

## A COMPARATIVE STUDY OF PID CONTROLLER TUNING TECHNIQUES FOR TIME DELAY PROCESSES

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*The Proportional-Integral-Derivative (PID) controllers are used in process/plant for controlling their parameters such as thermal or, electrical conductivity. By adjusting three parameters of PID controller, both transient and steady response can be improved, and better output can be obtained. There are many PID controller tuning techniques available in the literature and designing PID controllers for small delay processes with specified gain and phase margin is a well-known design technique. If the gain margin and phase margin are not specified, the system may not be optimum. A system with large gain and phase margins is more robust and gives better performance. When the system is robust, there will be no effect of slight changes in system parameters on the system performance. This paper describes a comparative analysis, among different types of tuning techniques available for first order plus delay time systems (FOPDT) on the basis of the various time integral performance criteria such as ISE, IAE, ITAE and gain margin and phase margin. This review concludes that 'Chien-Hrones-Reswick (CHR) no overshoot set point' method provides the best results.*

**Keywords:** PID controller, tuning method, performance index, robustness

### 1. Introduction

Proportional-Integral-Derivative (PID) type controllers are widely used in many industrial processes like temperature, pressure and flow control processes. The PID controllers are very simple in structure and easy to tune. By adjusting three parameters of a PID controller, both transient and steady response can be improved, and better output can be obtained using it. These controllers are also used in a wide range of applications such as flight control, motor drive, instrumentation, etc.

If the parameters of the PID controller are tuned in the proper way, it provides robust and reliable performance. Most of the industrial processes such as chemical processes have a different kind of non-linearities, and inherent dead time

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involved. The existence of nonlinearity in the process makes the controller tuning difficult.

There are many tuning formulas available for the design of PID controllers [1]–[3]. The first PID controller was developed by Minorsky [4] by which ship steering was controlled and in 1934 he also developed the first tuning technique for the PID controller of an integrating plus dead time process. In 1940 mechanical controls like hydraulic and pneumatic were used in industry [5]. The advantage of these controllers is their ruggedness, but they are lower in response.

Introducing the electronic controllers, the systems became much faster than in the case of mechanical control. The size of the electronics controller is less because of the small size of the electronic components but, it has the disadvantage that it is very sensitive to temperature. To overcome this problem, in 1980 a flexible digital PID controller was integrated into a control system [6]. In present days the complex control logic of electronic controllers is replaced by programming [7]. The researchers are still trying to find out the best tuning techniques for the PID controller. Several advancements have been done for PID controller design such as adaptive PID control [8] automatic tuning PID control [9] and intelligent PID control [10]. In an industrial application such as a medium chemical plant, more than 98% of the controllers are of PID type because of its previous successful track record [11]–[13].

In conventional PID control, the manual tuning technique is time-consuming and it also depends upon process knowledge of the operator. The comparison of several PID tuning rules is discussed in [14] and the survey of a different patent for PID controller is presented in [15].

The design and process analysis of a model such as a first-order process with a delay time (FOPDT) representing widely thermal and chemical processes are given in [16]. The delay time also known as dead time occurs due to the involvement of transport lag. The delay causes a decrease in the phase margin and a more oscillatory closed-loop response. If the gain margin is decreased the system will move towards instability [17]. Recently, numerous PID tuning techniques have been floated in the literature in the diverse field [18]–[21].

The different types of tuning techniques of optimal design of PID controllers applied to a FOPDT process have been considered in the present work and the techniques are compared on performance basis i.e. rise time, overshoot, settling time, Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), etc. The effect of disturbance rejection and instability introduced by the delay time has also been compared for different tuning techniques. System robustness is compared on the basis of gain margin and phase margin for different methods.

The contents of this paper have been organized as follows. Some well-known, classical tuning techniques of the PID controller are discussed in Section

2. The result and discussion about the time domain specification by minimizing performance index criteria are given in Section 3 and the final conclusion is given in Section 4.

## 2. Classical Tuning Methods of PID Controller:

There are two methods of PID tuning: (i) open loop (ii) closed loop. The block diagram of closed loop feedback PID control is shown in Fig 1. The open loop technique is being used when controllers have manual state and plant works in the open loop condition. The closed-loop method is used to tune the controller during an automatic state when the plant operates in the closed loop condition. There are several types of tuning techniques of the PID controller in present control literature and most of the tuning technique can be applied to the first order plus delay time (FOPDT) process. The FOPDT plant most commonly used in the chemical process [22]. In this paper close loop method with following general FOPDT process transfer function has been considered.

