It also shows an estimate of the process variable (with both disturbances and dead time) generated by adding the estimated disturbances back into the disturbance-free process variable. The result is a feedback control system with the dead time outside of the loop.

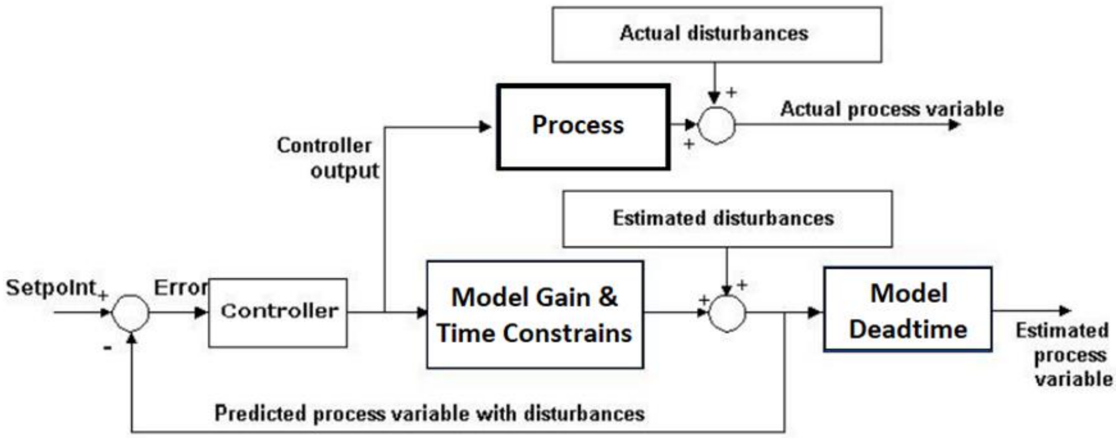



***Fig 4.3*** *Smith Predictor effectively removing the dead time from the loop*.

The Smith Predictor essentially works to control the modified feedback variable (the predicted process variable with disturbances included) rather than the actual process variable. If it is successful in doing so, and if the process model does indeed match the process, then the controller will simultaneously drive the actual process variable towards the set point whether the set point changes or a load disturbs the process.

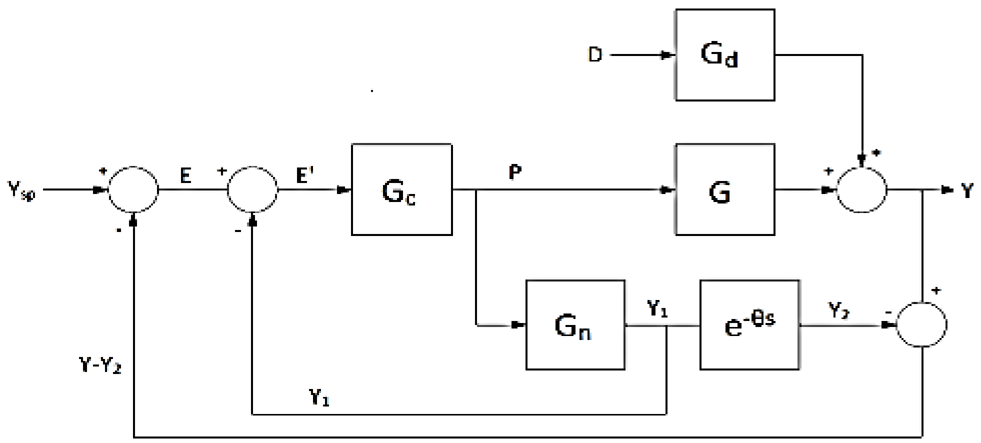



***Fig 4.4*** *Block diagram for a process with the Smith Predictor Controller*

As seen in Fig. 4.4, the Smith predictor structure can be divided into two parts. This includes the primary controller, $G_c(s)$, and the predictor structure. The predictor part consists of a model of the plant without time delay$\left(G_n(s)\right)$, and a model of the time delay $(e^{-\theta s})$[48] .

Thus, the complete process model is given by equation (4.3).

$$P_n(s) = G_n(s)e^{-\theta_s} \qquad 4.3)$$

The model without the dead-time is sometimes called the fast model and is used to compute an open-loop prediction. Thus, the model of the process without time delay $(\mathbf{G_n})$ is used to predict the effect of control actions on the undelayed output [49]. Then the controller uses the predicted response ($\mathbf{Y_1}$) to calculate its output signal (P). The actual holed-up output (Y) is compared with the delayed predicted output ($\mathbf{Y_2}$). In the case of no disturbances or modelling errors, the difference between the process output and the model output will be zero. This means that the output signal ($\mathbf{Y-Y_2}$) will be equal to the output of the plant without any time delay [48].

The block diagram for the Smith predictor given in Figure 4.4 can be re-drawn as two nested feedback loops as shown in Figure 4.5.

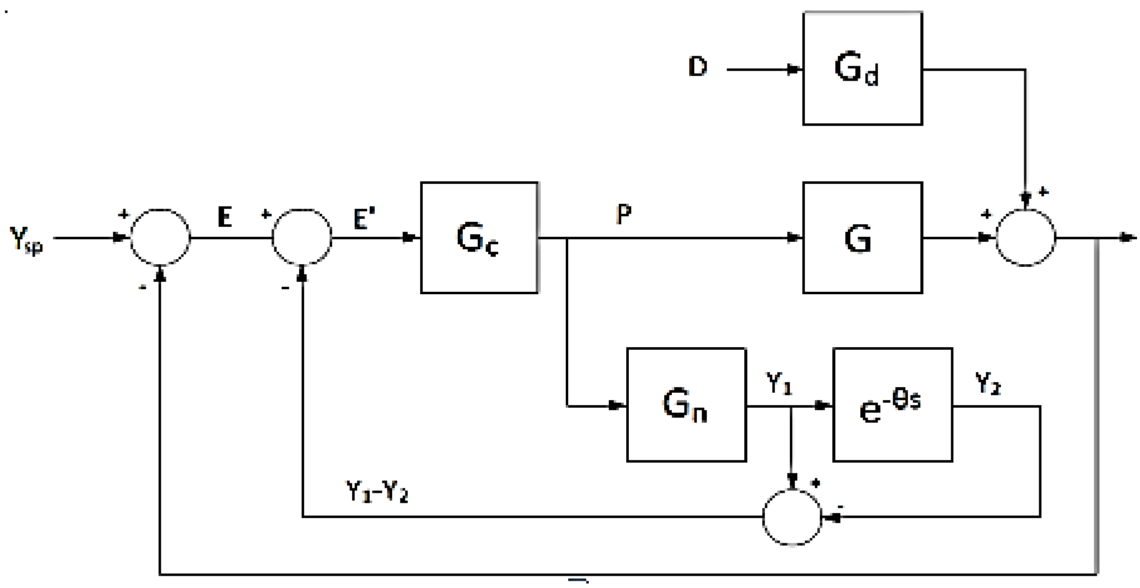



***Fig 4.5*** *The Smith Predictor block diagram re-drawn as two nested feedback loops*

Further on, the inner feedback loop can be reduced as shown in Figure 4.6.

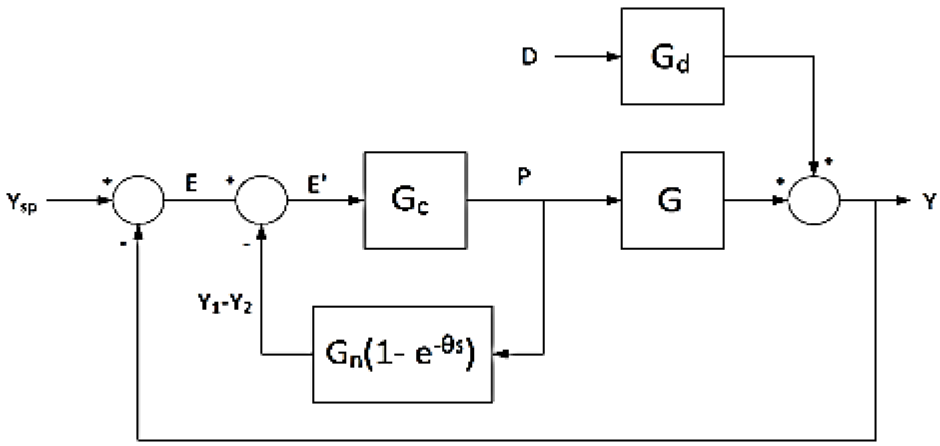



***Fig 4.6*** *The Smith Predictor block diagram drawn in reduced form*

To find the equivalent transfer function for the inner feedback loop in Figure 4.6, an expression for $\mathbf{P}/_{\mathbf{E}}$ is indeed. This function is derived by using the blocks in Figure 4.6. The goal is to find $G'$, given by

$$G' = \frac{P}{E}$$

Here in the equation (4.10), it is observed that the time delay part is missing from the characteristic equation of the Smith predictor controller, but it is present in the closed-loop set-point transfer function of the PI controller in the previous chapter. The characteristic equation is the denominator part of the closed-loop set-point transfer function for a given controller. This gives a theoretical explanation of the time delay compensating ability of the Smith predictor.

Investigation of the block diagram in Figure 4.6 gives the following:

$$\mathrm{P} = \mathrm{E}'\mathrm{G_c} \tag{4.4}$$

$$\mathrm{E}' = \mathrm{E} - (\mathrm{Y_1} - \mathrm{Y_2}) \tag{4.5}$$

$$(\mathrm{Y_1} - \mathrm{Y_2}) = \mathrm{PG_n}\left(1 - \mathrm{e}^{-\theta s}\right) \tag{4.6}$$

$$\mathrm{P} = \left[\, \mathrm{E} - \mathrm{PG_n}\left(1 - \mathrm{e}^{-\theta s}\right)\right]\mathrm{G_c} \tag{4.7}$$

Simplifying equation (4.7) gives

$$\mathrm{P}\left[1 + \mathrm{G_c G_n}\left(1 - \mathrm{e}^{-\theta s}\right)\right] = \mathrm{EG_c} \tag{4.8}$$

The transfer function for the inner feedback loop in Figure 4.6 is then obtained:

$$\mathrm{G} = \frac{\mathrm{P}}{\mathrm{E}} = \frac{\mathrm{G_C}}{1 + \mathrm{G_c G_n}(1 - \mathrm{e}^{-\theta s})} \tag{4.9}$$

By doing some rearrangement, the closed-loop set-point transfer function for the Smith predictor is given by:

$$\frac{\mathrm{Y}}{\mathrm{Y_{sp}}} = \frac{\mathrm{G_c G_n e^{-\theta s}}}{1 + \mathrm{G_c G_n}} \tag{4.10}$$

Here in the equation (4.10), it is observed that the time delay part is missing from the characteristic equation of the Smith predictor controller, but it is present in the closed-loop set-point transfer function of the PI controller in the previous chapter. The characteristic equation is the denominator part of the closed-loop set-point transfer function for a given controller. This gives a theoretical explanation of the time delay compensating ability of the Smith predictor.

## 4.3 Comparison between conventional PI controller and Smith Predictor control technique

Comparison between the response curve and performance index for a time delay function between conventional PI controller using Ziegler-Nichols (ZNPI) tuning method and Smith predictor control technique (SPC) for the time delay function $\mathbf{G(s)} = \frac{\mathbf{1}}{\mathbf{(s+1)}}\mathbf{e^{-05s}}$

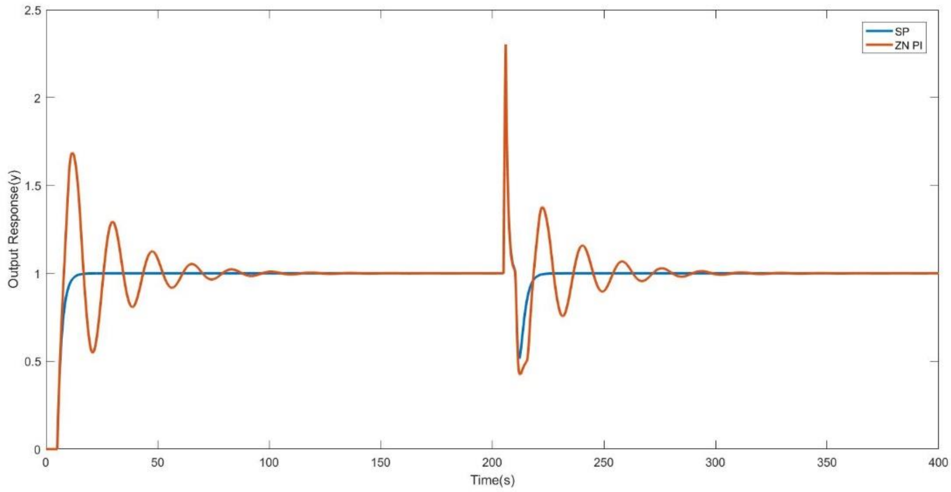



***Fig 4.7*** *Comparison between the PI controller and Smith Predictor control technique for the dead time*

**Table 4.1** Performance index for ZN PI tuning method of controller and Smith Predictor control technique

| **Controller** | **%OS** | **$T_r$** | **$T_s$** | **IAE** | **ITAE** |
|---|---|---|---|---|---|
| ZNPI | 91.5 | 0.83 | 14.38 | 6.274 | 79.72 |
| SPC | 39 | 1.39 | 10.41 | 2.909 | 46.25 |

Here from the performance index, we can conclude that for the specified transfer function the value of the parameters for Smith Predictor control technique is better than the convention PI controller. From comparing the results, we conclude that for the time delay systems the response of Smith Predictor control technique is better than the conventional techniques.

## 4.4 Modified Smith Predictor control techniques

The time-delay has been intensively investigated phenomenon during the last decades (Richard 2003), because it is very common in many process control applications and its presence in a control loop always brings serious complications. The relatively effective tool for compensation of time-delay term represents the classical Smith predictor which has been known to automation community since 1959 (Smith). However, this control structure has also its disadvantages and limitations. Some drawbacks of the Smith predictor have been eliminated by improving the idea and creating many modifications of the connection of conventional Smith predictor control technique. Smith predictor control technique is not suitable for all type of dead time processes. So to control the different types of transfer function with dead time, different types of modified Smith predictors are used. Basically, for the integrating and unstable processes with long dead time, it is difficult to handle using conventional technique. Modified Smith predictor control technique is basically the compensating method of disturbance input and process error.

For the conventional Smith predictor control technique only one controller is used (PI or PID controller). But for the modified control technique more than one controller are used for dedicated work. The mostly used modified Smith predictor control techniques are Watanabe et al. 1981, Astrom et al. 1994, Matausek et al. 1996, Majhi and Atherton 1998, Kaya and Atherton 1999. Here in are project we are concentrating about some of the modified Smith predictor control techniques (Watanabe et al. 1981, Astrom et al. 1994and Kaya and Atherton 1999). Also we implemented an auto tuning method of Kaya and Atherton for better response in terms of response curve and performance index compared to the conventional one.

### 4.4.1 Watanabe et al.'s dead Time compensator for integrating processes (1981)

If the pole of a transfer functions with dead time is located near the origin of a left-hand side of S plane, then the response by the conventional Smith predictor control technique may be sluggish enough to be unacceptable. Then if the pole is located at the origin or in near to the origin, of course in the left-hand side of the S plane. Then the time response we get from the conventional Smith predictor control technique in spite of having a good controller also will be sluggish. The sluggish response means that it will move very slowly. That means that the rise time increases also it effects the settling time. To avoid this type of problems mainly for the integrating system with large dead time, Watanabe et al. proposed a modified Smith predictor control technique. So, when it comes for the integrating process with large dead time modified Smith predictor of Watanabe et al. [52] will be considered for the control technique.

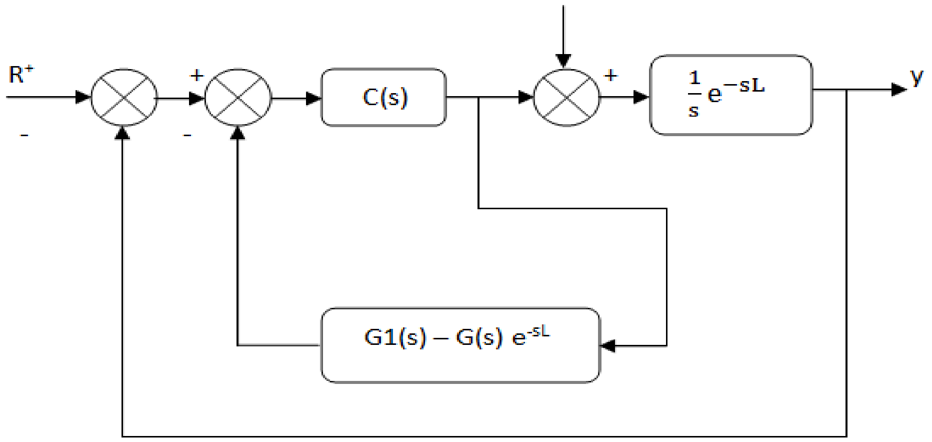



***Fig 4.8*** *Structure of Modified Smith predictor control technique proposed by Watanabe et al.(1981)*

Here from the structure we observed that this is basically a Smith predictor model where a same model of plant is used but in a different fashion. The $\mathbf{C(s)}$is basically a conventional controller may be PI or PID. In process industries PI and PID controllers are generally used due to their simple design and tuning methods. Due to the presence of measurement noise, PI controllers are more preferable than PID controllers. The absence of derivative action makes a PI controller simple and less sensitive to noise. In practice, nearly 90% of all industrial PID controllers have their derivative action turned off.

So, $$\frac{Y(S)}{U(S)} = G(s).e^{-sL} \tag{4.11}$$

Watanabe et al. modified Smith predictor control technique is preferable for integrating process. So we take the transfer function in the form of $G(s) = \frac{1}{S}e^{-sL}$**.** From this transfer function **s**denotes the dead time over here. Also the $G_1(s)$ is the plant model and $G(s)$ is the actual plant.

$$G_1(s) = \frac{1}{1+sL} \tag{4.12}$$

We will get an improved response where the ill effects of the poles at the origin or near to the origin can be overcome through this modified Smith predictor control technique. But this specified control technique only can perform well when it is an integrating system. For other types of systems may be it cannot performed as per the desired level.

### 4.4.2 Astrom's Compensator for integrating processes (1994)

Based on Watanabe et al.'s observation many people pursuit the conventional Smith predictor structure, and came up with many modified Smith predictor control techniques particularly for integrating processes. Here in this section we will discussed about the modified Smith predictor control technique proposed by Astrom et al. [50] where the Astrom's compensator for integrating process is having an another controller, apart from the feed forward controller k . The new controller is used basically as a gain controller, and another controller is used for improving the disturbance performances of the integrating process.

T he structure of Astrom's Smith predictor is shown in Figure 2, where *k* is the gain and *M*(*s*) is the compensator. The plant transfer function is

$$G_m(s) = \frac{1}{s} e^{-Ls} \tag{4.13}$$

The set point response is given by

$$H_r(s) = \frac{k}{k+s} e^{-Ls} \tag{4.14}$$

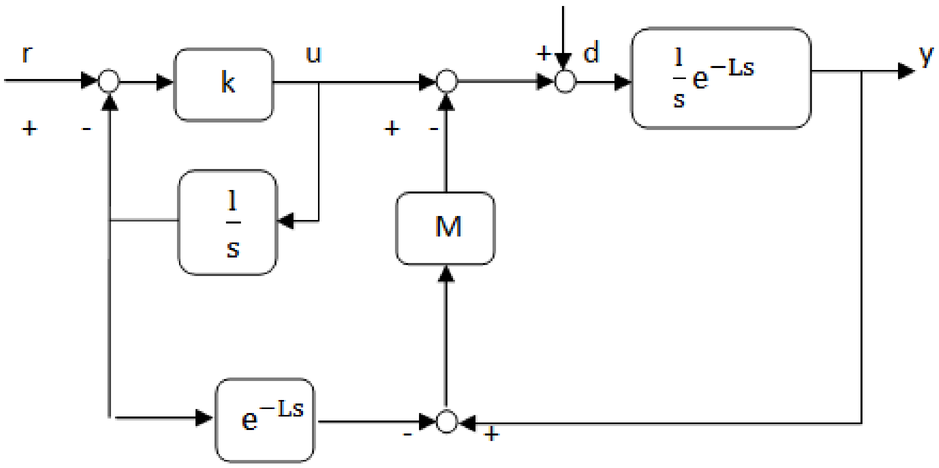



***Fig 4.9 -** Structure of Astrom's Smith Predictor*

Simply, it is a first-order system with time delay. The setpoint response of the system can be improved by choosing an appropriate value of the controller gain *k*. The disturbance response is given by

$$H_d(s) = \frac{\frac{1}{s} e^{-Ls}}{1 + M(s)\frac{1}{s} e^{-Ls}} \tag{4.15}$$

Thus, the scheme has decoupled the disturbance response from the setpoint response. It is possible to improve the disturbance response by choosing a different compensator M(s). Astromet al. proposed the following transfer function with three adjustable parameters

$k_1$,$k_2$ and$k_3$ :

$$M(s) = \frac{k_4 + \frac{k_3}{s}}{1 + k_1 + \frac{k_2}{s} + \frac{k_3}{s^2} - \left(\frac{k_4}{s} + \frac{k_3}{s^2}\right) - \left(\frac{k_4}{s} + \frac{k_3}{s^2}\right) e^{-Ls}} \tag{4.16}$$

Where,

$$k_4 = k_2 + k_3 L \tag{4.17}$$

However, the scheme has two limitations. First, for controller tuning, simplicity, as well as optimality, is important. The three parameters cannot be easily translated into the desired performance and robustness characteristics which the control system designer has in mind. The presence of simple rules which relate model parameters and experimental data to controller parameters serves to simplify the task of the designer. Second, though a general integrator/time delay process can be normalized to (3), it may not be easy to see how to select the structure and parameters of *M*(*s*).

