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# Modified Smith Predictor Design and Its Applications to Long Time Delay Systems

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## Abstract

*For the system that can't be described by the precise mathematical model and has long time delays, the conventional Smith predictor presents poor stability and large overshoot. Based on the conventional Smith predictor, an improved fuzzy adaptive PID-Smith predictor is proposed. It uses a fuzzy self-tuning PID controller as the primary controller instead of the traditional PID controller. In addition, a feedback loop and an adaptive regulator are imported to ensure the stability and enhance the adaptability of the variable environment. The simulation results show that the new scheme has excellent stability and robustness and can solve the problem of large overshoot in long time delay systems, even when the model mismatch rate comes to 40%.*

***Keywords:*** *long time delays, fuzzy self-tuning PID controller, predictor, robustness, model mismatch*

## 1. Introduction

The long time delay system is known as one of the difficulties in the industrial control. Processes with significant long time delays are difficult to control using standard feedback controllers mainly because of the effect of the perturbations is not felt until a considerable time has elapsed. Furthermore, the effect of the control action takes some time to be felt. The control action that is applied based on the actual error, tries to correct a situation that originated some time before [1]. Because of the simple control structure, ease of design and effectiveness for linear systems, most of the industrial processes are still using the conventional PID controller [2]. However, most of the real systems are nonlinearities, or without precise mathematical model or having time delays. Thus, the conventional PID controllers are usually not effective for this kind of real systems [3-4]. The standard Smith predictor (SP), and its many extensions, can be considered as the first control method for the long time delay system. The main advantage of the SP is that the time delay is eliminated from the characteristic equation of the closed loop system. Thus, the analysis and control design problems for processes with delay can be converted into one system without delay. That's why the Smith predictive control is widely used in recent years [5]. Unfortunately, the controller designed by the conventional Smith predictive control theory is only a PID controller, which is difficult to obtain satisfied control performance for the long time delay process. What's more, the Smith predictor control scheme requires the knowledge of the

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precise model of the plant. However, the mismatch between the plant and the model is inevitable, and it leads to unacceptable performance in the process [6-7].

As the effect of differential in PID is not very obvious in engineering practice, the fuzzy logic control (FLC) algorithm has been constructed to synthesize the linguistic control protocol of a skilled human operator. Although fuzzy control doesn't require a precise mathematical model and has strong anti-interference ability and outstanding robustness [8], it mainly depends on the operator's experiences and intuitive judgment, resulting in that the accuracy of fuzzy control is not high [9]. In order to improve the accuracy of system control, the Fuzzy-PID switching composite control came into being [10]. But for the time delay systems, the stability of the Fuzzy-PID switching composite controller can't be guaranteed when it is switching [11-12]. In order to avoid the influence caused by switching, a new fuzzy self-tuning PID Smith prediction controller is developed [13]. This approach improves the control performance of the system to some extent, but it is still difficult to obtain good control performance and the stability will be dramatically degraded once the differences between the model and the actual plant become significant.

In the face of inevitable mismatches between the actual plant and the model, a large amount of work has been done in terms of reducing the sensitivity to process model mismatch. For example, a Smith predictor configuration is represented as its equivalent internal model controller (IMC), which provides the parameters of PI or PID controller to be defined in terms of the desired closed-loop time constant, which can be adjusted by the operator and parameters of the process model [14-15]. Design for integrating processes with time delays in modified Smith predictor structure with cascade control has been discussed by [16-17]. In literature [18-19], various types of gain adaptive Smith predictors have been proposed. Making full use of the adaptive regulator to adjust the model parameters reduces the negative impact of the gain parameter changing. [20]Analysis the multi-objective optimization of Smith predictor parameters and makes use of the model mismatch to overcome the long dead time and nonlinearity of the system.

In this paper, based on the conventional Smith predictor and combining the fuzzy self-tuning PID controller with the gain adaptive regulator, an improved fuzzy adaptive PID-Smith predictor is proposed for overcoming the large overshoot and poor stability in long time delay system. The new scheme is not sensitive to parameters changing and the model parameters self-tuning can be done during control process. Thus, it has better adaptability and robustness than the conventional Smith predictor.