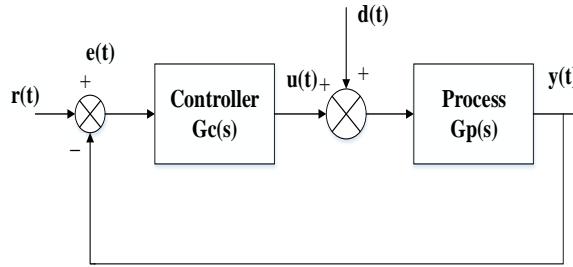


Fig. 1. Classical feedback control structure

$$G_p(s) = \frac{Ke^{-sL}}{Ts + 1} \quad (1)$$

where  $K$  is the process gain,  $L$  is the delay time and  $T$  is the time constant of the system. In the frequency domain the FOPDT system can be represented as:

$$G_p(jw) = \frac{Ke^{-(jw)L}}{T(jw) + 1} \quad (2)$$

The transfer function of the general PID controller is:

$$G_c(s) = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right) \quad (3)$$

The above transfer function can also be written as:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad (4)$$

## 2.1 Ziegler-Nichols Method (Z-N)

A very useful tuning method was presented by Ziegler and Nichols[23] in 1942. The Z-N method is of two types - one is based on the reaction curve of the system and another one depends upon the ultimate gain  $K_u$  and the ultimate period  $T_u$ . When the step response of the plant exhibits an S-shape curve with zero overshoot then the reaction curve method is applied. The reaction curve is characterized by two constant parameters - the delay time  $L$  and the time constant  $T$ . The second method considers trial and error tuning which is based on proportional gain  $K_p$ ; by increasing the value of  $K_p$  output exhibit oscillation. This rule works well only when the delay time is less than half the length of the time constant. The disadvantage of this technique is that it is time-consuming and not applicable for first and second order without time delay processes because some process does not have an ultimate gain. This method performs well in disturbance rejection, but it is poor in tracking reference change.

## 2.2 Cohen-Coon Method

A few sets of tuning rules for the PID controller were proposed by Cohen and Coon [24]. This method is based on a process reaction curve and can be applied to the first order plus delay time (FOPDT) system. It is well suited to a process where the delay time is less than two times the length of the time constant.

## 2.3 Internal Model Control (IMC)

There are many methods of tuning IMC-PID but the first method was developed by Morari et al. [25] which is called as an internal model controller. This method works on model-based control technique. The advantage of this approach is a good setpoint tracking, but sluggish disturbance response especially when the process has small “delay time”/“time constant” ratio. This is not desirable for industrial processes because, for many control process applications, disturbance rejection is more important than set point tracking [26]. The general block diagram of the IMC based approach is shown in Fig 2.

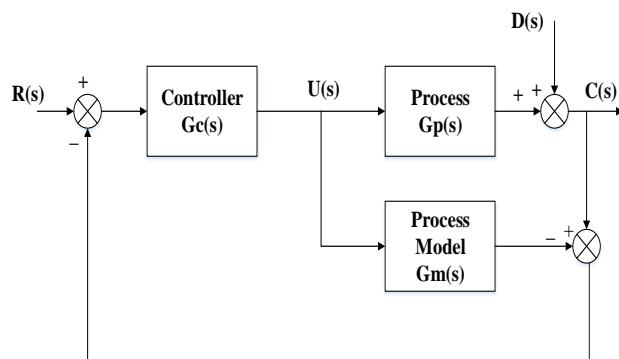


Fig. 2: Basic block diagram of an internal model control

In this diagram, the controller  $G_c(s)$  is used to control the process  $G_p(s)$  and the process model  $G_m(s)$ ,  $D(s)$  is the unknown disturbance. The settings of IMC- PID are given in [14] where  $\lambda$  is a closed loop time constant and the controller works differently for different value of  $\lambda$ . Here  $\lambda=0.25$  is selected for the controller tuning.

#### 2.4 Gain, Phase Margin Method (GP)

Gain margin and phase margin specifications are a well-known design technique of PID controller. The gain and phase margin exhibit the robustness of the system. This method was firstly proposed by Astrom [27] but it may not produce a satisfactory performance with large time delay, which results in oscillatory close loop response. Further Hangm et al. [28] proposed integral performance criteria, which gives better-closed loop response but the disadvantage of this method was that the transfer function has to be available. To overcome this problem a new tuning formula was given by Zhuang and Atherton [29] where both gain and phase margins are optimized.