**4.4.3 Modified Smith Predictor Structure (Kaya and Atherton, 1999)**

The modified Smith predictor control technique is the modification of structure using more than one controller for better response. The system dedicated for particular type of transfer function may be stable system, integrating system or unstable systems. Here we are discussing about the modification approached by Kaya & Atherton in 1999 [51]. This control technique is the modification of Matausek et al.1996 [52].

The Kaya & Atherton control technique consist of three controllers for long dead time processes. This technique mainly used for stable and integrating system where long dead time is present.

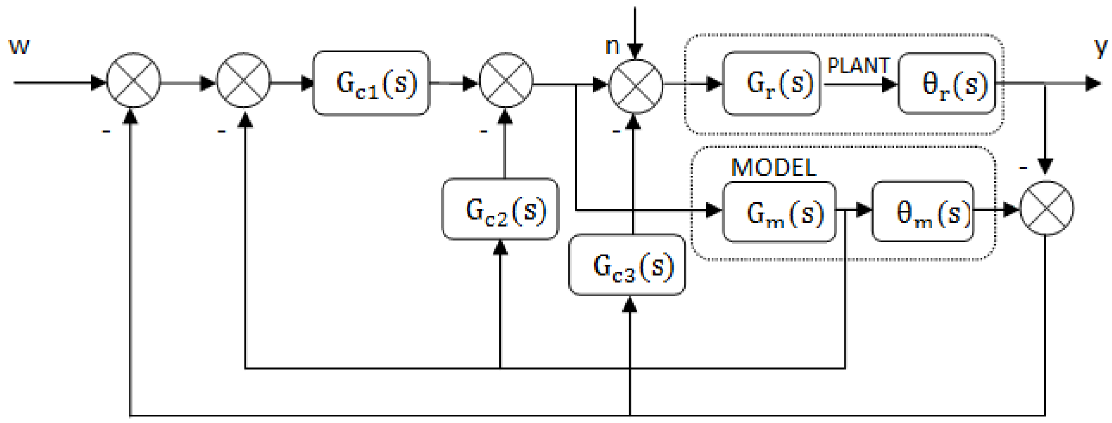



***Fig 4.10*** *Modified Smith predictor control structure of Kaya & Atherton 1999*

$G(s)e^{-\theta s}$ = Transfer function of the plant with delay.

$G_m(s)e^{-\theta_m s}$ = Plant’s dynamic model with delay.

$G_{c1}(s)$ = Conventional PI controller.

$G_{c2}(s)$ = Conventional P or PD controller.

$G_{c3}(s)$ = The disturbance controller introduced in (Matausek et al. 1996).

$D(s)$ = Disturbances incorporated in the system.

Here,

$$G_{c3}(s) = \frac{k_b(T_d s+1)}{0.1T_d s+1} \tag{4.18}$$

Where $k_b$ and $T_d$ are the parameters of the disturbance controller. All the controllers are tuning based on which type of process is given in the form of transfer function with large dead time. This control technique is very complicated to use because of the more no of controllers but the response for the system with complex poles or integrating process where the pole is located at the origin it gives a better result rather than the other control technique. But the controller is not suitable for the unstable processes.

## 4.5 Implementation of Modified Smith

Pole position at origin results integrating behaviour and hence to achieve desired performance from such processes is quite difficult especially in presence of time delay. Due to inherent non-self-regulating behaviour IPTD processes provide continuous fluctuations over considerable period once get disturbed from their steady state. Moreover, IPTD processes with dominant time constant exhibit undesirable sluggish behaviour. Processes like fractional distillation, liquid supply to storage tank, heating of batch process, super-heated steam supply to turbine [53] are the well-known integrating processes. Controlling IPTD processes in a desired way is always a difficult task for process engineers. Moreover, selection of improper control strategy and inappropriate controller settings fail to exhibit the required closed loop behaviour during transient and steady state operations.

To mitigate this limitation, control methodology involving MSP technique is widely accepted. MSP based control scheme is reported by Karan and Dey [54] for achieving enhanced disturbance rejection. Comparable approach is recently reported for unstable delay dominated processes by Karan and Dey where multiple controllers are involved to achieve overall satisfactory closed loop response. Novelty of the proposed MSP scheme comprises sole tuning parameter $\lambda$ (i.e., closed loop time constant) which is suitable enough to tune all the controllers involved. Proposed MSP design results zero overshoot while set point tracing and quicker load regulation. Robust behaviour is established while substantial perturbations in process gain accompanied by time delay. Superiority of suggested MSP scheme is demonstrated through integral error measure (IAE, ISE) and integral time multiplied error measure (ITAE, ITSE) [55]. Moreover, smoothness in control action for the proposed scheme is also estimated through computation of TV (control action variation) [55] along with other techniques

Control structure and the design of the controllers, tuning guideline for the controllers, stability and robustness is reported in the following sections.

### 4.5.1 Control structure

$$G(s)e^{-\theta_s} = G_m(s)e^{-\theta_m s} = \frac{K}{s}e^{-\theta_m s} \tag{4.19}$$

K - open loop gain and $\theta_m$ - dead time for IPTD model (Eq. 4.1)). Fig.4.11 exhibits the configuration of suggested MSP with controllers GC1 (s), GC2(s), and GC3(s). Forward path controller GC1 (s) is accountable for improved servo tracking. GC2(s) and GC3(s) are in feedback path acting towards enhanced disturbance suppression. Relations among the process response (Y) through set point variation (R) and load disturbance (D) are presented by Eqs. (4.1) and (4.2) separately

$$\frac{Y(s)}{R(s)} = \frac{G(s)G_{C1}(s)}{1 + G_m(s)\big(G_{C1}(s) + G_{c2}(s)\big)}e^{-\theta_m s} \tag{4.20}$$

$$\frac{Y(s)}{R(s)} = \frac{G(s)e^{-\theta_m s}}{1 + G_m(s)\big(G_{C1}(s) + G_{c2}(s)\big)}e^{-\theta_m s} \times \frac{1 + G_m(s)\big(G_{C1}(s) + G_{c2}(s)\big) - G_{C1}(s)G_{C3}(s)e^{-\theta_m s})}{1 + G_{C3}(s)G(s)e^{-\theta_m s})} \tag{4.21}$$

Delay term is absent in denominator Eq. (2), $G_{c1}(s)$ and $G_{c2}(s)$ work toward ensuring desirable set point response. However, $G_{c1}(s)$, $G_{c2}(s)$, and $G_{c3}(s)$ are present in Eq. (4.3) containing delay term in both the numerator and denominator, accountable toward desired regulatory behaviour. Here, $G_{c1}(s)$ is IMC-PI (proportional-integral) controller, $G_{c2}(s)$ is P (proportional) controller, and $G_{c3}(s)$ is PD (proportional-derivative) controller.

### 4.5.2 Controller Tuning

Expressions for GC1(s), GC2(s) and GC3(s) of the proposed MSP (Fig. 4.11) are given by the following relations

$$G_{c1}(s) = K_p\left(1 + \frac{1}{T_i}\right) \tag{4.22}$$

$$G_{c2}(s) = \beta K_p \tag{4.23}$$

$$G_{c3}(s) = \gamma K_p(1 + T_d s) \tag{4.24}$$

In Eq. (4.22), $G_{c1}(s)$ is an IMC-PI controller [56] having tuning parameters $K_p$ (proportional gain) and $T_i$ (integral time). In Eq. (4.23), $G_{c2}(s)$ is a proportional controller having the same proportional gain as with $G_{c1}(s)$ i.e., $K_p$. $G_{c2}$ (s) contains an additional tuning constant β which is obtained from Routh stability criterion [57] for Eq. (4.23). $G_{c3}(s)$ is PD controller having same proportional gain as with $G_{c1}(s)$ and $G_{c2}$ (s) i.e., $K_p$, and the derivative time $T_d$. $G_{c3}(s)$ has another parameter γ, achieved from Routh stability criterion [57] of Eq. (4.24). Notable quality of suggested MSP is Gc1(s), $G_{c2}$ (s), and $G_{c3}$ (s) employ the same proportional gain $K_p$.

Tuning guideline for the proposed control structure (Fig. 4.11) consisting of $G_{c1}(s)$, $G_{c2}(s)$, and $G_{c3}(s)$ are discussed in the following sections. Additional tuning parameters β and γ associated with $G_{c2}(s)$ and $G_{c3}(s)$ are also obtained from Routh stability criterion [57] employing the relations of Eqs. (4.23) and (4.24) respectively.

#### 4.5.2.1 Set point controller $G_{C1}(s)$

Forward path controller $G_{c1}(s)$ is accountable toward superior set point tracking. Steps toward designing of $G_{c1}(s)$ for IPTD process using conventional IMC control structure is realized by the following steps [58,59] as shown in Fig. 4.12

**Step 1**: Integrating process model is defined by $\widetilde{g_p(s)}$ without considering its time delay [55]

$$\widetilde{g_p}(s) = \frac{K}{s} \tag{4.25}$$

**Step 2:** q (s) (IMC controller) is realized from $\widetilde{g_p}(s)^{-1}$ (i.e. inverted model) derived from previous step with filter f(s) [58,59].

$$q(s) = g_p\widetilde{(s)q}(s) \tag{4.26}$$

**Step 3:** IMC equivalent feedback controller is given by Eq. (4.27) [58,59]

$$g_c(s) = \frac{q(s)}{1 - \widetilde{g_p}(s)q(s)} \tag{4.27}$$

Now, substituting the Eqs. (4.27) and (4.26) in Eq. (4.25)

$$g_c(s) = \frac{\dfrac{s(2\lambda s + 1)}{k(\lambda s + 1)^2}}{1 - \dfrac{K}{s} \cdot \dfrac{s}{K} \dfrac{(2\lambda s + 1)}{(\lambda s + 1)^2}} \tag{4.28}$$

**Step 4:** From Eq. (4.28), IMC based feedback controller is given by

$$g_c(s) = \frac{2\lambda s + 1}{K\lambda^2 s} \tag{4.29}$$

**Step 5:** For the IMC-PI controller Eq. (4.29) $K_p$ and $T_i$ are given by

$$K_p = \frac{2}{K\lambda}, \tag{4.30}$$

$$T_i = 2\lambda \tag{4.31}$$

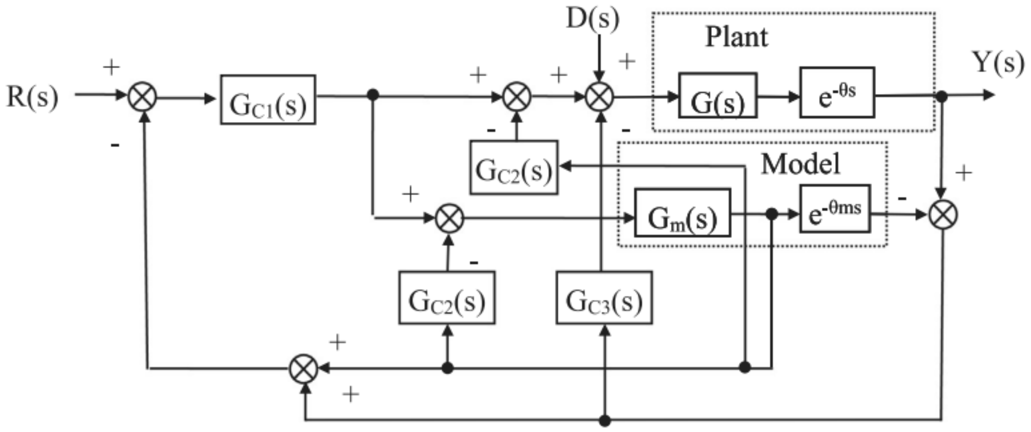



***Fig 4.11** Implemented MSP based closed loop structure*

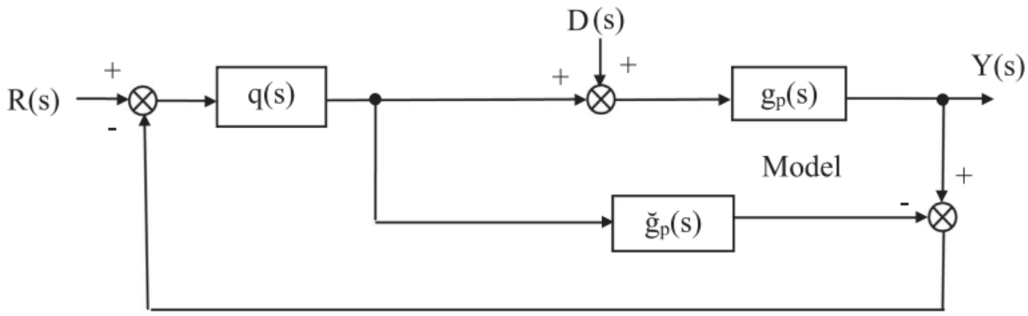



***Fig 4.12** Conventional IMC structure*

Guideline toward selection of λ is provided in the following section. Relation between λ and $\theta_m$ is found out [55] for IPTD model $g_p(s) = \frac{e^{-s}}{s}$ i.e., from Eq. (4.11) where K = 1 and $\theta_m$ = 1. The set point responses are shown in Fig. 4.13 for the proposed scheme while considering only the forward path controller $G_{c1}(s)$ with different values of $\lambda = \theta_m, \frac{\theta m}{2}, \frac{\theta m}{3}, \frac{\theta m}{4}$. Fig. 4.13 clearly demonstrates that $\lambda = \frac{\theta m}{4}$ results quicker set point response but with unwanted overshoot.

$$\lambda = \frac{\theta m}{4} \tag{4.32}$$

Hence, the overshoot must be restricted to avoid actuator saturation. Controller $G_{c2}(s)$ is placed in the feedback path and it plays significant role for stabilizing the process behaviour as discussed in the following section.

#### 4.5.2.2 Stabilising controller $G_{C2}(s)$

Proposed MSP design includes $G_{C2}(s)$ assuring overshoot free set point response. Proportional (P) controller $G_{C2}(s)$ (Eq. 4.15) with gain $\beta K_p$ ($K_p$- proportional gain and $\beta$ - additional parameter) obtained from stability criterion [57] of Eq. (4.12)

$$\frac{Y(s)}{R(s)} = \frac{G(s).G_{C1}(s)}{1 + G_{m(s)}\big(G_{C1}(s) + G_{C2}(s)\big)} e^{-\theta_m s}.$$

According to Karan and Dey [21], neglecting the time delay part from Eq. (4.20)

$$\frac{Y(s)}{R(s)} = \frac{G(s).G_{C1}(s)}{1 + G_m(s)(G_{C1}(s) + G_{C2}(s))} \tag{4.33}$$

Substituting the expressions of $G_{C1}(s)$, $G_{C2}(s)$, G(s) and $G_m(s)$ in Eq. (4.33)

$$\frac{Y(s)}{R(s)} = Y_r = \frac{\frac{K}{s}.K_P(1 + \frac{1}{T_i(s)}}{1 + \frac{K}{s}[K_p\left(1 + \frac{1}{Ti_s}\right) + \beta K_p} \tag{4.34}$$

Subsequently, Eq. (4.34) can be written as

$$Y_r = \frac{KK_p[T_i s + 1]}{T_i s^2 + KK_p[T_i s + 1] + \beta KK_p T_i s} = \frac{1}{\frac{s(T_i s + \beta KK_p T_i)}{KK_p(T_i s + 1)} + 1} \tag{4.35}$$

To reduce the expression of Eq. (4.35), bracketed terms of the denominator are considered to be given by Eq. (4.36)

$$T_i s + \beta KK_p T_i = T_i s + 1 \tag{4.36}$$

From Eq. (4.36), tuning parameter $\beta$ is derived as

$$\beta = \frac{1}{KK_p T_i} \tag{4.37}$$

Substituting the $K_p$ and $T_i$ values in Eq. (4.37)

$$\beta = \frac{1}{KK_p T_i} = \frac{1}{K\left(\frac{2}{K\lambda}\right)2\lambda} = 0.25 \tag{4.38}$$

Now, substituting $\beta$ from Eq. (4.38) in Eq. (4.35)

$$Y_r = \frac{KK_p}{s + KK_p} \tag{4.39}$$

Employing the Routh stability criterion [57] for Eq. (4.21), it is found that the product of open loop gain and the proportional gain must be positive (i.e., $KK_p > 0$) for IPTD process so that the desired stable behaviour can be ensured.

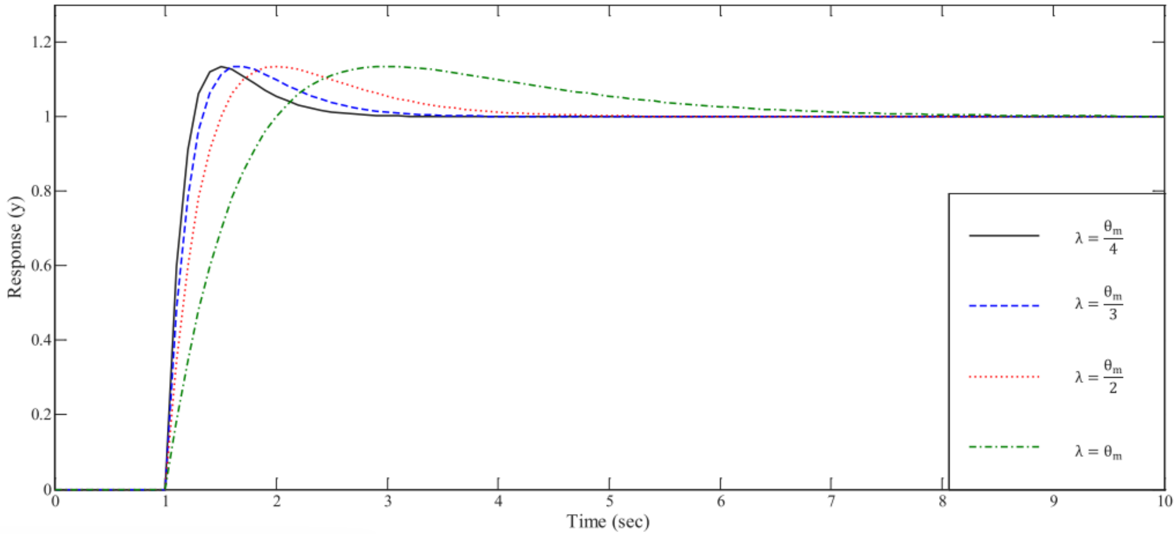



***Fig 4.13** Set point responses with different values of λ*

### 4.5.2.3 Disturbance Rejection controller $G_{C3}(s)$

$G_{C3}(s)$, PD controller (Eq. 4.6) by nature with derivative time $T_d$ and gain $\gamma\ K_p$ where $\gamma$ is obtained from Routh stability criterion [57] as follows

$$\frac{\boldsymbol{Y(s)}}{\boldsymbol{D(s)}} = \frac{Y(s)}{R(s)} = \frac{G(s)e^{-\theta_m s}}{1+G_m(s)\left(G_{C1}(s)+G_{C2}(s)\right)} \times \frac{1+G_m(s)\left(G_{C1}(s)+G_{C2}(s)\right)-G_{C1}(s)G_{C3}(s)e^{-\theta_m s}\,)}{1+G_{C3}(s)G(s)e^{-\theta_m s}\,)} \tag{4.40}$$

Corresponding characteristic equation is given by

$$1 + G_{C3}G(s)e^{-\theta_m s} = 0 \tag{4.41}$$

Replacing the expressions of $G_{C3}(s)$ and $G(s)$ in Eq. (4.41)

$$1 + \gamma K_p(1 + T_d S).\frac{K}{s}e^{-\theta_m s} = 0 \tag{4.42}$$

Implementing first-order Pade's approximation [21] in Eq. (4.42) is written as

$$1 + \gamma K_p(1 + T_d s).\frac{K}{s}\left(\frac{-0.5\theta_m s + 1}{0.5\theta_m s + 1}\right) = 0 \tag{4.43}$$

To ascertain improved load recovery [21] derivative time $T_d$ is given by

$$T_d = \lambda = \frac{\theta_m}{4} \tag{4.44}$$

Substituting Td from Eq. (4.44) in Eq. (4.43)

$$4s + K.\gamma.K_p(4 + \theta_m s)\frac{-0.5\theta_m s+1}{0.5\theta_m s+1} = 0 \quad (4.45)$$

Subsequently, Routh array is constructed from Eq. (4.45) where the first column terms are

$$2\theta_m - 2\gamma K_p {\theta_m}^2 K_p > 0, \quad (4.46)$$

$$4(1 - \gamma\theta_m K_p K) > 0, \quad (4.47)$$

$$16\gamma K_p K > 0 \quad (4.48)$$

To ascertain stability, lower and upper limit of γ is obtained from Eqs. (4.46), (4.47), and (4.48). Hence, for absolute stability, boundary value of γ is given by

$$0 < \gamma < \frac{1}{\theta_m K K_p} \quad (4.49)$$

Therefore, the intermediate value in between the upper and lower boundaries is considered to be suitable for γ as given by the Eq. (4.49)

$$\gamma = \frac{0.5}{\theta_m K K_p} \quad (4.50)$$

Now, substituting the values of proportional gain Kp from Eq. (4.12) and closed loop time constant λ from Eq. (4.49) in Eq. (4.50), the value of γ can be defined by Eq. (4.51)

$$\gamma = \frac{0.5}{\frac{\theta_m.K.2}{K\lambda}} = \frac{0.5}{\frac{\theta_m.K.8}{K.\theta_m}} = 0.06 \quad (4.51)$$