## 2. Overview of the Smith Predictor

Plants with long time delays can’t get satisfactory performance by using a simple PID controller. This is mainly because the additional phase lag contributed by the time delay tends to destabilize the closed loop system. Although it is easy to decrease the controller gain to improve the stability, in this case, the response obtained will be extremely sluggish. The structure of the Smith predictor is shown in Figure 1.

According to Figure l, the transfer function of the closed-loop system after compensation is:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G(s)\,e^{-\tau s}}{1 + G_c(s)\,[G_m(s) + G_e(s)]} \tag{1}$$

 

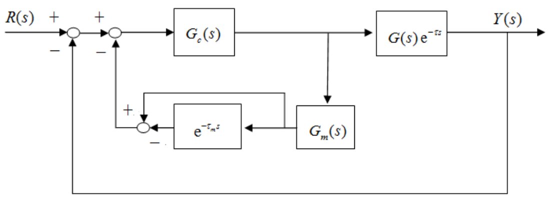


**Figure 1. Structure of the Smith Predictor**

Where $G_e(s) = G(s)e^{-\tau s} - G_m(s)e^{-\tau_m s}$ , $G(s)e^{-\tau s}$ , $G_m(s)e^{-\tau_m s}$ and $G_c(s)$ are, respectively, the transfer functions of the plant and the plant's dynamic model and the controller which is usually a PID controller. The stability of the Smith predictor depends on the differences between the dynamic model and the plant. When the model used matches perfectly with the plant, namely, $G_e(s)$ is equal to zero. Then, the closed loop transfer function of Eq. (1) reduces to:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G(s)e^{-\tau s}}{1 + G_c(s)G(s)} \tag{2}$$

Its characteristic equation is:

$$1 + G_c(s)G(s) = 0 \tag{3}$$

According to Eq. (3), there is no time delay in the characteristic equation, indicating that the time delay is eliminated. Since there is no time delay in the feedback, the performance of the system will be improved. But in most of the time delay systems, the model can only approximately represent the plant. What's more, the actual parameters of the plant are often time-varying or unknown. When there are some differences between the dynamic model and the plant, $G_e(s)$ will change with time.The bigger differences among $G(s)$ and $G_m(s)$ as well as $\tau$ and $\tau_m$ , the performance of the output becomes worse. Due to the time delay is exponential form, the differences between $\tau$ and $\tau_m$ is more important, that is, the accuracy of $\tau$ is more critical.

## 3. Design of the fuzzy adaptive PID-Smith predictor controller

### 3.1. Fuzzy Self-tuning PID Controller

The fuzzy adaptive PID controller, which is shown in Figure 2, is mainly made up of PID controller and fuzzy inference engine. The inputs of fuzzy controller are the error and the rate of change of the error, and the increments of PID control parameters are obtained by fuzzy inference. The actual PID control parameters are achieved by adding these increments to initial values of PID control parameters. Calculated as follows:

$$k_p = k_p' + \Delta k_p \tag{4}$$

$$k_i = k_i' + \Delta k_i \tag{5}$$

$$k_d = k_d' + \Delta k_d \tag{6}$$

 