#### 2.5 Optimum PID Tuning for SetPoint Changes and Disturbance Rejection

The shape of the system closed loop response from initial state  $t=0$  to the final state could be used to find the exact controller setting. These rules are used to derive an optimum tuning value of PID controller parameters to minimize Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Integral Square Time Error (ISTE), Integral Square Time Square Error (IST2E) performance criteria. These tuning formulas were found by Zhuang and Atherton [29]. IAE is good to eliminate small errors, but it produces a slower response and it does not add weight to any of the errors in system response. ISE will tolerate small errors for a long period of time, low amplitude and oscillation. To overcome this disadvantage ITAE and ISTE performance criteria are used which settle faster as compared to the previous two methods because they integrate the absolute value of error multiplied by the time [30]. The different performance criteria are given as

$$IAE = \int_0^t |e(t)| dt \quad (5)$$

$$ISE = \int_0^t e^2(t) dt \quad (6)$$

$$ITAE = \int_0^t t|e(t)|dt \quad (7)$$

$$ISTE = \int_0^t t^2 e(t) dt \quad (8)$$

$$IST^2E = \int_0^t t^2 e^2(t) dt \quad (9)$$

## 2.6 Chien-Hrones-Reswick (CHR) PID Tuning

This method was proposed by Chien et al. [31], which focuses on the important observation on set point (S.P) response and disturbance rejection. It is a modified form of the open loop Z-N method and uses the quickest response with 0% overshoot or quickest response with 20% overshoot as a design criterion. The CHR tuning formula based on 20% overshoot design criteria is quite same as the Ziegler-Nichols tuning method. But when designing on the criteria of 0% overshoots, the proportional gain  $K_p$  and the derivative time  $T_d$  both were smaller, the integral time  $T_i$  was larger as compared to the Z-N method. It means all these three parameters are smaller. Table 1 is used to get the controller parameter, where  $T$  is the time constant,  $L$  is the delay time,  $K$  is the gain and the value of the constant  $a=KL/T$ .

## 2.7 Wang-Juang-Chan (W.J.C) Tuning

This tuning formula is based on optimum ITAE Criterion. It was proposed by Wang et al.[32]. It is a very simple and efficient method to find out PID parameters. If the parameters of the plant are known i.e.  $K$  the plant gain,  $L$  the time delay and  $T$  the time constant, the parameters of the controller are

$$K_p = \frac{(0.7303 + \frac{0.5307T}{L})(T + 0.5L)}{k(T + L)} \quad (10)$$

$$T_i = T + 0.5L \quad (11)$$

$$T_d = \frac{0.5LT}{(T + 0.5L)} \quad (12)$$

## 2.8 Robust PID Controller

A robust controller deals with plant uncertainty. If there is a slight change in gain  $K$ , time constant  $T$  and delay time  $L$ , the robust controller will provide uncertainty and achieves robustness and stability. Parada et al. [33] proposed a

robust algorithm for designing PID parameter for the FOPDT system but this technique is complex itself. A simple and effective technique based on the  $H\infty$  control theory for PID controller design was given by Liu and Wang [34]. The performance of PID is determined by taking two different values of the tunable parameter  $\lambda$  as 0.1 and 0.3 respectively.

$$G_c(s) = K_p \left( 1 + \frac{1}{T_i s} + \frac{T_d s}{T_f s + 1} \right) \quad (13)$$

The PID parameters are

$$T_f(s) = \frac{\lambda^2}{2\lambda + \frac{L}{2}} \quad (14)$$

$$K_p(s) = \frac{T_i}{k(2\lambda + L/2)} \quad (15)$$

$$T_i = T + \frac{L}{2} - T_f \quad (16)$$

$$T_d = \frac{TL}{2T_i} - T_f \quad (17)$$

### 3. Simulation Result Discussions

The following FOPDT process has been considered here [14], [35], [36]

$$G_p(s) = \frac{1}{s+1} e^{-0.5s} \quad (18)$$

The different types of tuning techniques of the PID controller have been implemented to FOPDT process with a unit step input. The step responses of the Wang-Juang-Chan (WJC) Tuning, Chien-Hrones-Reswick (CHR) no overshoot set point, robust  $H\infty$ , optimum tuning technique, i.e. IAE set point and ISE set point are shown in fig 3. It is clear, that the WJC tuning technique provides lower rise time and lower settling time with zero overshoot.