**4.5.3 Controller tuning parameters**

For the process $\frac{0.2}{s}e^{-7.4}$, the values obtained are

| $G_{c1}$ | $G_{c2}$ | $G_{c3}$ |
|---|---|---|
| Kc = 5.4<br>τi = 3.70 | Kc= 5.4<br>β = 0.25 | Kc = 5.4<br>τd = 1.85<br>γ = 0.06 |

For the process $\frac{0.05}{s}\, e^{-6}$ , the values obtained are

| $G_{c1}$ | $G_{c2}$ | $G_{c3}$ |
|---|---|---|
| $Kc = 26.67$ | $Kc = 26.67$ | $Kc = 26.67$ |
| $\tau i = 3.00$ | $\beta = 0.25$ | $\tau d = 1.50$ |
| | | $\gamma = 0.06$ |

**4.6 Stability and Robustness**

Stability and robustness of the suggested MSP methodology is evaluated with parametric uncertainties of the process model and unwanted load fluctuations. Uncertainties are present during process gain estimation and time delay measurement for IPTD process. Robust stability [26] of the closed loop system is ensured if

i.e., $\left|\left|\Delta_m(j\omega)C(j\omega)\right|\right| < 1$ for $\forall\omega\epsilon(-\infty,\infty)$ (4.52)

$C(s = j\omega)$ is complementary sensitivity function (CSF) and $\Delta_m j\omega$ s multiplicative uncertainty. CSF during set point response is given by Eq. (4.33)

$$C(j\omega) = \frac{4\lambda(j\omega) + 2}{2K\lambda^2(jw)^2 + 5\lambda(j\omega) + 2} \tag{4.53}$$

From Eq. (4.32) complementary sensitivity may be given by

$$\Delta_m(j\omega) < \left|\frac{G(j\omega)e^{-\theta s} - G_m(j\omega)e^{-\theta_m s}}{G_m(j\omega)e^{-\theta_m s}}\right| \tag{4.54}$$

Here, $G(j\omega)e^{-\theta s}$ is true process model and $G_m(j\omega)e^{-\theta_m s}$ is plant model. With uncertainty in time delay tuning parameter must be chosen as

$$||C(j\omega)||_\infty < \frac{1}{|e^{-\Delta\theta_m s} - 1|} \tag{4.55}$$

Likewise, in presence of uncertainty in process gain, tuning parameters need to be chosen as

$$||C(j\omega)||_\infty < \frac{1}{\frac{|\Delta K|}{K}} \tag{4.56}$$

In addition, if the uncertainties are present in process gain accompanied by time delay simultaneously, then the tuning parameters must be selected as

$$||C(j\omega)||_{\infty} < \frac{1}{|(\frac{\Delta K}{K}+1)e^{-\Delta\theta_m s}-1|} \tag{4.57}$$

However, the sensitivity and CSF accomplish the condition of robust performance by Eq. (4.38) for closed loop structure

$$||\Delta_m(j\omega)C(j\omega)+w_m(j\omega)(1-C(j\omega)|| < 1 \tag{4.58}$$

Here, $w_m$ (jω) is the uncertainty bound and likewise stability conditions for regulatory response can also be verified by Eq. (4.21)

# Chapter 5

# Performance Evaluation

## 5.1 Objective

The project report evaluates the performance of different processes used in the industry based on the control technique applied. The concerned processes are of the purely integrating type with long time delays. Hence the first step is to demonstrate the performance after implementing conventional controller tuning methods like relay-based tuning. The results would justify the reason to switch to model-based tuning methods like IMC and from there- the requirement of Smith Predictor-based control techniques. The final objective is to implement a Modified Smith Predictor for controlling the processes and comparing with the various contemporary control techniques developed through research to show the improvements introduced by the Modified Smith Predictor. The evaluation is conducted in a virtual environment in Simulink.

## 5.2 Popular integrating process models

### 5.2.1 Model 1

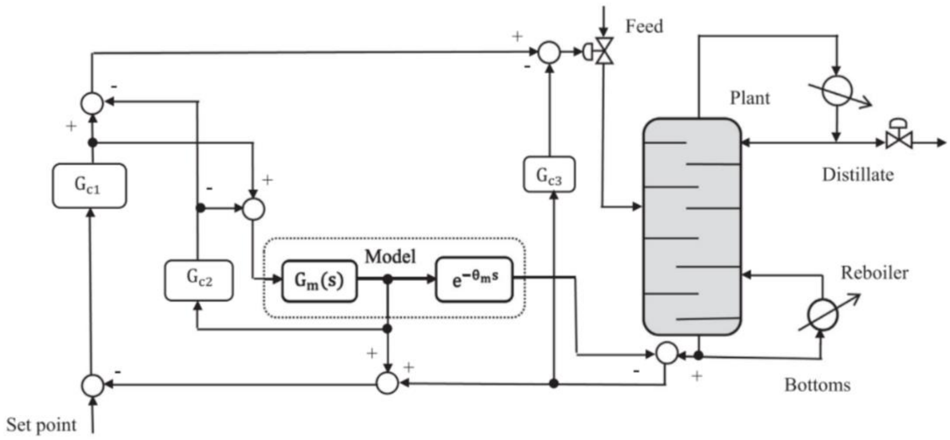



***Fig 5.1*** *Distillation column process model*

This popular IPTD model is reported by Kumar and Padma Sree [61], and Goud and Rao [62] signifying the behaviour of distillation column (Fig. 5.1) where two outputs are considered as top and bottom products. The bottom product along with time delay is considered to be a level control system as realized by

$$G_{p1} = \frac{0.2}{s} e^{-7.4s} \tag{5.1}$$

### 5.2.2 Model 2

Model 2 is reported by Goud and Rao [62] obtained through reduction [62] of the unstable process model

$$G_{p2} = \frac{5}{100s-1} e^{-6s} \tag{5.2}$$

$$G_{p3} = \frac{0.05}{s} e^{-6s} \tag{5.3}$$

## 5.3 Performance evaluation of Relay-based tuning and IMC based PID control

A relay-based tuning is used to find the oscillating output for the process, The result is used to determine the gain (Ku) and period (Pu). This is then plugged into the Zeigler Nichol's tuning formula. However, a stable response is not found for the obtained values of $Kc, \tau i$ and $\tau d$. This primarily to the large time delay of the processes. So, when the action reached the output, the input had already changed and the control action represented a past state.

Similarly, it is not possible to obtain a stable state for IMC based control for both processes. Hence, as stated before, the focus was shifted to Smith Predictor based control methods.

For the process $\frac{0.2}{s} e^{-7.4s}$ , the values obtained are

| **Relay-Based Tuning** | **IMC Based Tuning** |
|---|---|
| Ku $= 3.692$<br>Pu=29.50 | λ= 1.85 |
| Kc = 0.6 $x\ Ku$ = 2.22<br>τi = Pu / 2 = 14.76<br>τd = $Pu$ / 8 = 3.69 | Kc= $((\tau p+0.5\theta))/(kp(\lambda+0.5\theta)) = 4.23$<br>τi =$\tau p + 0.5\theta$= 8.40<br>τd = $\tau p\theta/(2\tau p+\theta) = 0.79$ |
| **Expression of Controller**<br>$(1 + 1/14.76 + 3.96)$ x2.22e(t) | **Expression of Controller**<br>$(1 + 1/8.40 + 0.79)$ x4.23 e(t) |

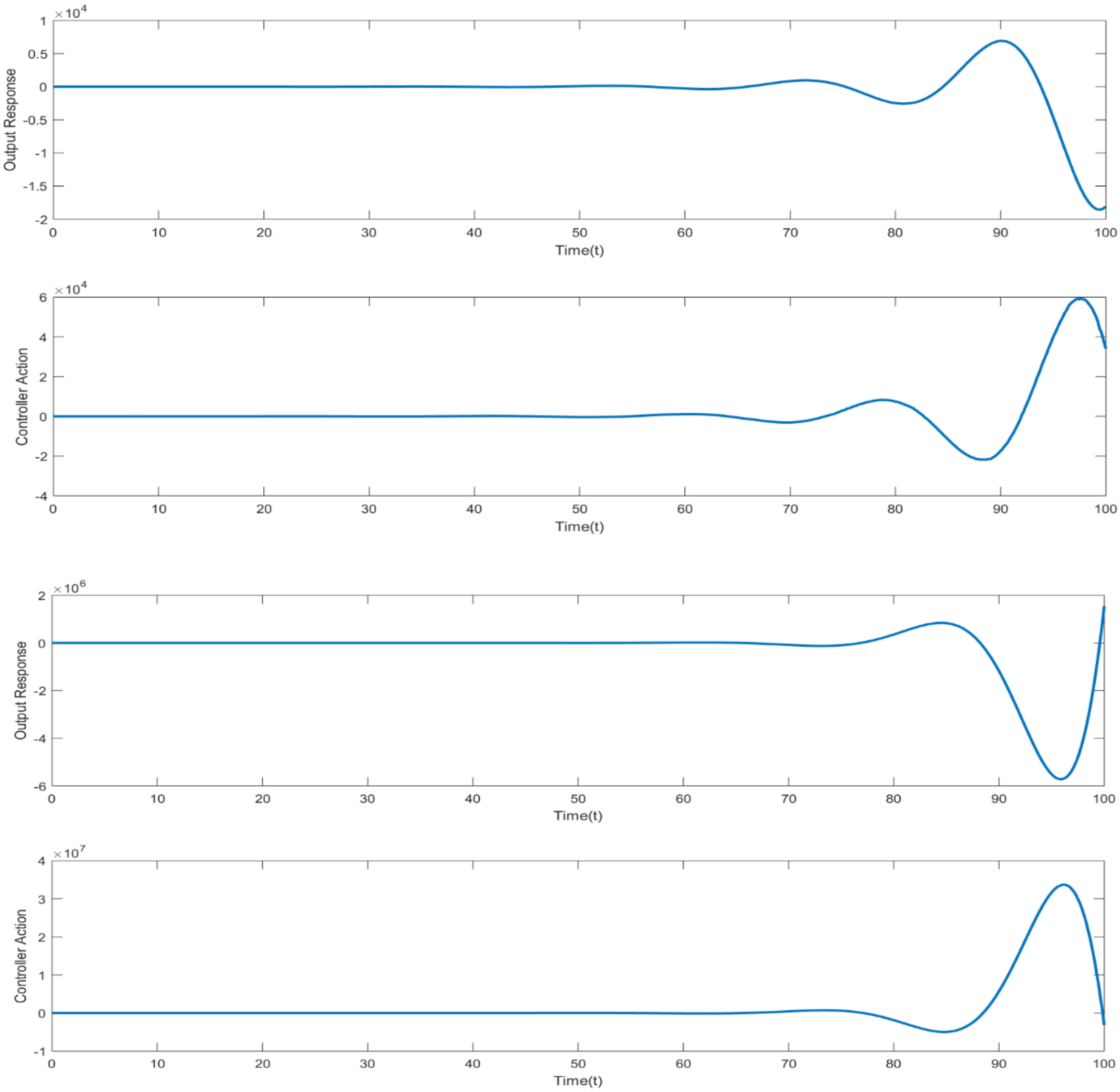



***Fig 5.2*** *Time domain performance Analysis of Relay based tuning (above) and IMC based tuning (below) for model 1*

## 5.4 Performance evaluation of conventional Smith Predictor and Modified Smith Predictor

For both control schematics, the $G_{c1}$ of [54] was considered as the main controller.

Design parameter $\lambda = 1.85$ (5.4)

Controller gain $Kc = 5.4$ (5.5)

Integral time constant $\tau i = 3.70$ (5.6)

Integral gain $Ti = 0.27$ (5.5)

### 5.4.2 Experimental results

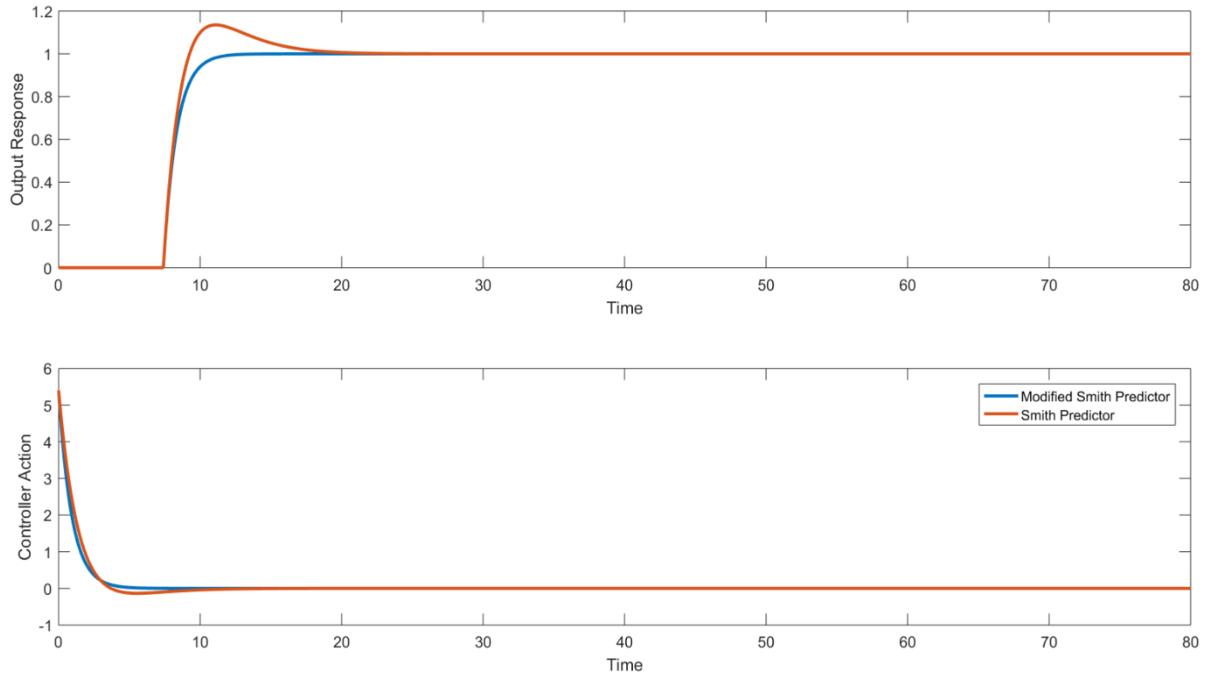



***Fig 5.3*** *Frequency domain performance index analysis of Modified Smith Predictor and conventional Smith Predictor*

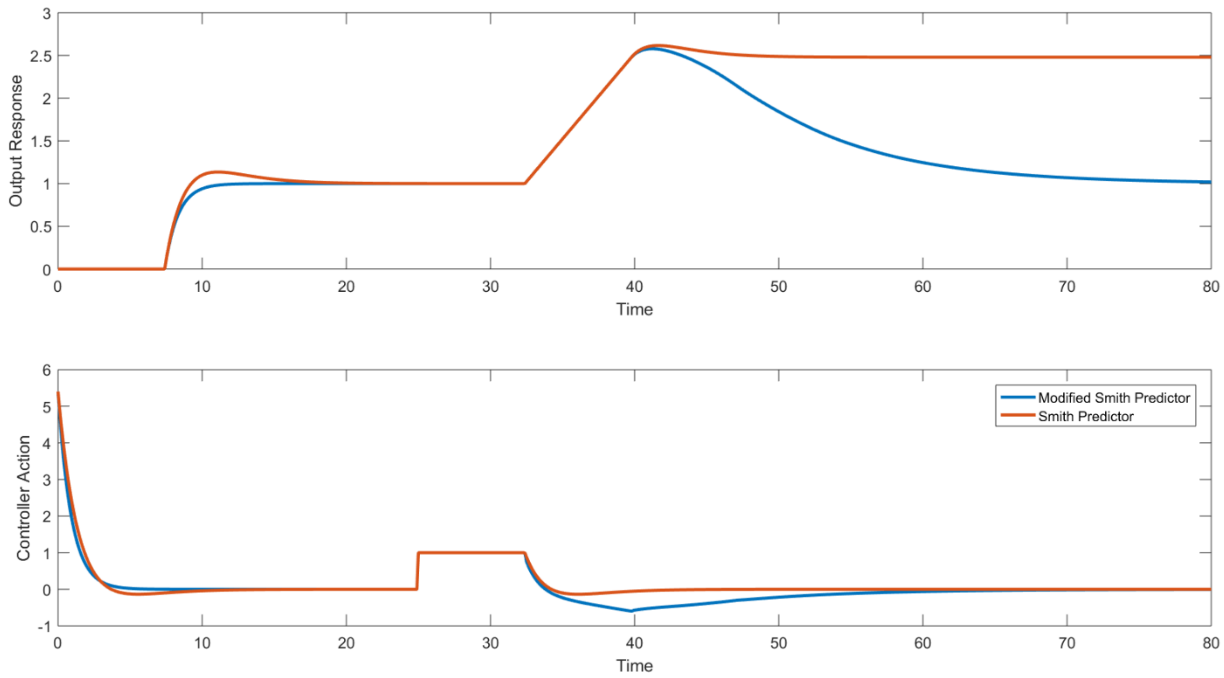



***Fig 5.4*** *Time domain performance index analysis of Modified Smith Predictor and conventional Smith Predictor*

**Table 5.1** Frequency domain performance index analysis of Modified Smith Predictor and conventional Smith Predictor

| Parameter | Modified Smith Predictor | Smith Predictor |
|---|---|---|
| Gm (dB) | 7.56 | 6.02 |
| Pm (Degrees) | 26.4 | 56.00 |
| Wco (rad/sec) | 0.90 | 0.76 |
| Wpm (rad/sec) | 0.10 | 0.16 |

**Table 5.2.1** Time domain performance index analysis of Modified Smith Predictor and conventional Smith Predictor

| Parameter | Modified Smith Predictor | Smith Predictor |
|---|---|---|
| Rise Time (Sec) | 2.04 | 1.35 |
| Settling Time (Sec) | 11.02 | 17.39 |
| Settling Min | 0.91 | 0.91 |
| Settling Max | 1.00 | 1.14 |
| Overshoot (%) | 0.00 | 13.53 |
| Undershoot (%) | 0.00 | 0.00 |
| Peak | 1.00 | 1.14 |
| Peak Time (Sec) | 40.40 | 11.10 |

**Table 5.2.2** Time domain performance index analysis of Modified Smith Predictor and conventional Smith Predictor for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | Smith Predictor | |
|---|---|---|---|---|
| | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** |
| **ISE** | 0.46 | 0.83 | 0.46 | 0.53 |
| **ITSE** | 0.21 | 14.97 | 0.43 | 2.67 |
| **IAE** | 0.93 | 3.78 | 1.36 | 2.05 |
| **ITAE** | 0.86 | 123.30 | 4.14 | 28.89 |
| **TV** | 5.00 | 20.74 | 6.35 | 15.12 |

### 5.4.3 Observations

The impact of the modifications can clearly be seen in overshoot compensation and load disturbance rejection. The Modified Smith Predictor result does not have an overshoot with the maximum value of 1.00 which is the setpoint of the given process. This is due to the addition of the $G_{c2}$ controller. Again, it can be seen that the $G_{c3}$ is able to bring down the amplitude of the output when a long disturbance is added. This is to simulate real-life implications of disturbances that may affect the process and the addition of $G_{c3}$ makes a great difference as compared to the conventional Smith Predictor which lacks it.

The responses for Model 2 were very similar. The modifications to the Smith Predictor made their effect felt greatly.

### 5.4.4 Conclusion

The addition of $G_{c2}$ and $G_{c3}$ as modifications to the already powerful Smith Predictor based control technique are thus justified through this evaluation. Hence, the Modified Smith Predictor is preferred over the conventional one.

## 5.5 Performance evaluation of Modified Smith Predictor and various Model based tuning techniques

The main objective of this section is to show how the proposed Modified Smith Predictor compares to the latest tuning techniques developed for each process on an individual process. This includes a mix of single loop-based IMC Controllers with filters, IMC based control loops with noise filters and other forms of Modified Smith Predictor control.

Evaluation was done at nominal conditions and perturbed conditions to evaluate performance under simulated real-conditions such as model mismatch, changes in delay time, etc.

### 5.5.1 Comparison references

For Model 1, the proposed Modified Smith Predictor [54] was compared with the single controller-based scheme as proposed by Kumar and Padma Sree [61] and the scheme as mentioned by Goud and Rao [62].

For Model 2, the proposed Modified Smith Predictor [54] was compared with the IMC based Modified Smith Predictor scheme as proposed by Karan and Dey [63] and the scheme as mentioned by Goud and Rao [62].

Controller parameters were taken as mentioned in the proposed research papers [54] [61-63].

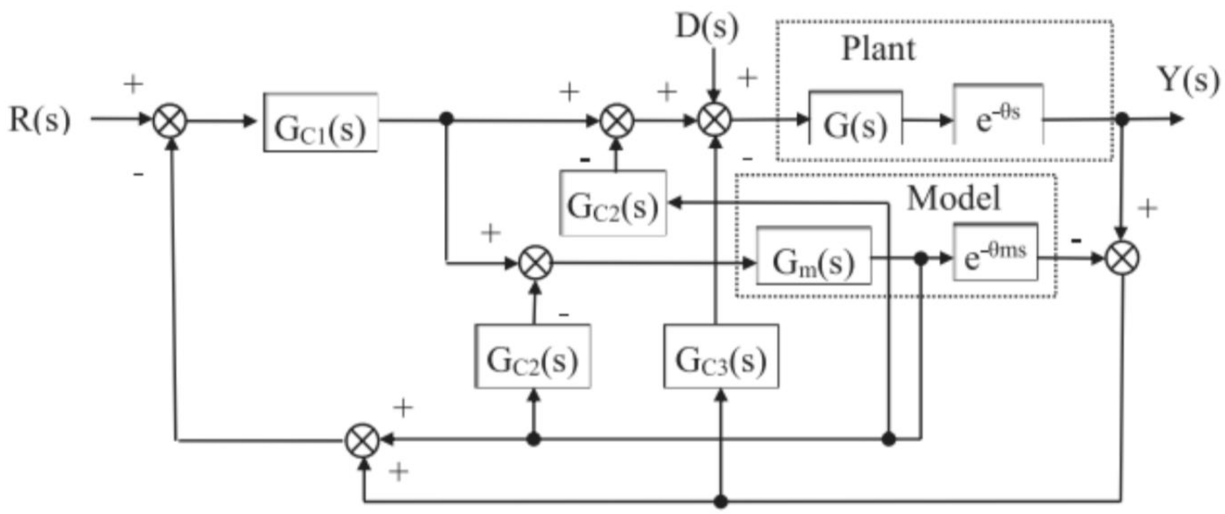



***Fig 5.5** IMC Based MSP as proposed by Karan and Dey*

### 5.5.2 Performance evaluation at nominal conditions

Here conditions were left at nominal values a t both gain and time delay values were not perturbed

#### 5.5.2.1 Model 1

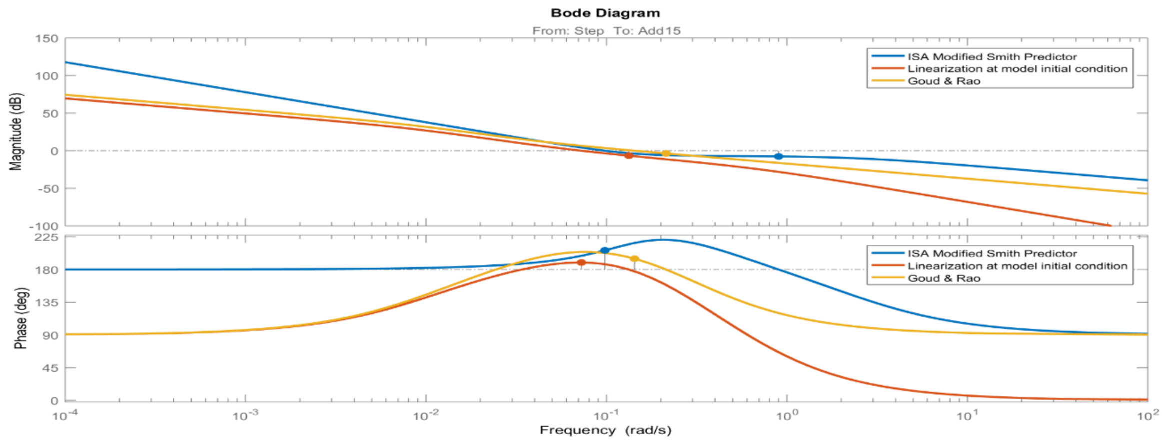



***Fig 5.6*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1*

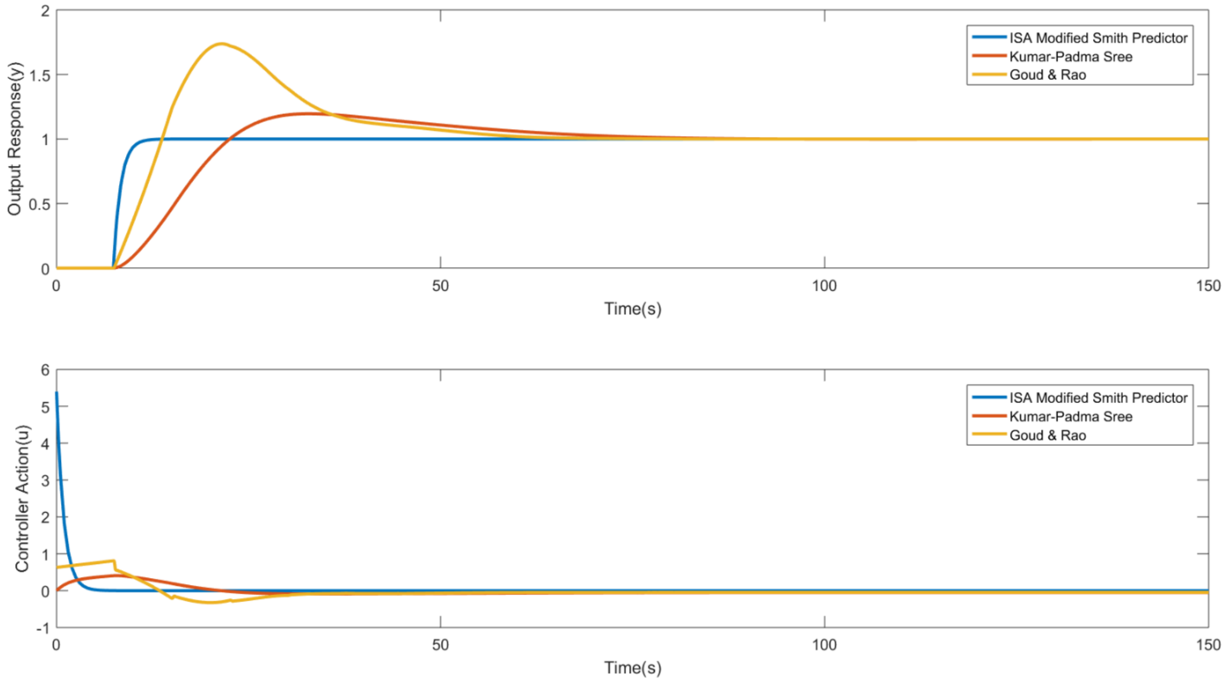



***Fig 5.7*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1*

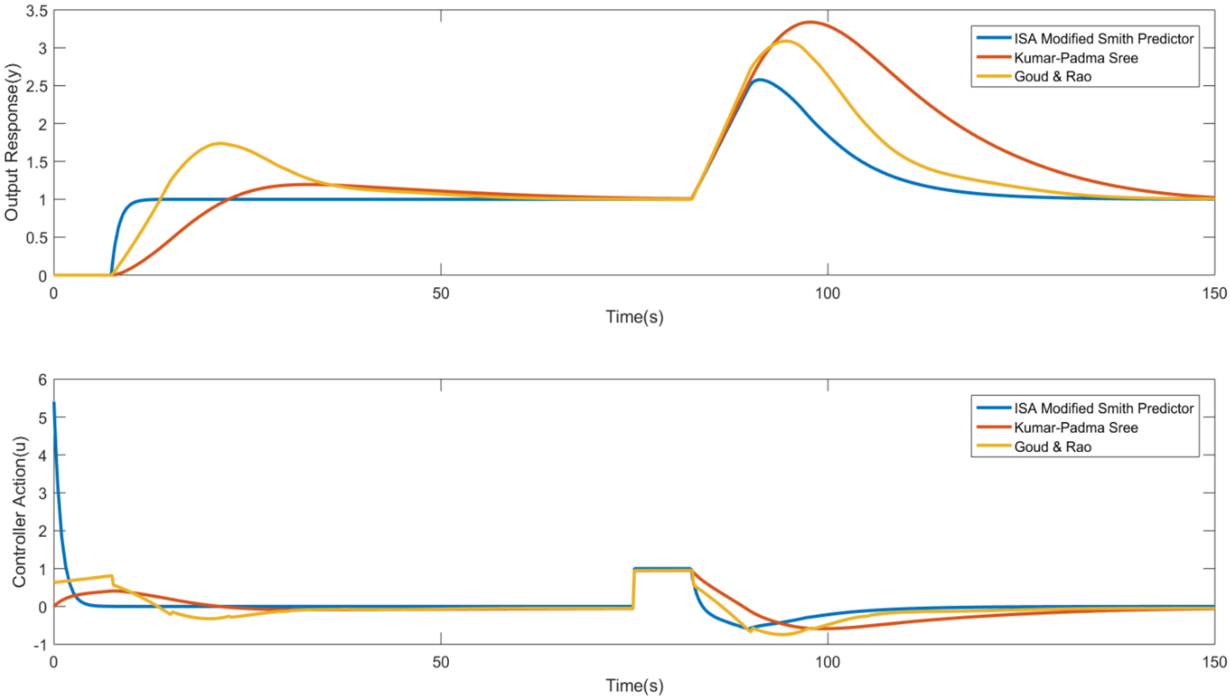



***Fig 5.8*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 for single disturbance (positive)l*

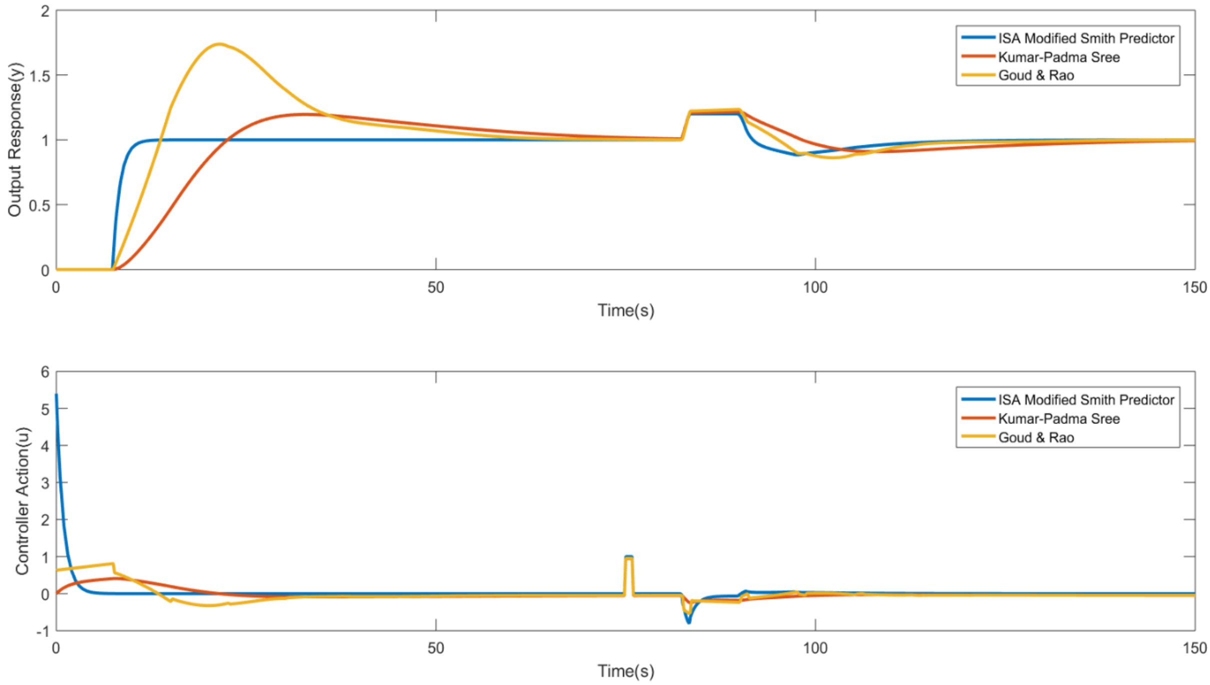



***Fig 5.9*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 for double disturbance (positive & negative)*

**Table 5.3** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 7.56 | 6.61 | 3.64 |
| Pm (Degrees) | 26.40 | 9.71 | 14.9 |
| Wco (rad/sec) | 0.90 | 0.13 | 0.21 |
| Wpm (rad/sec) | 0.10 | 0.07 | 0.14 |

**Table 5.4.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 2.06 | 10.58 | 4.99 |
| Settling Time (Sec) | 11.05 | 73.12 | 59.80 |
| Settling Min | 0.91 | 0.91 | 0.92 |
| Settling Max | 1.00 | 1.20 | 1.74 |
| Overshoot (%) | 0.00 | 19.58 | 73.79 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.00 | 1.20 | 1.74 |
| Peak Time (Sec) | 45.70 | 32.89 | 21.50 |

**Table 5.4.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | Kumar - Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** |
| **ISE** | 0.46 | 0.83 | 7.76 | 117.10 | 15.85 | 73.98 |
| **ITSE** | 0.21 | 33.43 | 137.93 | 11233.26 | 194.93 | 5796.00 |
| **IAE** | 0.93 | 3.78 | 21.10 | 87.49 | 23.53 | 65.22 |
| **ITAE** | 0.86 | 267.00 | 626.03 | 7582.45 | 414.04 | 4558.44 |
| **TV** | 5.00 | 20.78 | 12.72 | 35.87 | 17.27 | 35.81 |

**Table 5.4.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | Kumar - Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** |
| **ISE** | 0.46 | 0.48 | 7.76 | 8.40 | 15.85 | 16.45 |
| **ITSE** | 0.21 | 1.49 | 137.93 | 197.37 | 194.93 | 251.03 |
| **IAE** | 0.93 | 1.30 | 21.10 | 24.98 | 23.53 | 27.70 |
| **ITAE** | 0.86 | 34.73 | 626.03 | 1013.66 | 414.04 | 821.35 |
| **TV** | 5.00 | 8.16 | 12.72 | 14.63 | 17.27 | 19.34 |

### 5.5.2.2 Model 2

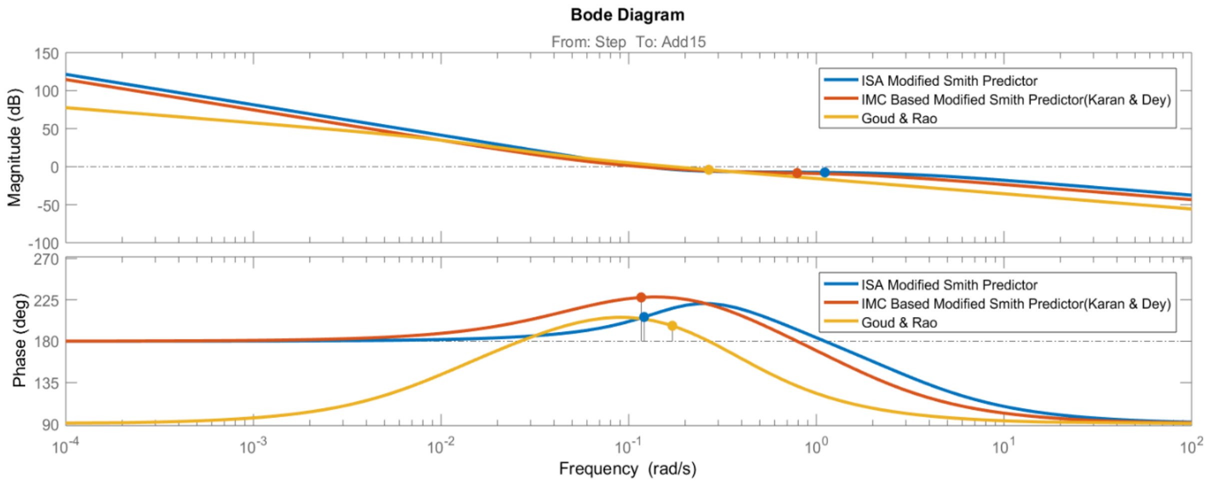



***Fig 5.10*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2*

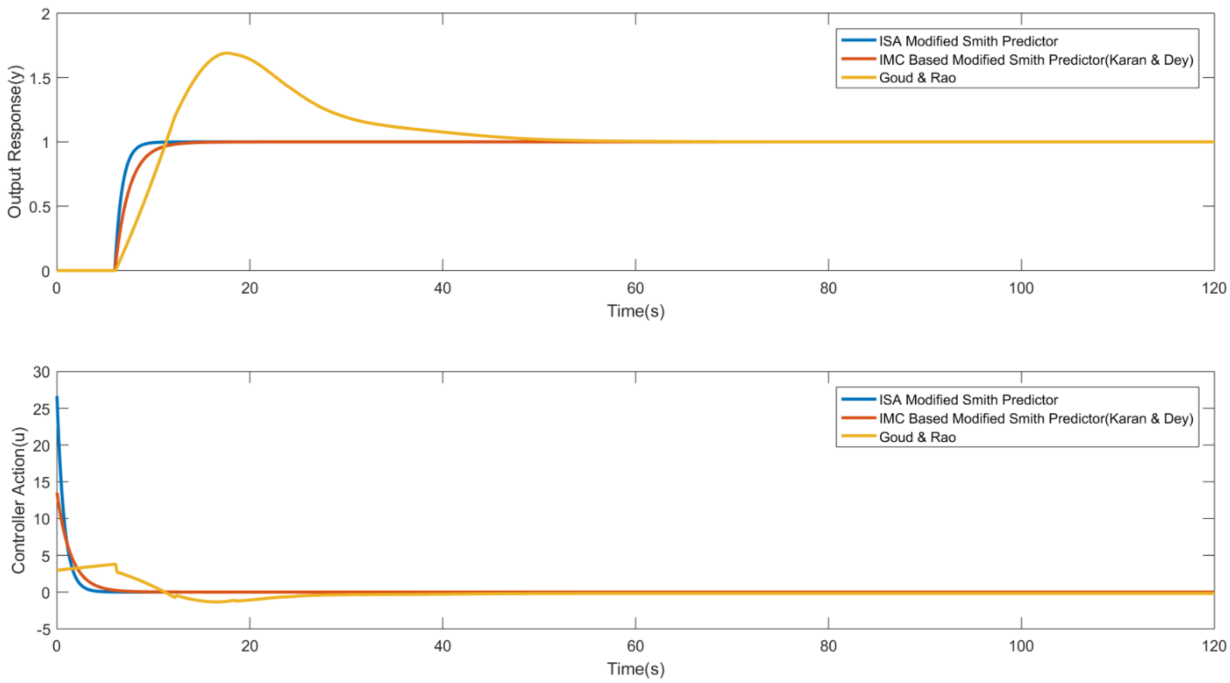



***Fig 5.11*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2*

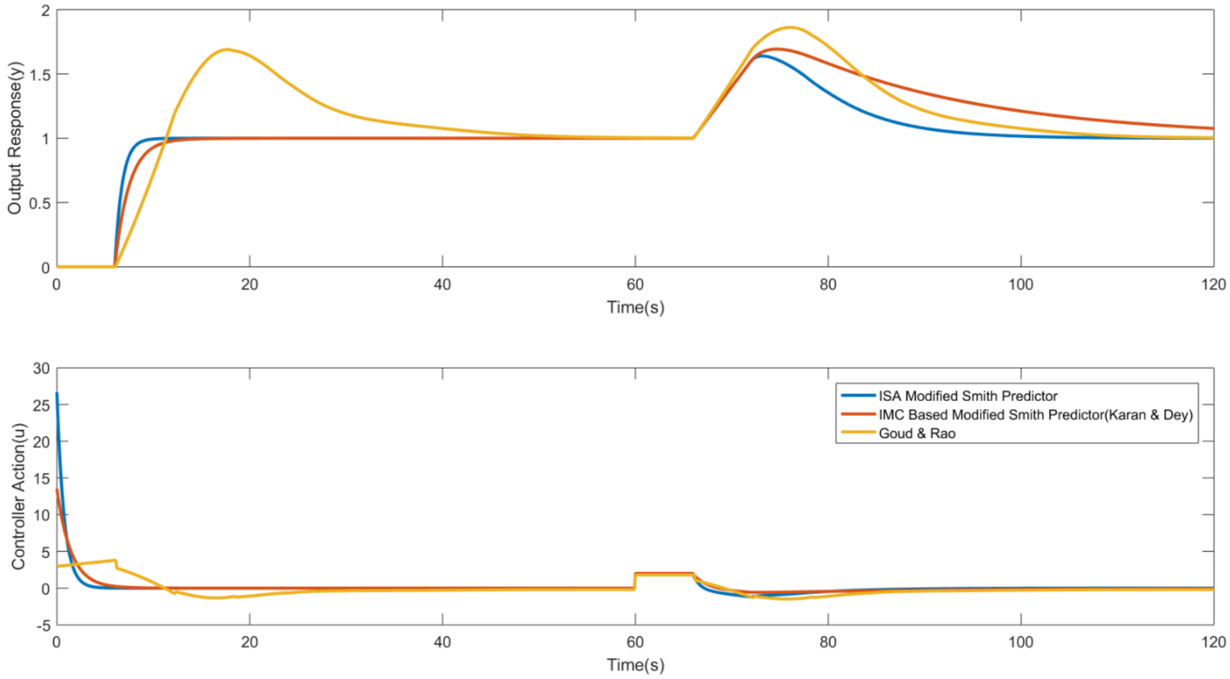



***Fig 5.12*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 for single disturbance (positive)l*

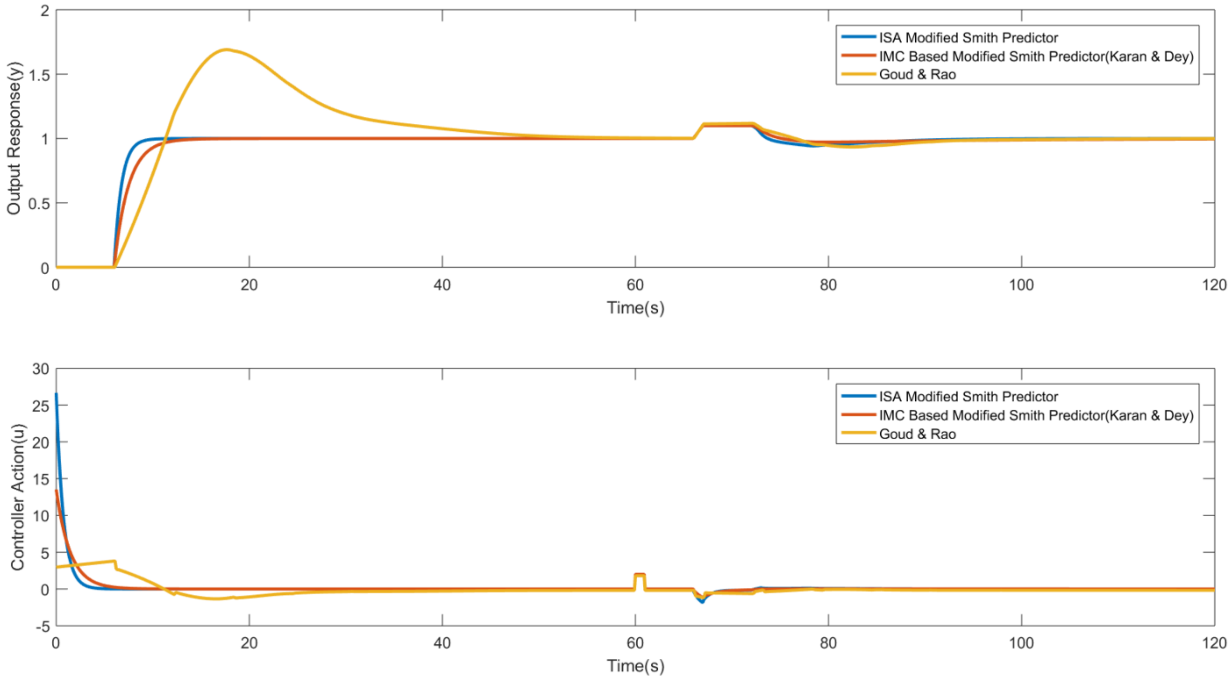



***Fig 5.13*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 for double disturbance (positive & negative)*

**Table 5.5** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2

| Parameter | Modified Smith Predictor | IMC Based Modified Smith Predictor (Karan & Dey) | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 7.57 | 8.44 | 4.06 |
| Pm (Degrees) | 26.30 | 47.60 | 16.80 |
| Wco (rad/sec) | 1.11 | 0.79 | 0.27 |
| Wpm (rad/sec) | 0.121 | 7.12 | 0.17 |