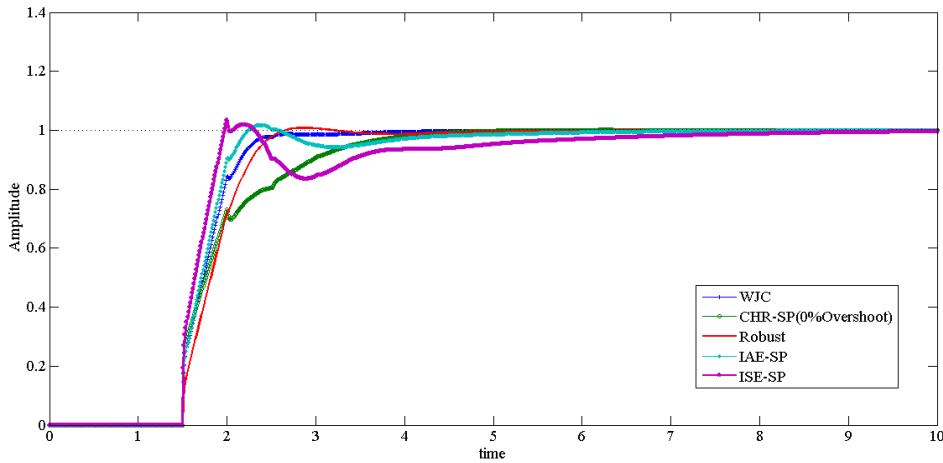


Fig. 3: Step response with different PID controllers of the original system, when delay  $L=0.5$

A comparison of controllers in time domain specifications taking rise time, settling time and maximum overshoot using different PID tuning techniques, has been shown in table 2. The values of  $K_p$ ,  $K_i$  &  $K_d$  using different PID tuning methods, are also mentioned in table 2.

When the delay is increased by 50%, Table 2 provides the transient behavior of the plant for the same tuning parameter of PID. It can be observed from Fig 4 that CHR tuning technique for set point (S.P) with zero overshoot provides higher rise time, but lower settling time and minimum overshoot as compared to other techniques.

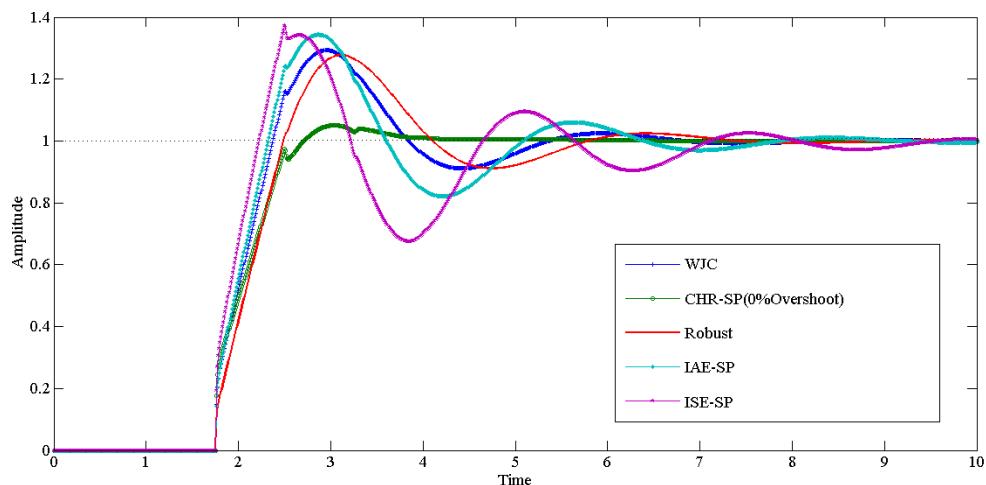


Fig. 4: Step response with different PID controllers when delay increased by 50% ( $L=0.75$ )

The WJC technique is close to the robust controller, but it has lower rise time, lower overshoot, as well as lower settling time as compared to optimum tuning technique i.e. IAE, set point and ISE set point.

When the delay is decreased by 50%, Fig. 5 shows zero overshoot, but the WJC technique is one of the best tuning techniques because it gives lower rise and settling time as compared to other tuning techniques like robust controller, CHR set point regulation with 0% and 20% overshoot and IAE set point.

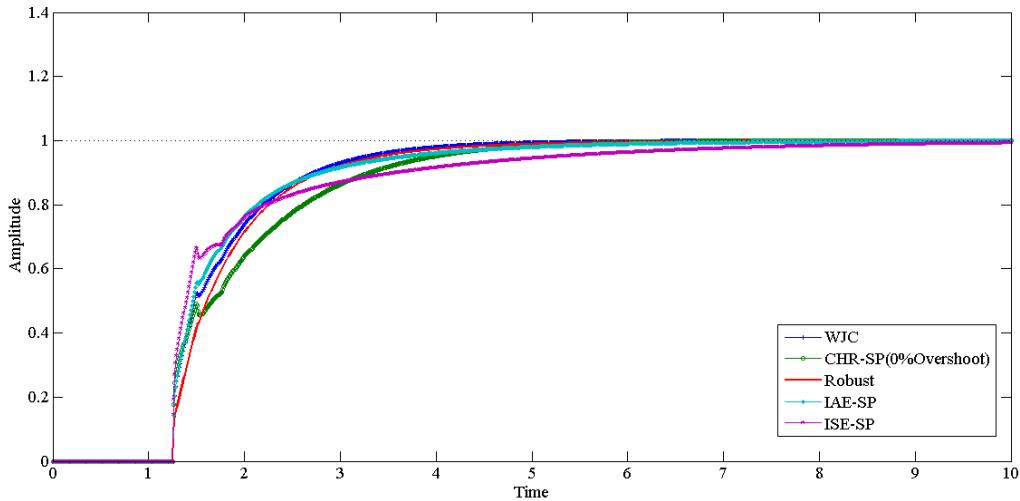


Fig. 5: Step response with different PID controllers when delay decreased by 50% ( $L=0.25$ )

The comparative analysis of performance index criteria such as Integral Square Error (ISE), Integral Absolute Value of the Error (IAE) and Integral of Time-Weighted Absolute Error (ITAE) is shown in Table 3. For the original process and when the delay time is increased and decreased by 20%, it can be observed that by using CHR set point 0% overshoot design technique performance index is minimum.

The comparison of controller tuning techniques in the frequency domain is done in Table 4. where gain margin and phase margin play a vital role in measuring the robustness and performance of the system. The higher the gain and phase margin, the higher will be the robustness of the system [35]. The oscillatory magnitude response of the controllers is shown in Fig. 6 and 7; it can be observed that all controllers are stable.

As shown in fig 8, with 50% deviation in delay time  $L$  from their value because of external disturbances and model uncertainty, the closed loop response of CHR set point (S.P.) has no overshoot, is stable, whereas WJC, robust controller, IAE set point has more overshoot resulting in an unstable system. It also observed that CHR set point 0% overshoot has larger robustness.