**Table 5.6.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2

| Parameter | Modified Smith Predictor | IMC Based Modified Smith Predictor (Karan & Dey) | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 1.66 | 3.32 | 4.20 |
| Settling Time (Sec) | 8.99 | 12.10 | 49.84 |
| Settling Min | 0.91 | 0.90 | 0.91 |
| Settling Max | 1.00 | 1.00 | 1.69 |
| Overshoot (%) | 0.00 | 0.00 | 69.00 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.00 | 1.00 | 1.69 |
| Peak Time (Sec) | 96.70 | 103.40 | 17.70 |

**Table 5.6.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.38 | 0.43 | 0.75 | 1.06 | 12.56 | 20.94 |
| **ITSE** | 0.14 | 3.74 | 0.56 | 25.56 | 124.30 | 775.3 |
| **IAE** | 0.76 | 1.70 | 1.52 | 4.98 | 19.06 | 33.62 |
| **ITAE** | 0.60 | 71.36 | 2.41 | 292.50 | 277.50 | 1447.00 |
| **TV** | 20.00 | 45.59 | 20.00 | 46.61 | 61.65 | 89.98 |

**Table 5.6.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.38 | 0.38 | 0.75 | 0.75 | 12.56 | 12.68 |
| **ITSE** | 0.14 | 0.33 | 0.56 | 1.01 | 124.30 | 133.50 |
| **IAE** | 0.76 | 0.91 | 1.52 | 1.80 | 19.06 | 20.78 |
| **ITAE** | 0.60 | 11.69 | 2.41 | 24.10 | 277.50 | 412.9 |
| **TV** | 20.00 | 26.29 | 20.00 | 25.07 | 61.65 | 65.28 |

### 5.5.3 Performance evaluation at +10% time delay perturbation

Here the time delay was increased by 10%. So, the dead times for Model 1 and Model 2 became 8.14 and 6.6 respectively. It can be considered an extreme case of model time delay mismatch with respect to the practical world. Such a high value was chosen to test the limits of stability for all the control techniques applied. This time delay was applicable to only the process model and not the actual plant model in case of the Modified Smith Predictor. However, for single controller-based models, this perturbation was applied to the time delay in the forward path.

#### 5.5.3.1 Model 1

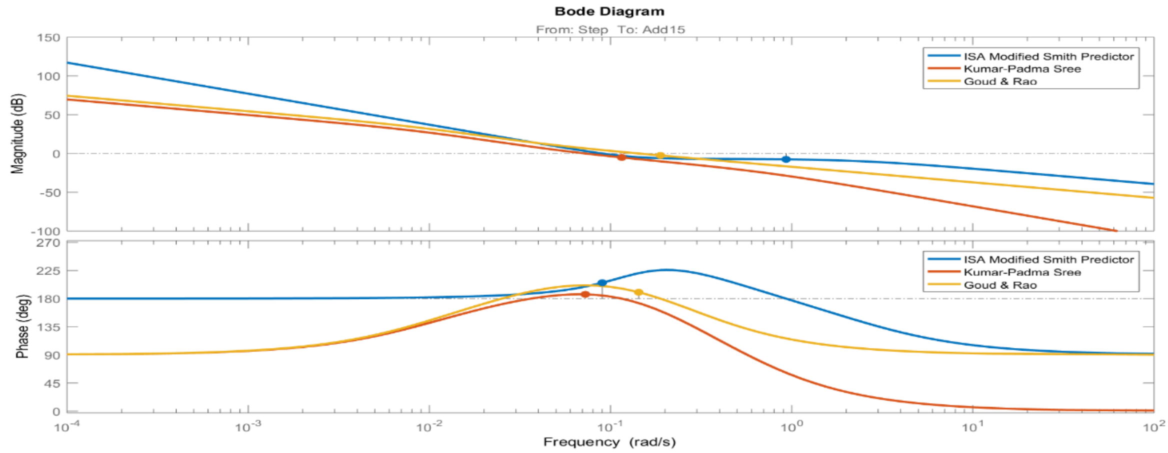



***Fig 5.14*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation*

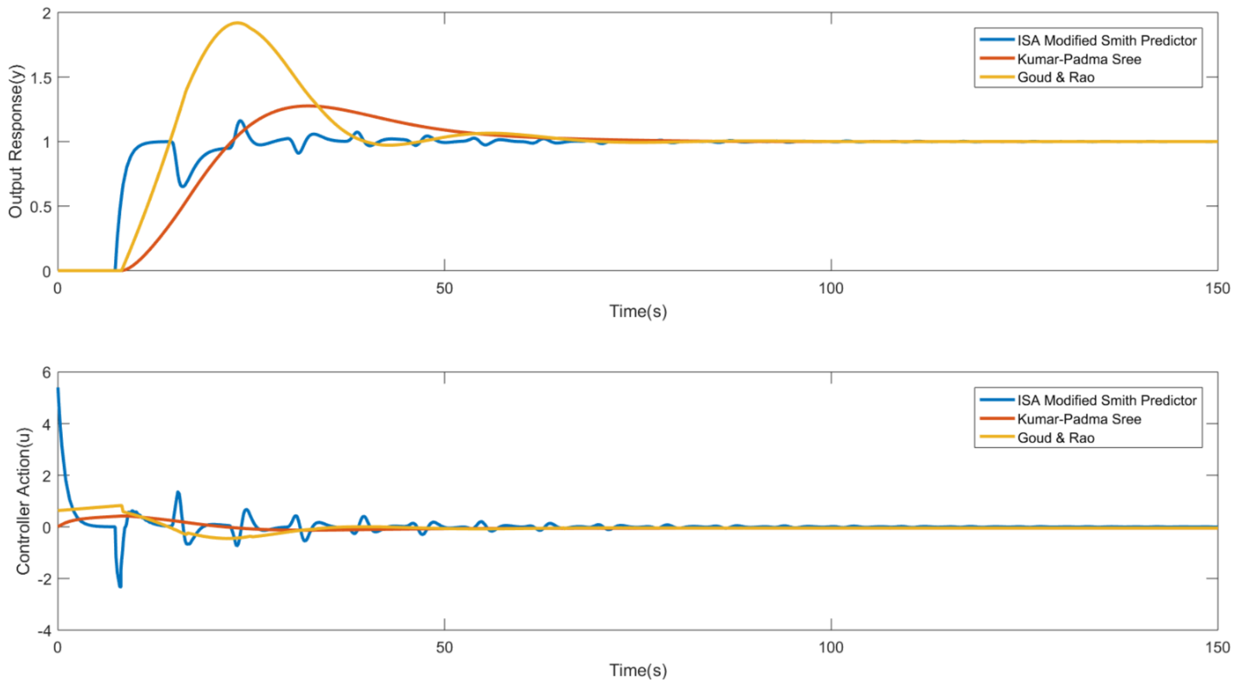



***Fig 5.15*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation*

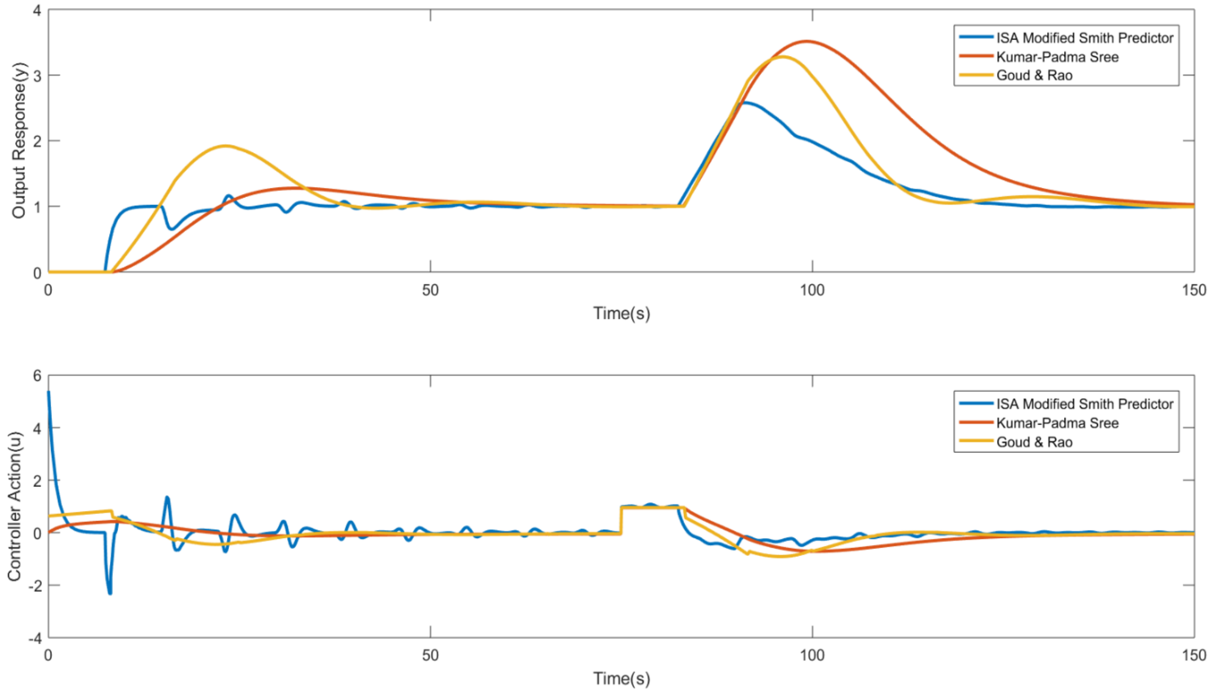



***Fig 5.16*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation for single disturbance (positive)l*

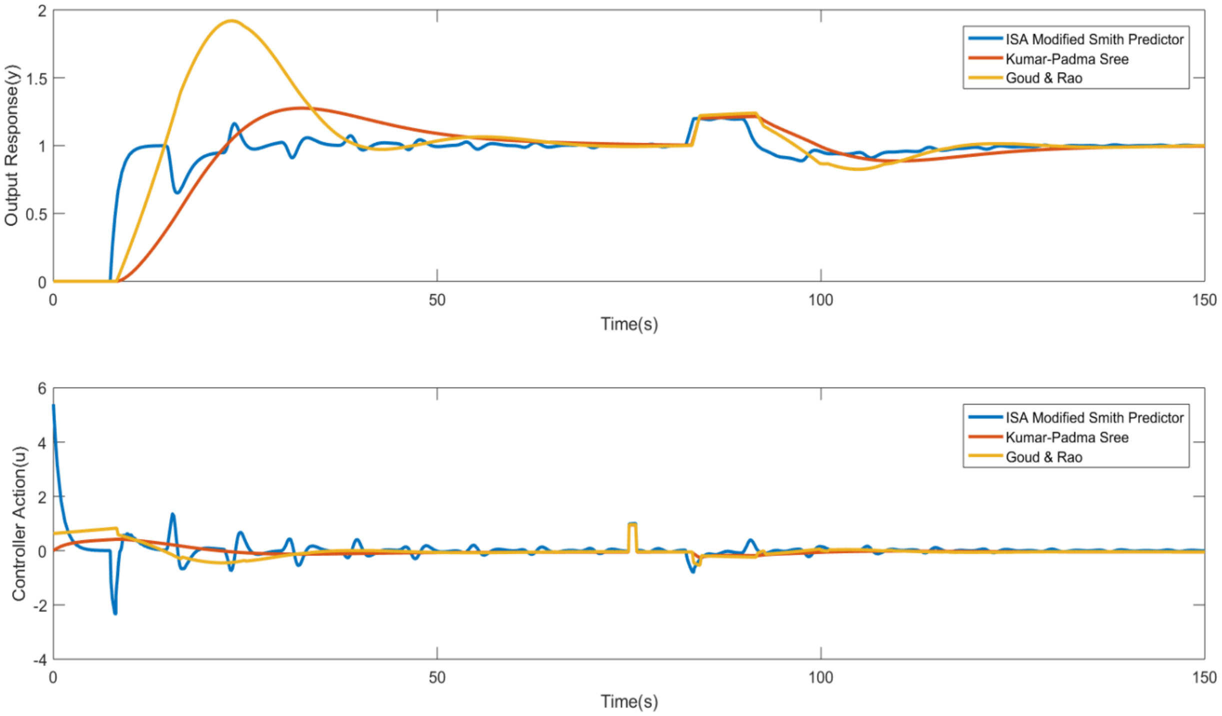



***Fig 5.17*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation for double disturbance (positive & negative)*

**Table 5.5** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 7.56 | 5.12 | 2.52 |
| Pm (Degrees) | 25.40 | 6.86 | 10.2 |
| Wco (rad/sec) | 0.93 | 0.12 | 0.19 |
| Wpm (rad/sec) | 0.09 | 0.07 | 0.14 |

**Table 5.8.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 2.06 | 10.11 | 4.99 |
| Settling Time (Sec) | 63.05 | 67.31 | 65.33 |
| Settling Min | 0.65 | 0.90 | 0.90 |
| Settling Max | 1.16 | 1.28 | 1.92 |
| Overshoot (%) | 16.08 | 27.58 | 91.94 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.16 | 1.28 | 1.94 |
| Peak Time (Sec) | 23.62 | 32.27 | 23.22 |

**Table 5.8.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | Kumar & Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.62 | 0.97 | 8.81 | 126.80 | 19.38 | 85.72 |
| **ITSE** | 2.70 | 34.77 | 161.48 | 12153.49 | 272.30 | 6700.35 |
| **IAE** | 2.76 | 5.60 | 22.18 | 88.17 | 25.40 | 67.03 |
| **ITAE** | 56.18 | 323.50 | 638.88 | 7525.23 | 449.63 | 4584.00 |
| **TV** | 16.73 | 32.09 | 13.53 | 38.07 | 18.77 | 38.83 |

**Table 5.8.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% time delay perturbation for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | Kumar & Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.62 | 0.64 | 8.81 | 9.52 | 19.38 | 20.15 |
| **ITSE** | 2.70 | 4.50 | 161.48 | 228.52 | 272.30 | 345.40 |
| **IAE** | 2.76 | 3.25 | 22.18 | 26.35 | 25.40 | 30.08 |
| **ITAE** | 56.18 | 104.90 | 638.88 | 1054.85 | 449.63 | 913.78 |
| **TV** | 16.73 | 20.95 | 13.53 | 15.42 | 18.77 | 21.21 |

### 5.5.3.2 Model 2

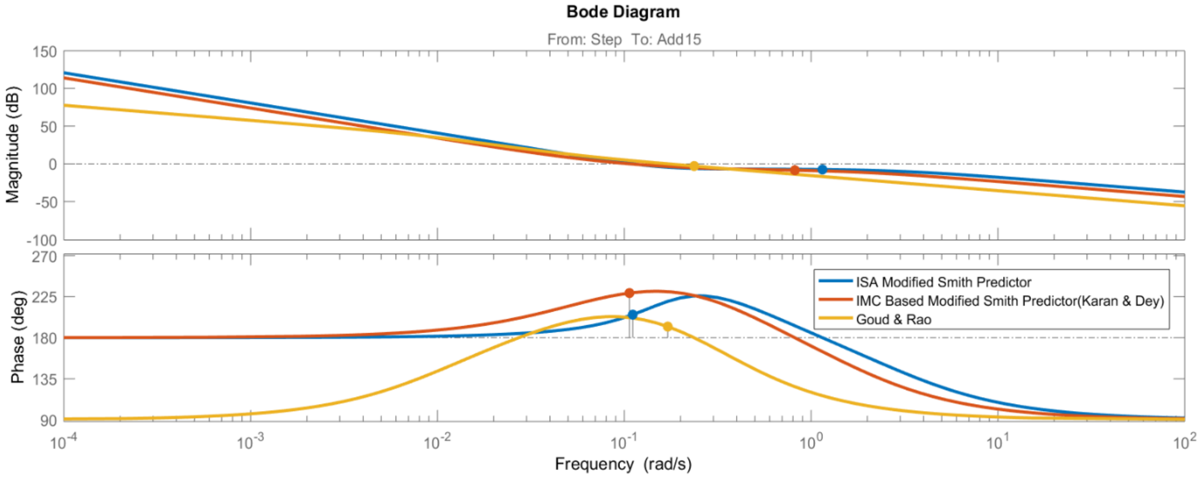



***Fig 5.18*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation*

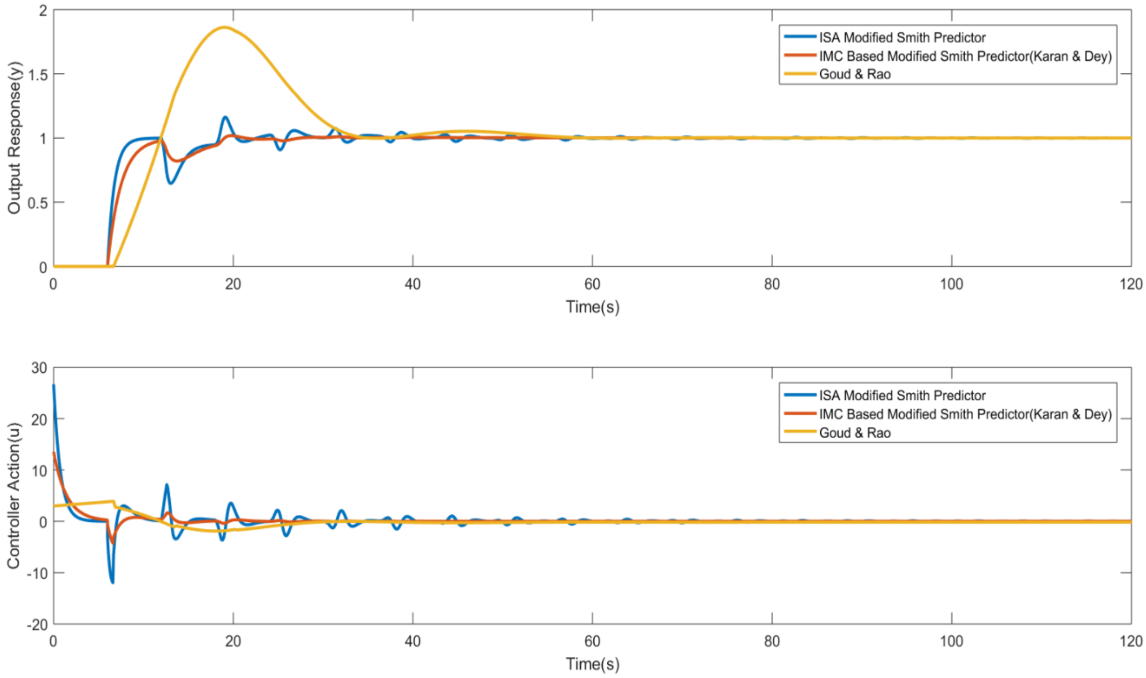



***Fig 5.19*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation*

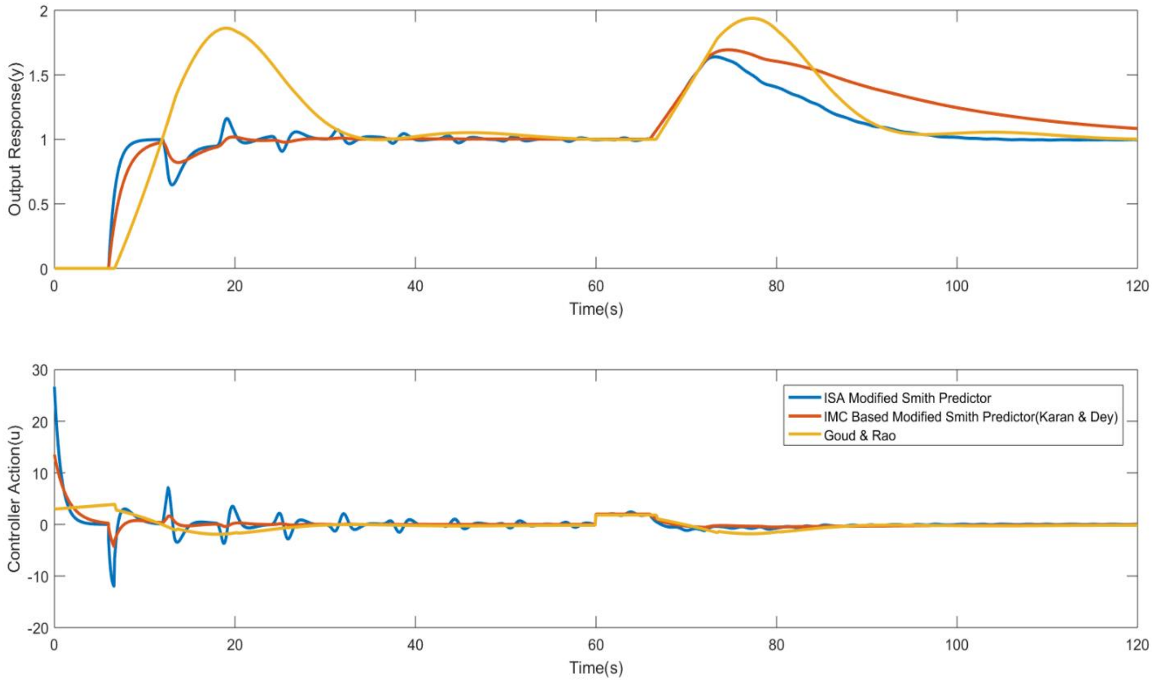



***Fig 5.20*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation for single disturbance (positive)l*

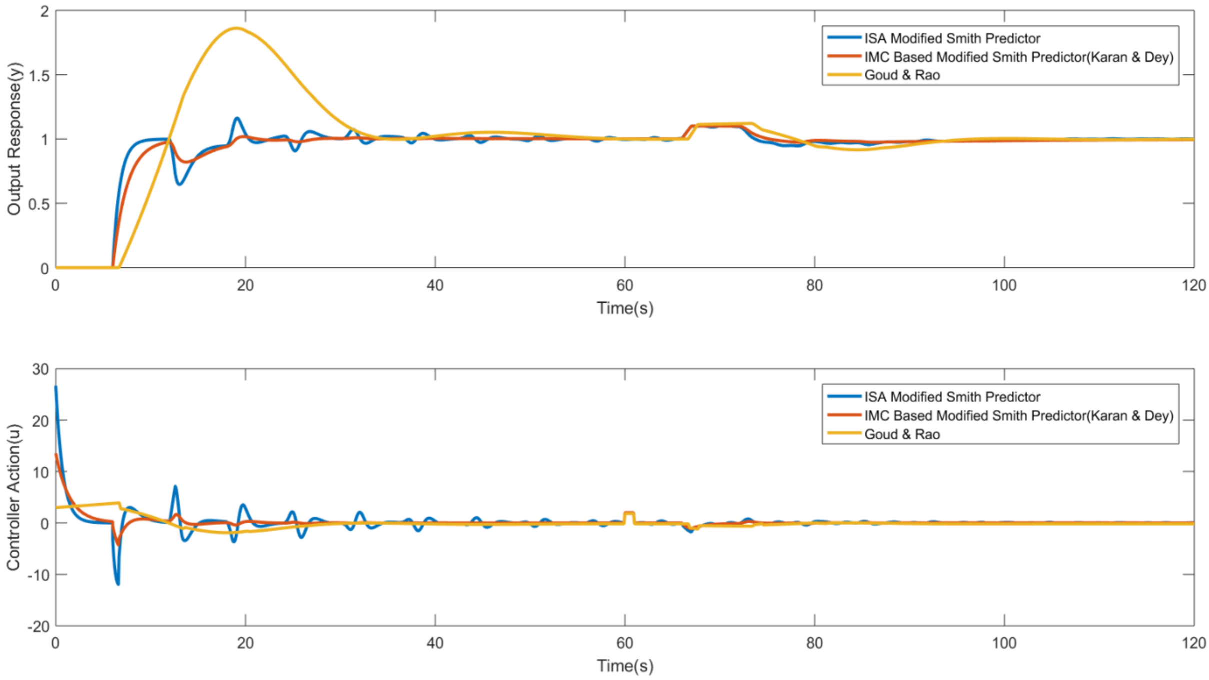



***Fig 5.21*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation for double disturbance (positive & negative)*

**Table 5.9** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 7.57 | 8.48 | 2.96 |
| Pm (Degrees) | 25.30 | 48.90 | 12.20 |
| Wco (rad/sec) | 1.15 | 0.81 | 0.24 |
| Wpm (rad/sec) | 0.111 | 0.10 | 0.17 |

**Table 5.10.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation

| Performance Index | Modified Smith Predictor | IMC Based Modified Smith Predictor (Karan & Dey) | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 1.66 | 3.32 | 4.20 |
| Settling Time (Sec) | 51.13 | 25.85 | 53.89 |
| Settling Min | 0.65 | 0.82 | 0.91 |
| Settling Max | 1.16 | 1.02 | 1.87 |
| Overshoot (%) | 16.36 | 1.82 | 86.19 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.16 | 1.02 | 1.86 |
| Peak Time (Sec) | 19.10 | 19.80 | 19.00 |

**Table 5.10.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.51 | 0.56 | 0.80 | 1.11 | 15.15 | 24.63 |
| **ITSE** | 1.84 | 5.28 | 0.99 | 25.72 | 169.60 | 909.2 |
| **IAE** | 2.27 | 3.16 | 2.10 | 5.58 | 20.29 | 34.83 |
| **ITAE** | 37.86 | 104.90 | 10.06 | 303.20 | 289.00 | 1454.00 |
| **TV** | 67.60 | 90.48 | 28.74 | 55.25 | 67.28 | 97.94 |

**Table 5.10.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% time delay perturbation for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.51 | 0.51 | 0.80 | 0.80 | 15.15 | 15.31 |
| **ITSE** | 1.84 | 2.07 | 0.99 | 1.46 | 169.60 | 181.50 |
| **IAE** | 2.27 | 3.25 | 2.10 | 2.38 | 20.29 | 22.18 |
| **ITAE** | 37.86 | 49.51 | 10.06 | 31.88 | 289.00 | 438.90 |
| **TV** | 67.60 | 74.34 | 28.74 | 34.30 | 67.28 | 70.96 |

### 5.5.4 Performance evaluation at +10% gain perturbation

Here the process gain was increased by 10%. So, the process gains for Model 1 and Model 2 became 0.22 and 0.055 respectively. It can be considered an extreme case of model time mismatch with respect to the practical world. Such a high value was chosen to test the limits of stability for all the control techniques applied. This process gain increase was applicable to only the process model and not the actual plant model in case of the Modified Smith Predictor. However, for single controller-based models, this perturbation was applied to the process gain in the forward path.

#### 5.5.4.1 Model 1

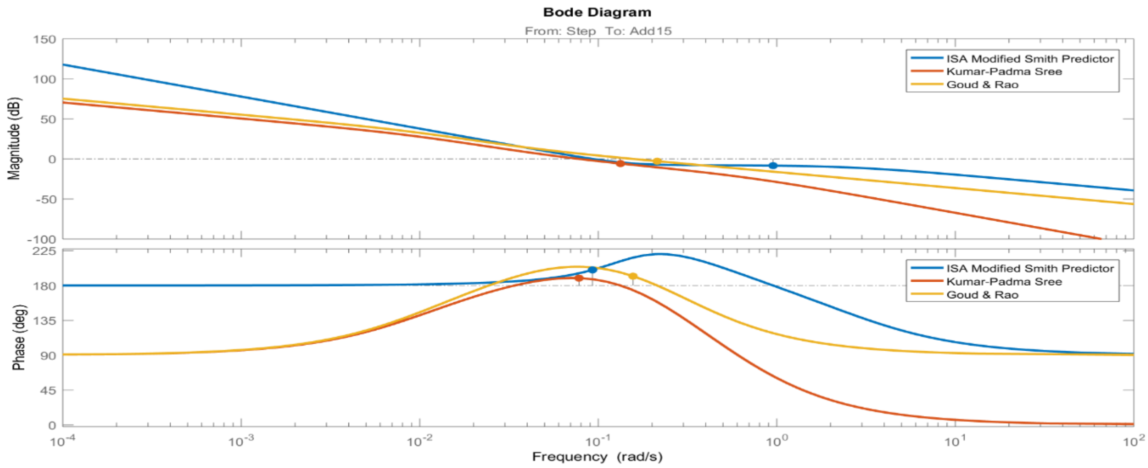



***Fig 5.22*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation*

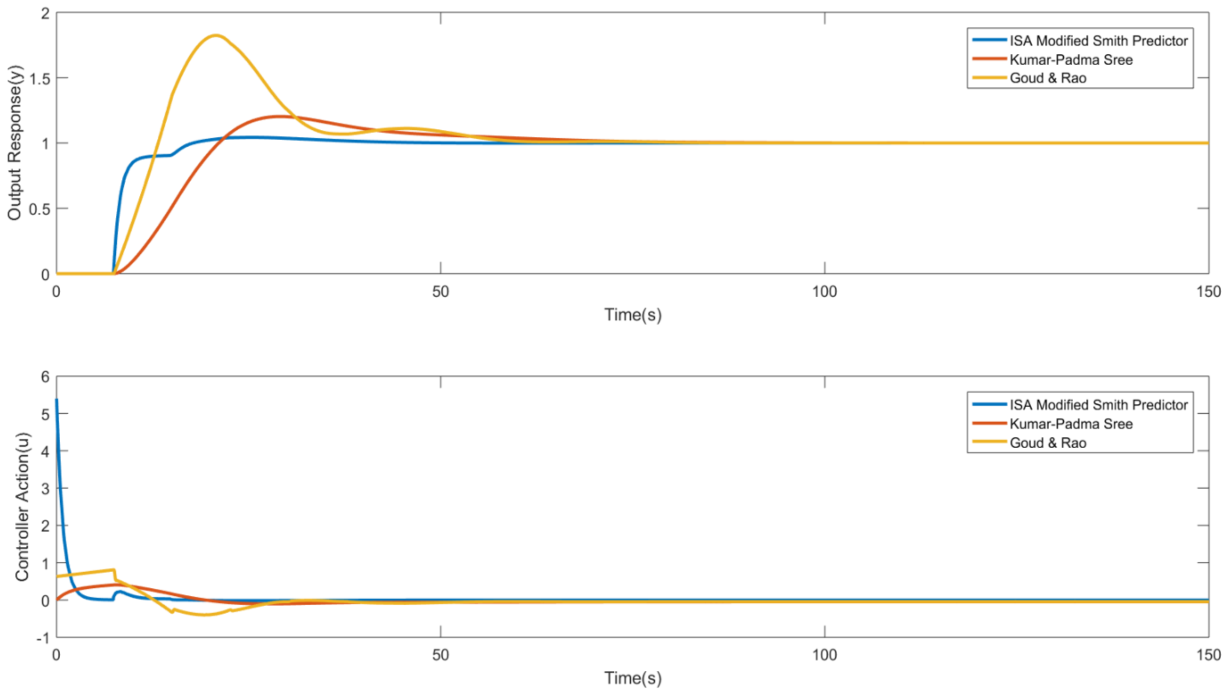



***Fig 5.23*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation*

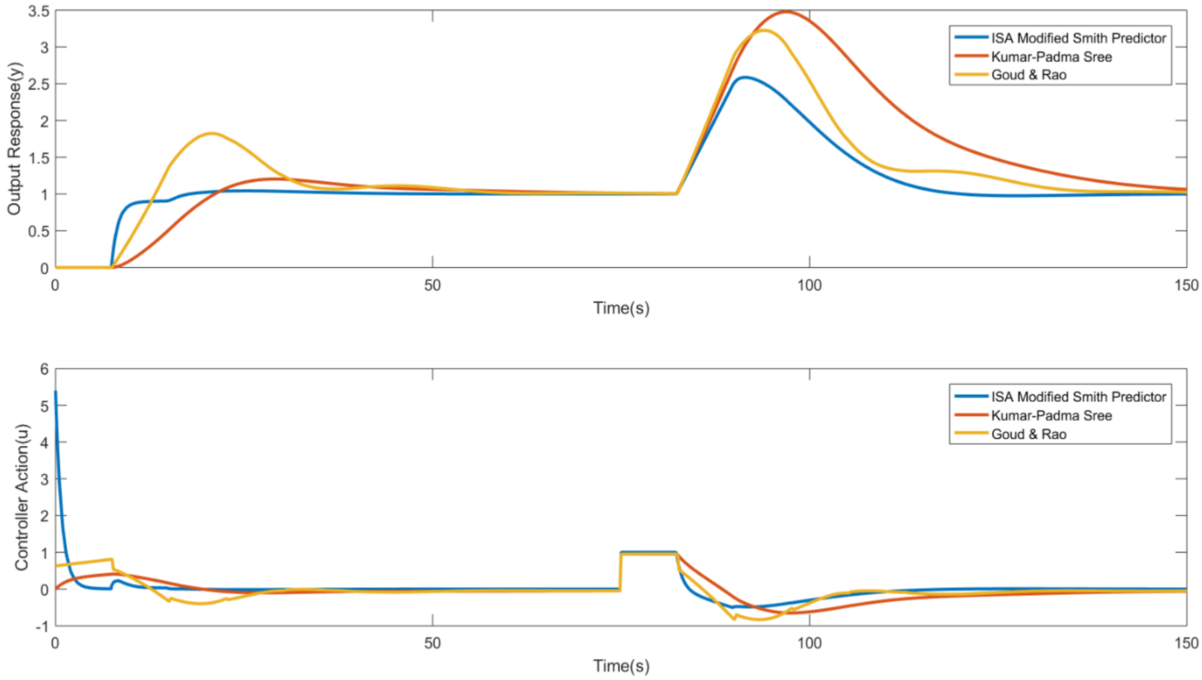



***Fig 5.24*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation for single disturbance (positive)l*

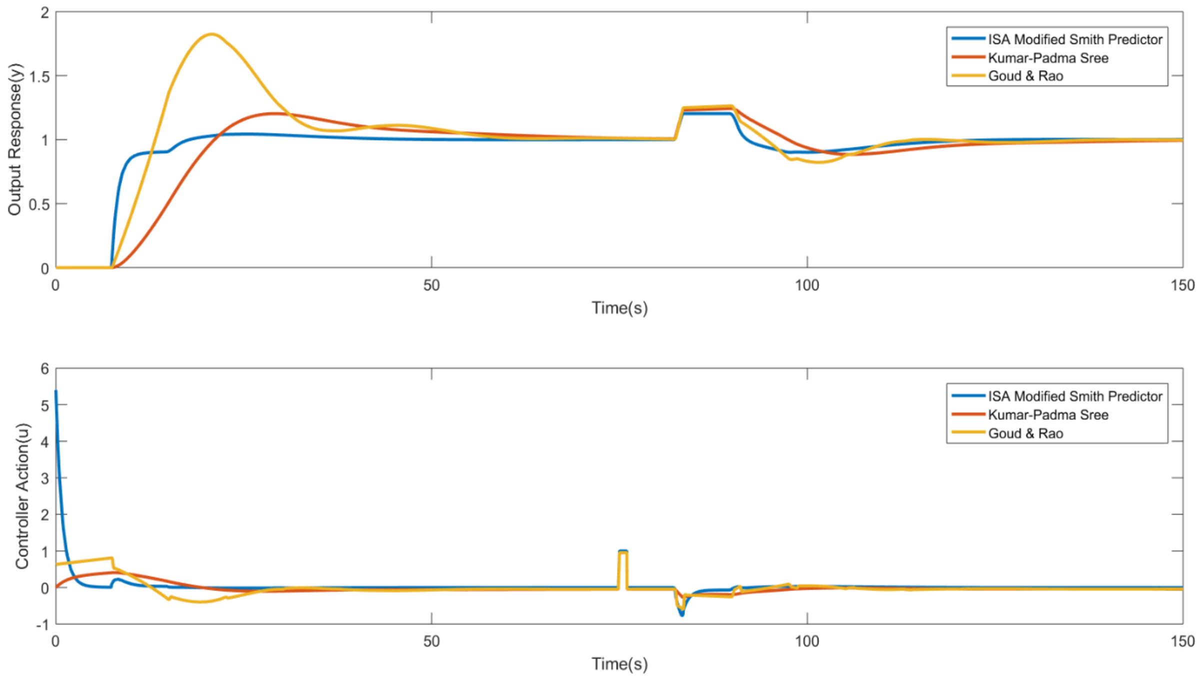



***Fig 5.25*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation for double disturbance (positive & negative)*

**Table 5.11** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation

| Parameter | Modified Smith Predictor | Kumar & Padma Sree | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 8.39 | 5.58 | 1.38 |
| Pm (Degrees) | 20.10 | 9.54 | 12.06 |
| Wco (rad/sec) | 0.95 | 0.13 | 0.21 |
| Wpm (rad/sec) | 0.09 | 0.08 | 0.16 |

**Table 5.12.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation

| Parameter | Modified Smith Predictor | Kumar - Padma Sree | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 5.33 | 9.58 | 4.59 |
| Settling Time (Sec) | 36.08 | 68.39 | 58.23 |
| Settling Min | 0.90 | 0.90 | 0.91 |
| Settling Max | 1.04 | 1.20 | 1.82 |
| Overshoot (%) | 4.30 | 20.30 | 82.34 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.04 | 1.20 | 1.82 |
| Peak Time (Sec) | 25.41 | 29.14 | 20.76 |

**Table 5.12.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation for single disturbance (positive)l

| **Performance Index** | **Modified Smith Predictor** | | **Kumar - Padma Sree** | | **Goud & Rao** | |
|---|---|---|---|---|---|---|
| | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** |
| **ISE** | 0.43 | 0.82 | 7.39 | 117.30 | 15.95 | 75.52 |
| **ITSE** | 0.22 | 35.49 | 119.99 | 11122.88 | 188.96 | 5873.86 |
| **IAE** | 1.09 | 4.03 | 20.14 | 85.47 | 22.81 | 64.30 |
| **ITAE** | 4.01 | 278.30 | 576.44 | 7375.49 | 387.49 | 4507.12 |
| **TV** | 5.44 | 21.54 | 11.82 | 33.99 | 16.42 | 34.39 |

**Table 5.12.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation for double disturbance (positive & negative)

| **Performance Index** | **Modified Smith Predictor** | | **Kumar - Padma Sree** | | **Goud & Rao** | |
|---|---|---|---|---|---|---|
| | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** | **Without Load Disturbance** | **With Load Disturbance** |
| **ISE** | 0.43 | 0.45 | 7.39 | 8.17 | 15.95 | 16.74 |
| **ITSE** | 0.22 | 1.41 | 119.99 | 191.12 | 188.96 | 261.81 |
| **IAE** | 1.09 | 1.46 | 20.14 | 24.20 | 22.81 | 82.24 |
| **ITAE** | 4.01 | 38.50 | 576.44 | 973.41 | 387.49 | 819.51 |
| **TV** | 5.44 | 8.494 | 11.82 | 13.77 | 16.42 | 19.00 |