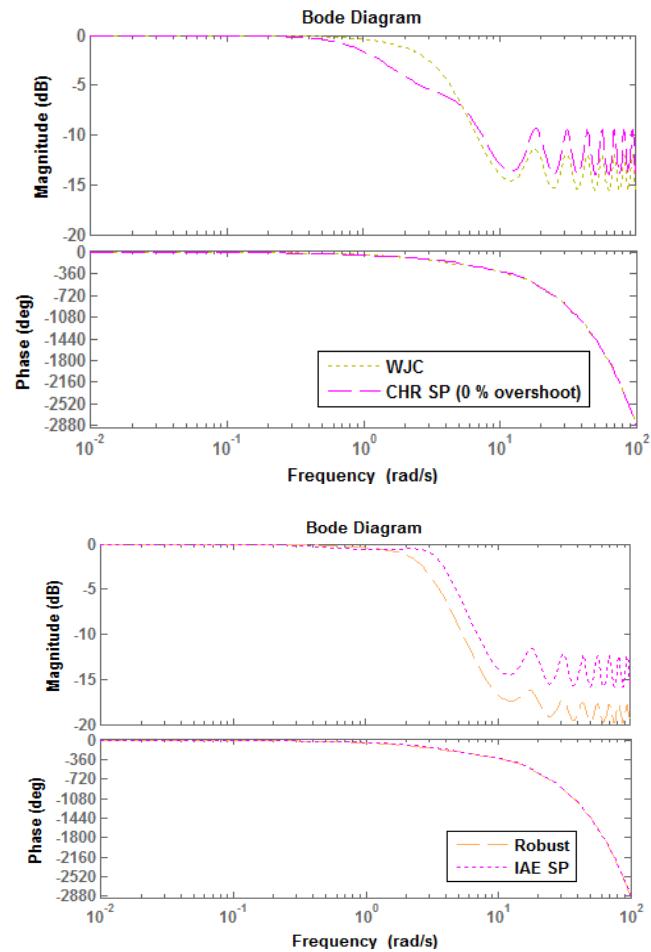
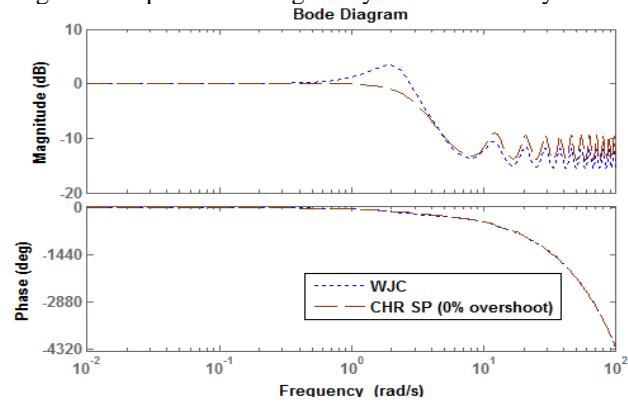
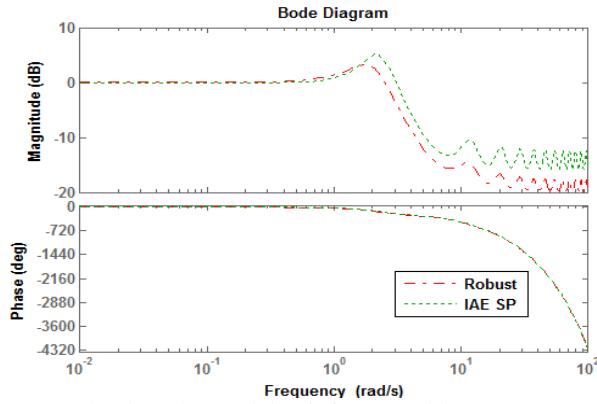
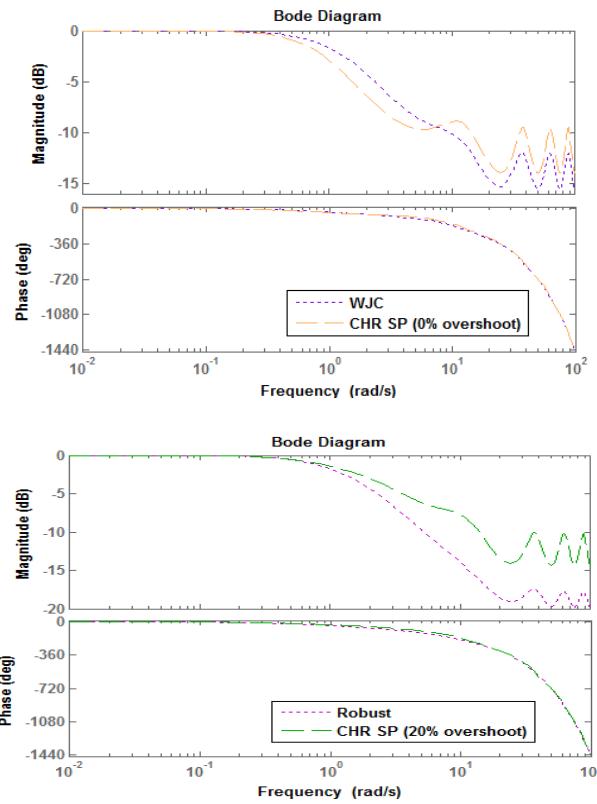


Fig. 6 Bode plot of the original system when delay  $L=0.5$



Fig. 7 Bode plot when a delay is increased by 50% ( $L=0.75$ )Fig. 8 Bode plot when a delay is decreased by 50% ( $L=0.25$ )

#### 4. Conclusion

Numerous controllers are available in the literature for FOPDT processes such as conventional PID controller and IMC-PID controller etc., with a number of tuning techniques. In this paper, a comprehensive study of well-known tuning techniques for the PID controller to control the FOPDT process has been carried

out. Five tuning techniques have been applied to the FOPDT process with different values of the delay process, and in order to identify the best tuning technique among them, time and frequency responses are compared. By rigorous review analysis, it is revealed that the CHR set point (0% overshoots) method exhibit better performance comparatively. It is also observed that CHR set point (0% overshoot) method minimizes Integral Absolute Error (IAE), Integral Square Error (ISE) and Integral Time Absolute Error (ITAE).

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