### 5.5.4.2 Model 2

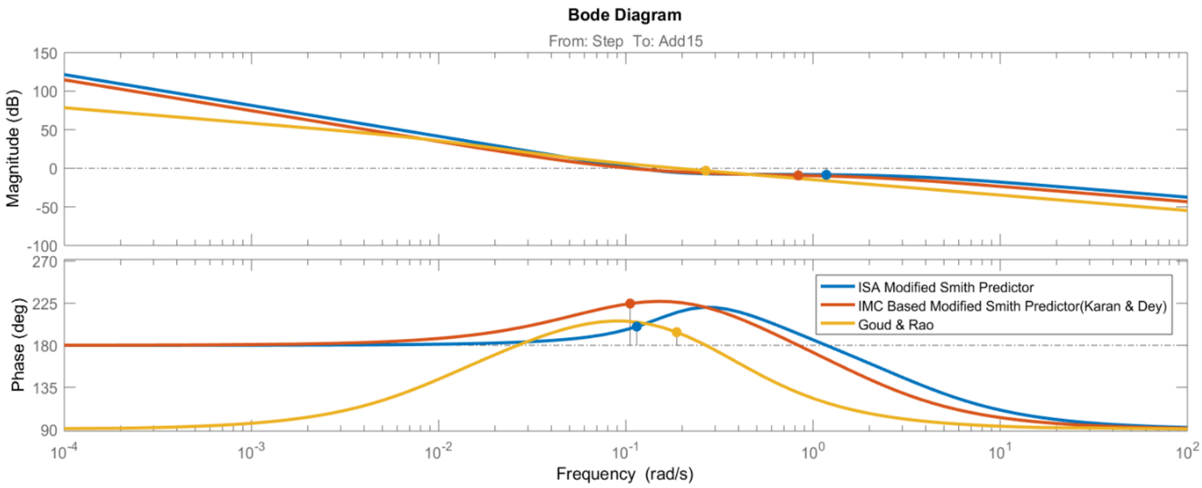



***Fig 5.26*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation*

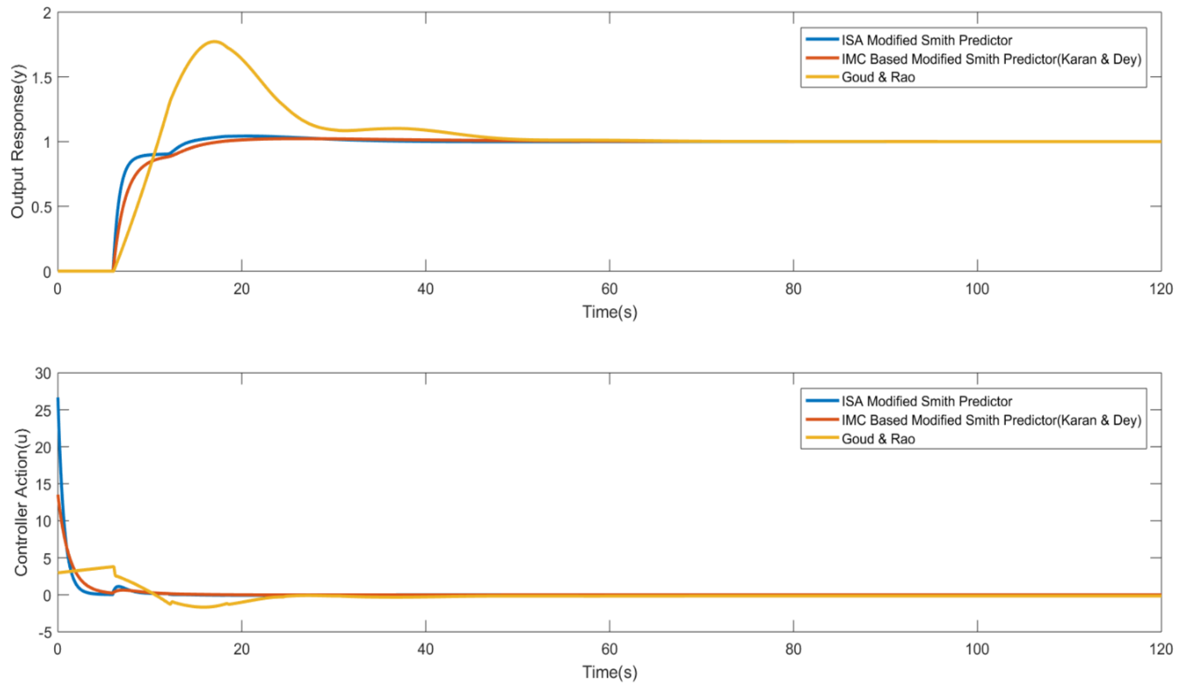



**Fig 5.27** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation

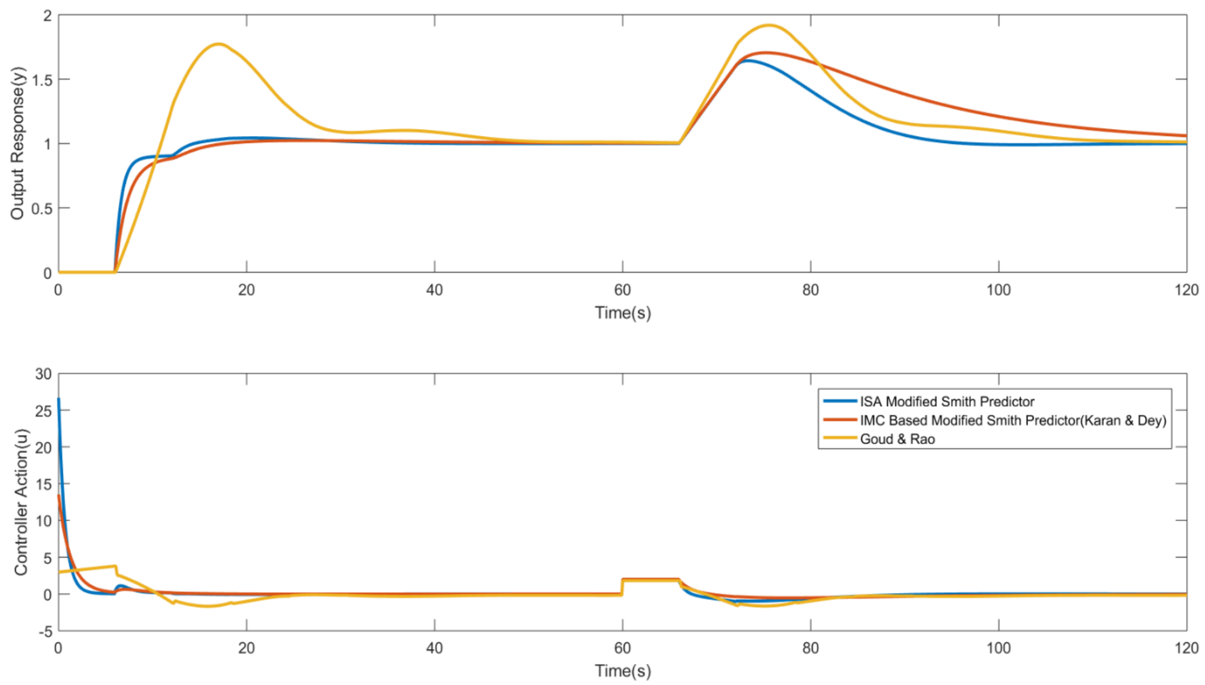



***Fig 5.28*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation for single disturbance (positive)l*

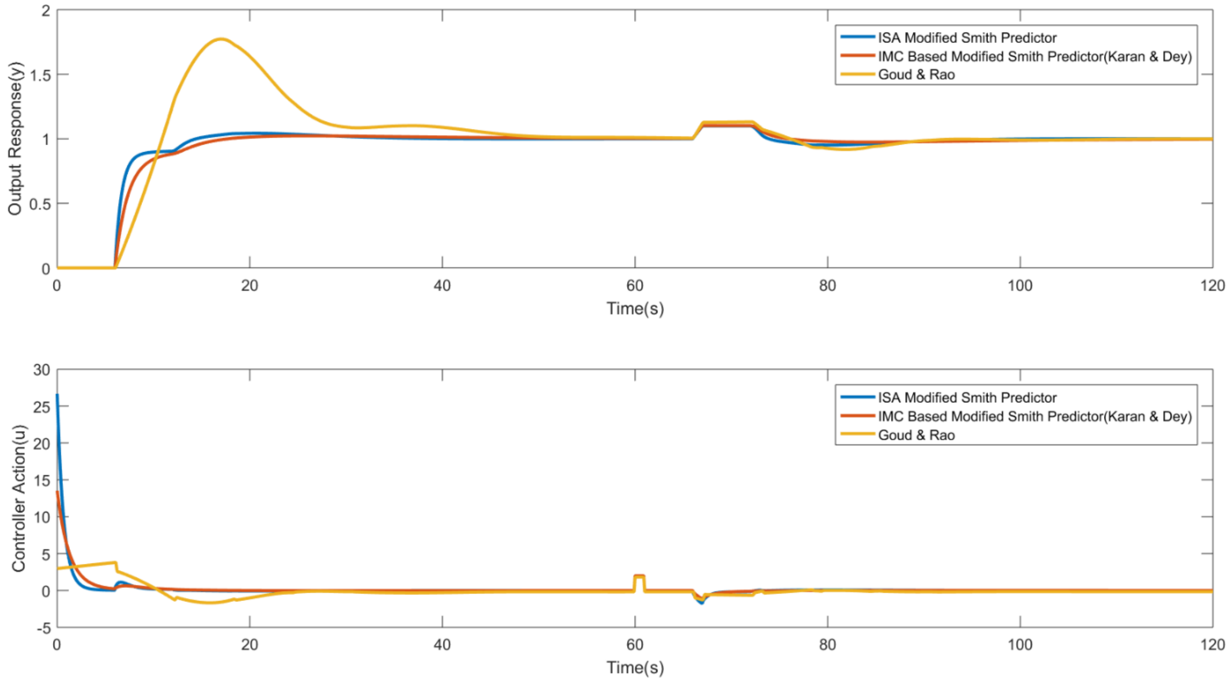



***Fig 5.29*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation for double disturbance (positive & negative)*

**Table 5.13** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation

| Parameter | Modified Smith Predictor | IMC Based Modified Smith Predictor (Karan & Dey) | Goud & Rao |
|---|---|---|---|
| Gm (dB) | 8.39 | 9.27 | 3.23 |
| Pm (Degrees) | 20.10 | 44.60 | 14.00 |
| Wco (rad/sec) | 1.18 | 0.83 | 0.27 |
| Wpm (rad/sec) | 0.11 | 0.11 | 0.19 |

**Table 5.14.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation

| Parameter | Modified Smith Predictor | IMC Based Modified Smith Predictor (Karan & Dey) | Goud & Rao |
|---|---|---|---|
| Rise Time (Sec) | 4.51 | 6.55 | 3.86 |
| Settling Time (Sec) | 29.31 | 31.24 | 49.01 |
| Settling Min | 0.90 | 0.90 | 0.91 |
| Settling Max | 1.04 | 1.02 | 1.77 |
| Overshoot (%) | 4.29 | 2.27 | 77.24 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.04 | 1.02 | 1.77 |
| Peak Time (Sec) | 20.70 | 25.90 | 17.00 |

**Table 5.14.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation for single disturbance (positive)l

| Parameter | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.35 | 0.40 | 0.71 | 1.05 | 12.59 | 21.18 |
| **ITSE** | 0.15 | 3.97 | 0.58 | 27.79 | 119.30 | 779.90 |
| **IAE** | 0.89 | 1.86 | 1.76 | 5.32 | 18.48 | 32.95 |
| **ITAE** | 2.68 | 75.63 | 8.19 | 305.40 | 259.50 | 1419.00 |
| **TV** | 21.74 | 47.86 | 20.91 | 48.19 | 58.77 | 86.31 |

**Table 5.14.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation for double disturbance (positive & negative)

| Parameter | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.35 | 0.35 | 0.71 | 0.71 | 12.59 | 12.74 |
| **ITSE** | 0.15 | 0.32 | 0.58 | 1.00 | 119.30 | 130.80 |
| **IAE** | 0.89 | 1.04 | 1.76 | 2.022 | 18.48 | 20.27 |
| **ITAE** | 2.68 | 13.78 | 8.19 | 29.02 | 259.50 | 398.80 |
| **TV** | 21.74 | 27.73 | 20.91 | 25.88 | 58.77 | 62.62 |

### 5.5.5 Performance evaluation at +10% gain perturbation and +10% time delay perturbation

Here both the time delay and process gain were increased by 10%. It can be considered the most extreme case of model time mismatch with respect to the practical world. Such a high value was chosen to test the limits of stability for all the control techniques applied. This process gain and time delay increase was applicable to only the process model and not the actual plant model in case of the Modified Smith Predictor. However, for single controller-based models, this perturbation was applied to the process gain and time delay in the forward path.

#### 5.5.5.1 Model 1

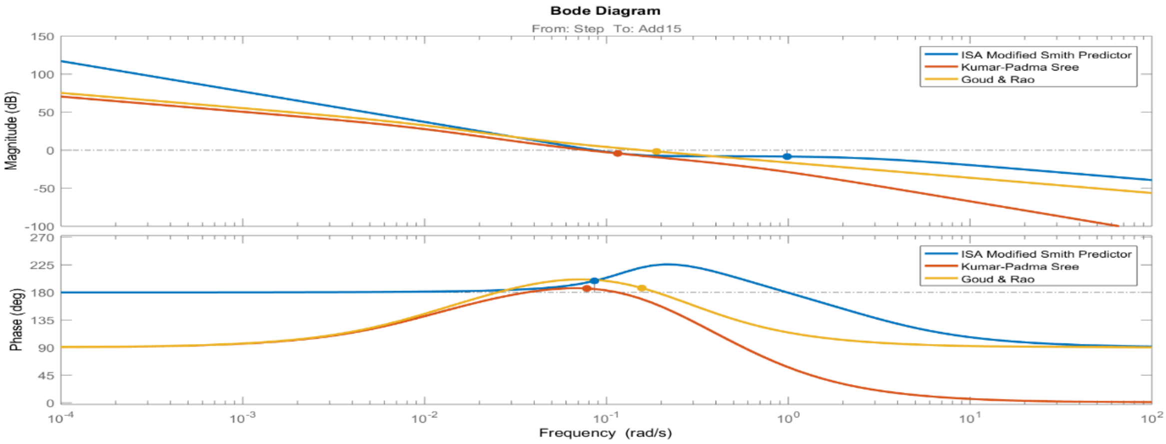



***Fig 5.30*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% perturbation in process gain and time delay*

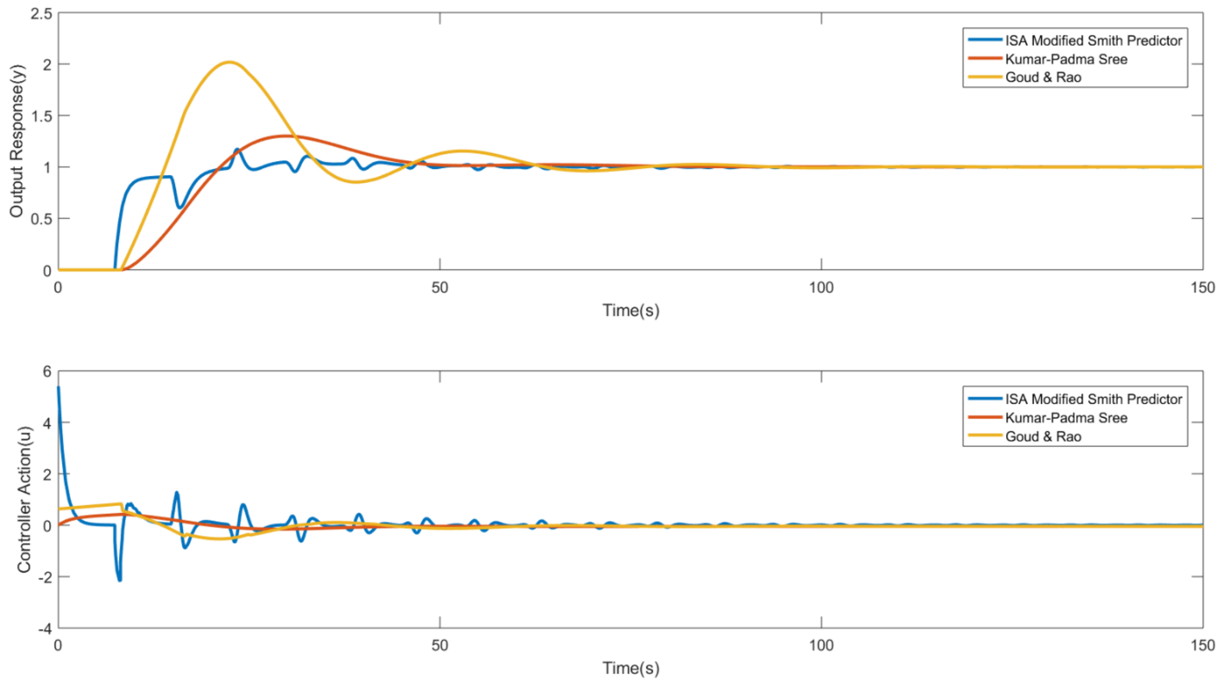



***Fig 5.31*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% perturbation in process gain and time delay*

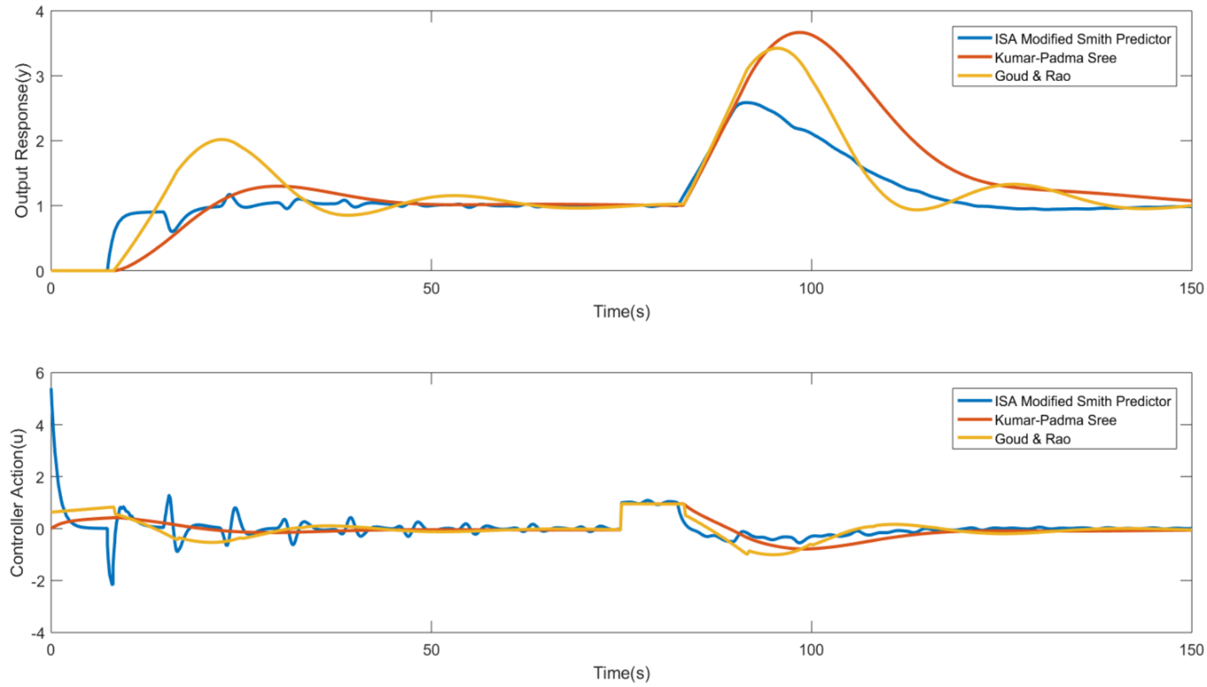



***Fig 5.32*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% perturbation in process gain and time delay for single disturbance (positive)l*

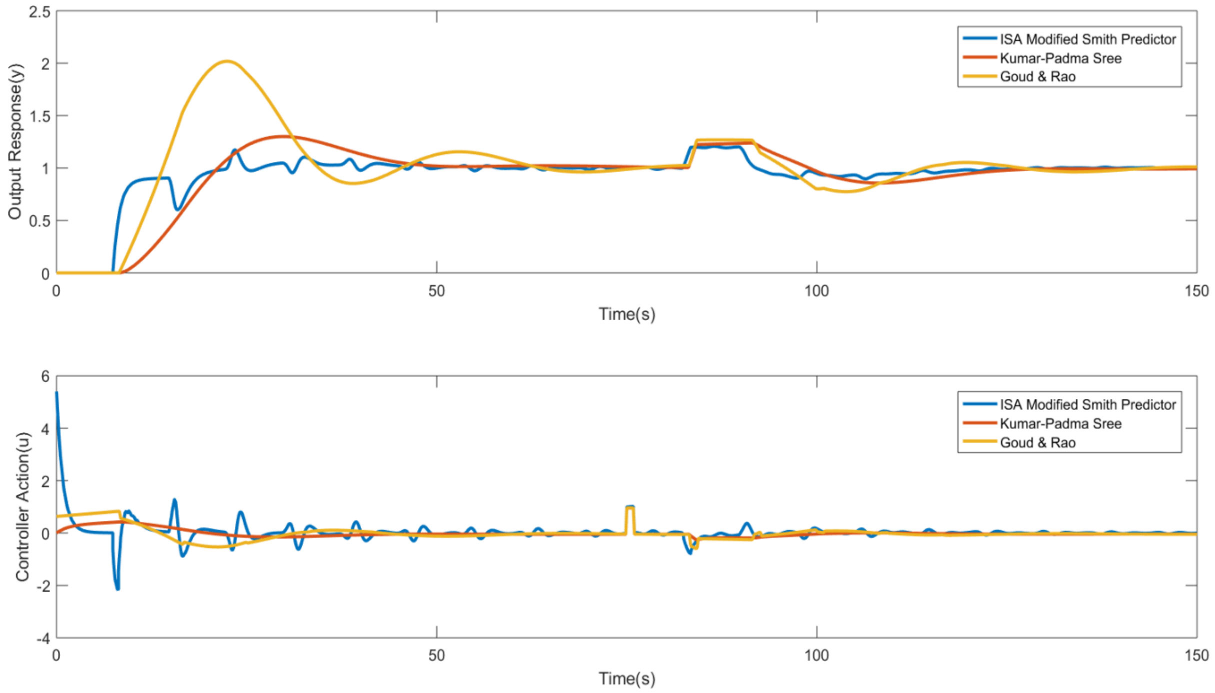



***Fig 5.33*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% perturbation in process gain and time delay for double disturbance (positive & negative)*

**Table 5.15** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation and +10% time delay perturbation

| **Parameter** | **Modified Smith Predictor** | **Kumar - Padma Sree** | **Goud & Rao** |
|---|---|---|---|
| Gm (dB) | 8.38 | 4.29 | 1.21 |
| Pm (Degrees) | 18.80 | 6.51 | 7.19 |
| Wco (rad/sec) | 0.99 | 0.12 | 0.19 |
| Wpm (rad/sec) | 0.09 | 0.08 | 0.16 |

**Table 5.16.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation and +10% time delay perturbation

| **Parameter** | **Modified Smith Predictor** | **Kumar - Padma Sree** | **Goud & Rao** |
|---|---|---|---|
| Rise Time (Sec) | 5.44 | 9.21 | 4.59 |
| Settling Time (Sec) | 62.67 | 68.70 | 86.85 |
| Settling Min | 0.60 | 0.90 | 0.85 |
| Settling Max | 1.17 | 1.30 | 2.02 |
| Overshoot (%) | 17.21 | 30.02 | 101.75 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.17 | 1.30 | 2.02 |
| Peak Time (Sec) | 23.41 | 29.77 | 22.45 |

**Table 5.16.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation and +10% time delay perturbation for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | Kumar - Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.58 | 0.96 | 8.54 | 128.10 | 20.36 | 90.06 |
| **ITSE** | 2.74 | 36.79 | 145.46 | 12138.08 | 293.03 | 7005.46 |
| **IAE** | 2.81 | 5.80 | 21.23 | 86.33 | 27.17 | 69.31 |
| **ITAE** | 61.15 | 343.6 | 589.14 | 7346.58 | 546.11 | 4747.64 |
| **TV** | 16.97 | 32.61 | 12.65 | 36.24 | 19.35 | 40.52 |

**Table 5.16.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 1 with +10% process gain perturbation and +10% time delay perturbation for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | Kumar - Padma Sree | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.58 | 0.60 | 8.54 | 9.41 | 20.36 | 21.46 |
| **ITSE** | 2.74 | 4.49 | 145.46 | 226.69 | 293.03 | 397.71 |
| **IAE** | 2.81 | 3.301 | 21.23 | 25.61 | 27.17 | 32.83 |
| **ITAE** | 61.15 | 109.50 | 589.14 | 1018.15 | 546.11 | 1118.76 |
| **TV** | 16.97 | 21.18 | 12.65 | 14.59 | 19.35 | 22.50 |

### 5.5.5.2 Model 2

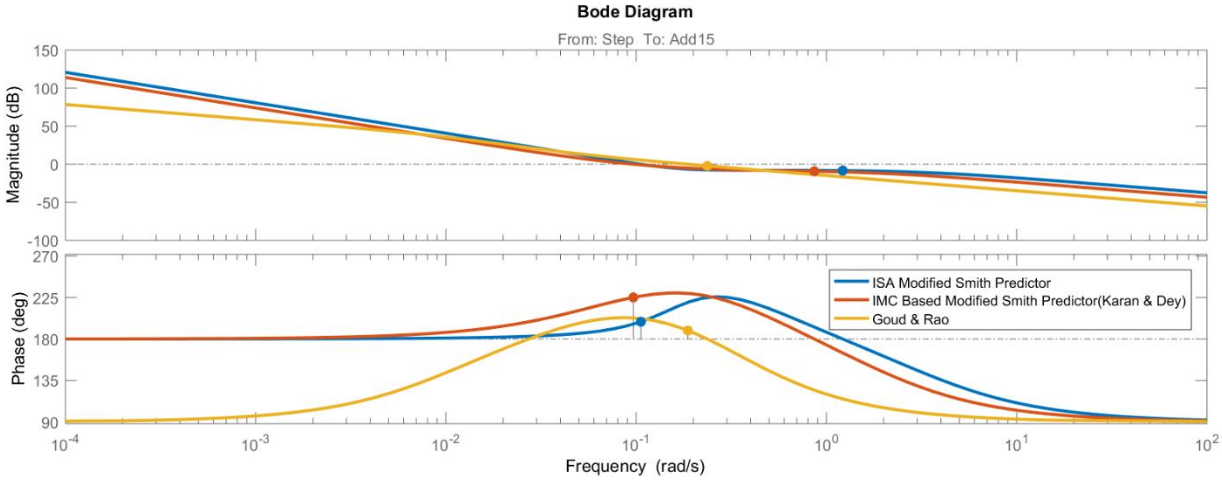



***Fig 5.34*** *Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% perturbation in process gain and time delay*

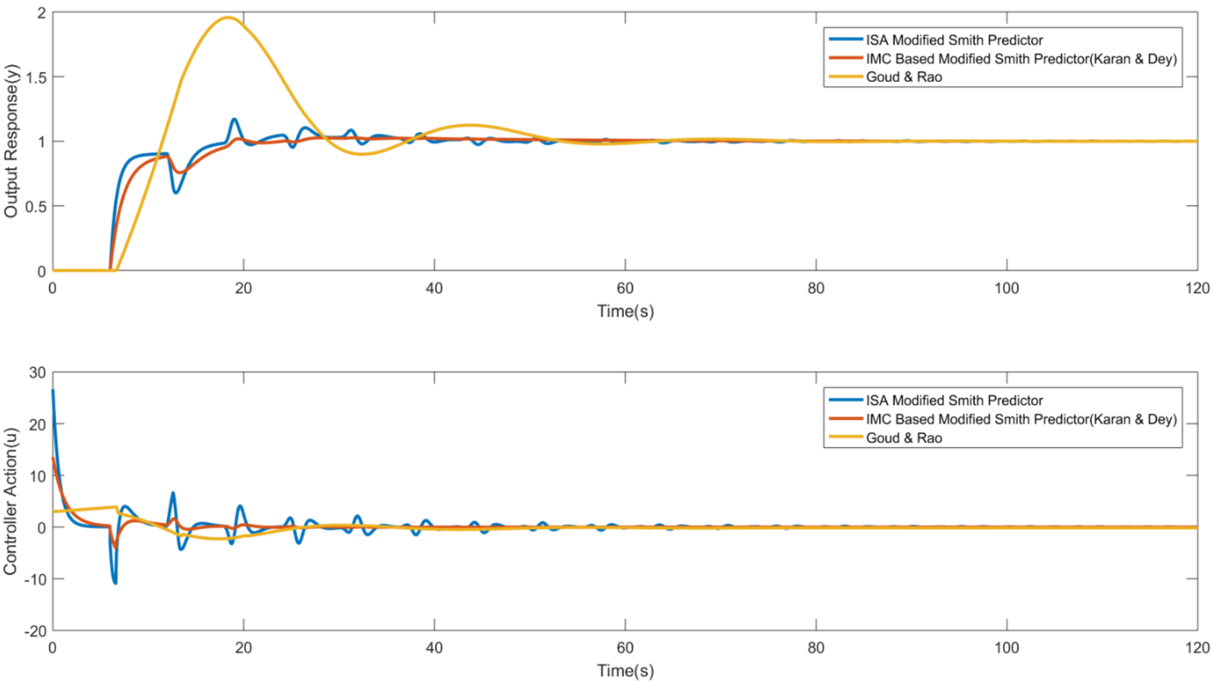



***Fig 5.35*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% perturbation in process gain and time delay*

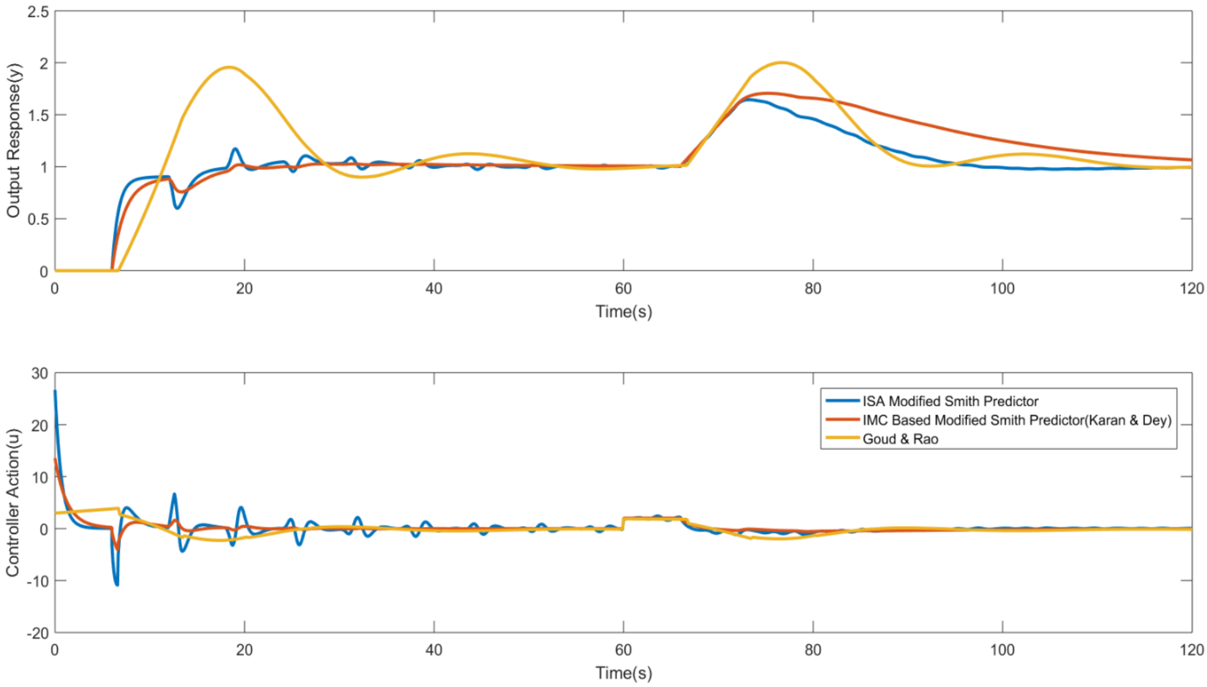



***Fig 5.36*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% perturbation in process gain and time delay for single disturbance (positive)l*

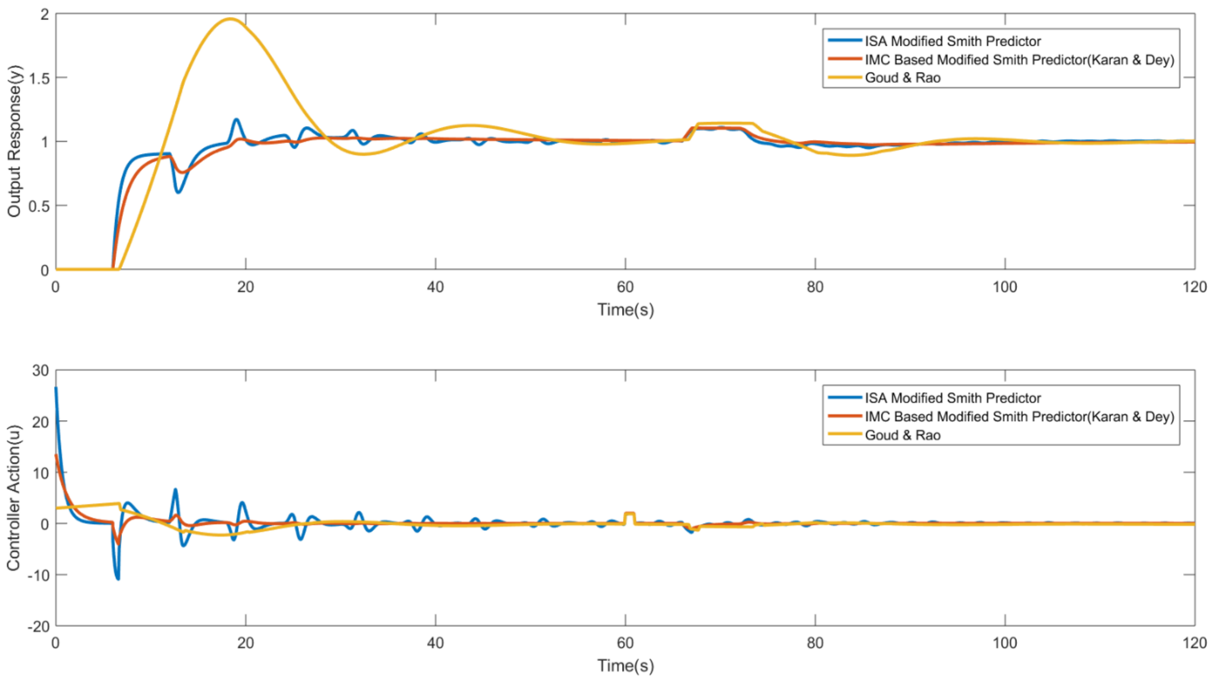



***Fig 5.37*** *Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% perturbation in process gain and time delay for double disturbance (positive & negative)*

**Table 5.17** Frequency domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation and +10% time delay perturbation

| **Parameter** | **Modified Smith Predictor** | **IMC Based Modified Smith Predictor (Karan & Dey)** | **Goud & Rao** |
|---|---|---|---|
| Gm (dB) | 8.38 | 9.30 | 2.13 |
| Pm (Degrees) | 18.70 | 45.10 | 9.18 |
| Wco (rad/sec) | 1.22 | 0.86 | 0.24 |
| Wpm (rad/sec) | 0.11 | 0.10 | 0.19 |

**Table 5.18.1** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation and +10% time delay perturbation

| **Parameter** | **Modified Smith Predictor** | **IMC Based Modified Smith Predictor (Karan & Dey)** | **Goud & Rao** |
|---|---|---|---|
| Rise Time (Sec) | 4.38 | 10.11 | 3.86 |
| Settling Time (Sec) | 50.83 | 40.46 | 58.75 |
| Settling Min | 0.60 | 0.90 | 0.90 |
| Settling Max | 1.17 | 1.03 | 1.96 |
| Overshoot (%) | 17.31 | 2.68 | 95.63 |
| Undershoot (%) | 0.00 | 0.00 | 0.00 |
| Peak | 1.17 | 1.03 | 1.96 |
| Peak Time (Sec) | 19.00 | 31.50 | 18.40 |

**Table 5.18.2** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation and +10% time delay perturbation for single disturbance (positive)l

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.48 | 0.53 | 0.75 | 1.09 | 15.74 | 25.70 |
| **ITSE** | 1.83 | 5.52 | 0.99 | 27.91 | 177.80 | 949.00 |
| **IAE** | 2.30 | 3.24 | 2.20 | 5.79 | 21.10 | 35.52 |
| **ITAE** | 40.82 | 111.5 | 14.27 | 315.3 | 325.70 | 1481.00 |
| **TV** | 68.13 | 91.35 | 28.08 | 55.28 | 68.32 | 98.77 |

**Table 5.18.3** Time domain performance index analysis of the Modified Smith Predictor and recently published works for model 2 with +10% process gain perturbation and +10% time delay perturbation for double disturbance (positive & negative)

| Performance Index | Modified Smith Predictor | | IMC Based Modified Smith Predictor (Karan & Dey) | | Goud & Rao | |
|---|---|---|---|---|---|---|
| | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance | Without Load Disturbance | With Load Disturbance |
| **ISE** | 0.48 | 0.60 | 0.75 | 9.41 | 15.74 | 21.46 |
| **ITSE** | 1.83 | 4.49 | 0.99 | 226.69 | 177.80 | 397.71 |
| **IAE** | 2.30 | 3.301 | 2.20 | 25.61 | 21.10 | 32.83 |
| **ITAE** | 40.82 | 109.50 | 14.27 | 1018.15 | 325.70 | 1118.76 |
| **TV** | 68.13 | 21.18 | 28.08 | 14.59 | 68.32 | 22.50 |

## 5.6 Robustness and stability analysis

**Table 5.19** Robustness and Stability Limits

| Model | Complementary Sensitivity Function (CSF) C (jω) | Process gain perturbation (ΔK) | Stability with gain perturbation $\|C(j\omega)\|_\infty < \left(\frac{1}{\frac{\Delta K}{K}}\right)$ | Time delay perturbation ($\theta_m$) | Stability with time delay perturbation $\|C(j\omega)\|_\infty < \left(\frac{1}{\frac{-j\omega\theta m}{j\omega\frac{\theta m}{2}+1}}\right)$ |
|---|---|---|---|---|---|
| $\frac{0.2}{s}e^{-7.4s}$ | $\frac{7.44\,j\omega+2}{1.38j\omega^2+9.3j\omega+2}$ | 0.16 (+80%) | $\|C(j\omega)\|_\infty < \left(\frac{1}{0.80}\right)$ | 0.296 (+%4) | $\|C(j\omega)\|_\infty < \left(\frac{j0.148\omega+1}{-j0.296\omega}\right)$ |
| $\frac{0.05}{s}e^{-6s}$ | $\frac{6.4\,j\omega+2}{0.256j\omega^2+8j\omega+2}$ | 0.035 (+70%) | $\|C(j\omega)\|_\infty < \left(\frac{1}{0.70}\right)$ | 0.06 (+%1) | $\|C(j\omega)\|_\infty < \left(\frac{j0.3\omega+1}{-j0.06\omega}\right)$ |

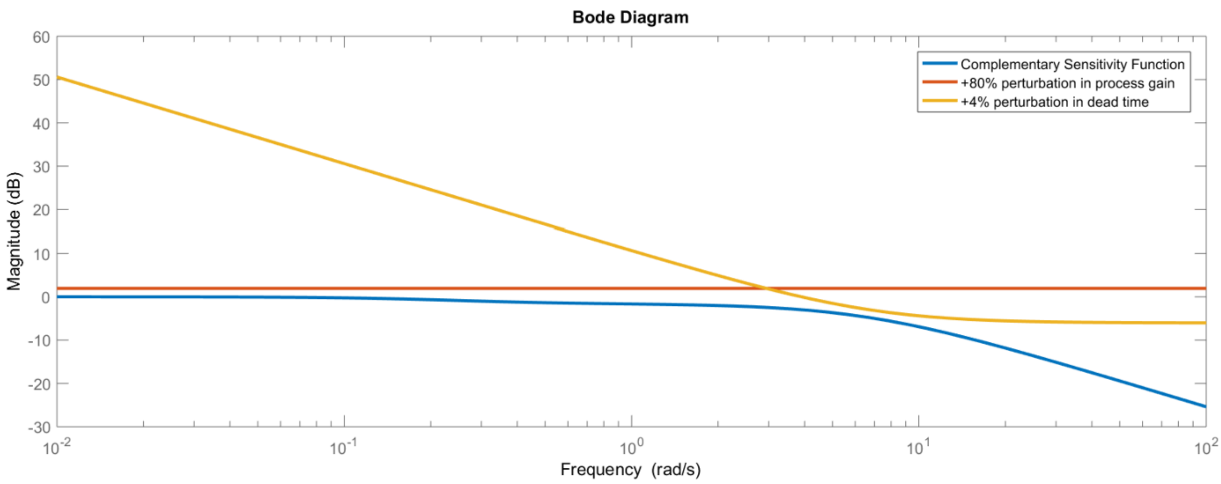
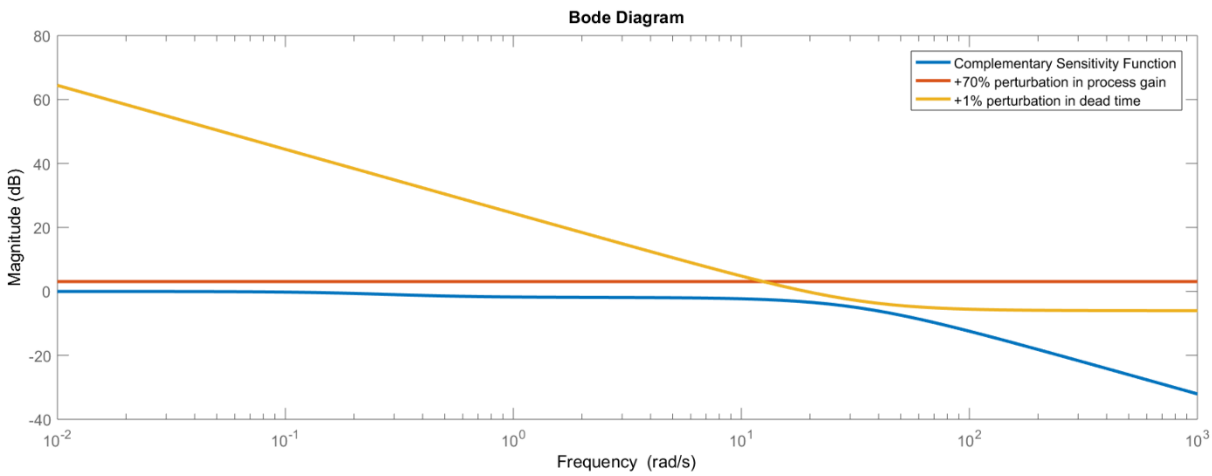



*Fig 5.38 Stability Analysis for model 1 (above) and model 2 (below)*



## 5.7 Observation

The Modified Smith Predictor control techniques are capable of providing better performance than the conventional Smith Predictor control technique in terms of closed-loop response and performances. This augmentation provides the better results for the integral and unstable processes, where the conventional technique fails to perform satisfactorily. However, for both the techniques the almost similar strategy is realized to eliminate the dead time but in different manners. For the Modified Smith Predictor control technique, the focus is more towards elimination of the disturbances. The Modified Smith Predictor was found to provide performance and stability along with robustness compared to conventional control policies in presence of model perturbations.

## 5.8 Future scope

In this report, a number of recently published works along with well accepted findings on Modified Smith Predictors have been evaluated in terms of time domain and frequency domain performance indices. Till there is some scope to further improve the tuning of Modified Smith Predictor so that one can ascertain desired closed loop performance with some auto-tuning feature in presence of large load disturbances and significant model uncertainties.

# Conclusion

In this project, the various strategies for dead time compensation have been discussed. It involves evaluating the performances offered by conventional tuning techniques, Smith Predictor control technique and Modified Smith Predictor control techniques. The objective is to get a proper understanding of the working of time delay or dead time and the methods of compensation in the virtual environment of Simulink and its parallels practical world.

For the long-dead time processes, the effectiveness of the Smith Predictor control technique is found to be the maximum when compared to other conventional and model-based tuning control methods. In many instances, it was not possible to create a suitable control loop using traditional methods. Even if possible, the results were unsatisfactory after an intense performance analysis and thus not applicable in the virtual environment, let alone the real world. This effect was greatly amplified when perturbations in process gain and time delay were introduced to simulate model mismatch.

However, the Smith Predictor control technique was unable to compensate for the large overshoot, the longer settling time and disturbances to the process. Hence modifications were added, in the form of properly tuned multiple controller loops to make it tackle these issues.

The Modified Smith Predictor was finally evaluated taking all the latest control methods for some of the more complex long time-delay integrating processes available in the industry such as heat exchangers and distillation columns.

Finally, suggestions were made to improve this control technique. This involves getting a better understanding of all the disturbances that may affect the process in the real world and incorporating them into the model as far as possible. Auto-tuning was suggested for even more robust control.

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