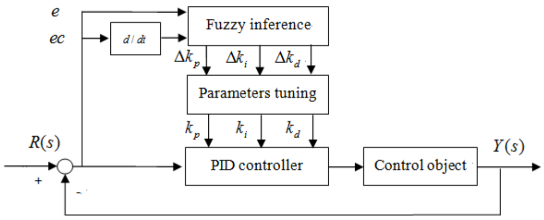


**Figure 2. Diagram of Fuzzy Self-Tuning PID Control System**

The basic domain of $e$ 、 $ec$ 、 $\Delta k_p$ 、 $\Delta k_i$ 、 and $\Delta k_d$ are [-10,10]、[-1,1]、[-3,3]、[-0.03,0.03]、[-0.03,0.03], respectively ,and then, all of the variables are quantized to the region of [-3,3]. Fuzzy linguistic terms of them are expressed as negative big (NB), negative middle (NM), negative small (NS), zero (ZE), positive small (PS), positive middle (PM), and positive big (PB). Since the triangular membership function owns the advantage of high sensitivity, Hence, all of the input and output variables of the fuzzy adaptive PID controller use triangular fuzzy membership function as a function of a subset. According to the actual control experiences, the three parameters of fuzzy adaptive PID have to meet the following three principles to adjust parameters effectively under different error and error rate of change:

①When the absolute value of the error e is large, it should take the great $\Delta k_p$ and $\Delta k_d$ , and make $\Delta k_i$ =0 to speed up the system response and avoid the large overshoot.

② When the absolute value of the error and the rate of change of the error ec are medium, it should take the small $\Delta k_p$ and the medium $\Delta k_i$ and $\Delta k_d$ .

③ When the absolute value of the error is small, it should take the great $\Delta k_p$ and $\Delta k_i$ , and the value of $\Delta k_d$ depends on the rate change of the error ec. If the absolute value of ec is large, it should take the small $\Delta k_d$ , otherwise it should take the great value.

Based on the above principles, the control rules for output variables $\Delta k_p$ , $\Delta k_i$ and $\Delta k_d$ are listed in Table 1.

**Table 1. Fuzzy Control Rules of $\Delta k_p$ , $\Delta k_i$ and $\Delta k_d$**

| e | ec | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | ZO | PS | PM | PB |
| NB | PBPBPB | PBPBPB | PBPBPB | PBPBPB | PSNSNB | ZONMNM | NSNBNS |
| NM | PBPBPB | PBPBPB | PMPMPM | PMPMNM | ZONMZO | NSNBPS | NMNBPM |
| NS | PBPBPB | PMPMPM | PMPSPM | PSPSNS | NSNBPM | NMNBPB | NBNBPB |
| ZO | ZOZOZO | ZOZOZO | ZOZOZO | ZOZOZO | ZOZOZO | ZOZOZO | ZOZOZO |
| PS | NBNBPB | NMNBPB | NSNBPM | PSPSNS | PMPSPM | PMPMPM | PBPBPB |
| PM | NMNBPM | NSNBPS | ZONMZO | PMPMNM | PBPMPM | PBPBPB | PBPBPB |
| PB | NSNBNS | ZONMNM | PSNSNB | PBPBNB | PBPBPB | PBPBPB | PBPBPB |

### 3.2. Fuzzy adaptive PID-Smith Predictor Controller

The main reason that the Smith predictor is so sensitive to model mismatch lies in that both the PID controller and the Smith predictor are designed based on the precise mathematical model. Once the model mismatch occurs in the actual production process, the system response will be unstable and have substantial oscillation. As a result, it is difficult to obtain satisfied performance for the conventional Smith predictor. In order to get a better performance, a fuzzy self-tuning PID Smith prediction controller, which combines fuzzy self-tuning PID controller and the Smith predictor to improve the robustness and stability, is proposed in [13]. However, this method is just suitable for the model parameters changing within 20%.When it reaches more than 20%，the effect of the fuzzy self-tuning PID controller will be small and the performance will be significantly worse, even divergent, taking +40% change in this paper for an example. For the limitations of above predictor controllers, a new fuzzy adaptive PID-Smith predictor controller is developed by combining the fuzzy self-tuning PID controller and the gain adaptive regulator, and its structure is shown in Figure 3. Where *R*(s) is the input of the system, *Y*(s) is the output of the system, $k_m$ is the proportional controller. $G_m(s)e^{-\tau_m s}$ , $G(s)e^{-\tau s}$ and $G_c(s)$ are, respectively, the plant's dynamic model, and the transfer functions of the plant and the primary controller designed at Section 3.1 instead of the traditional PID controller.

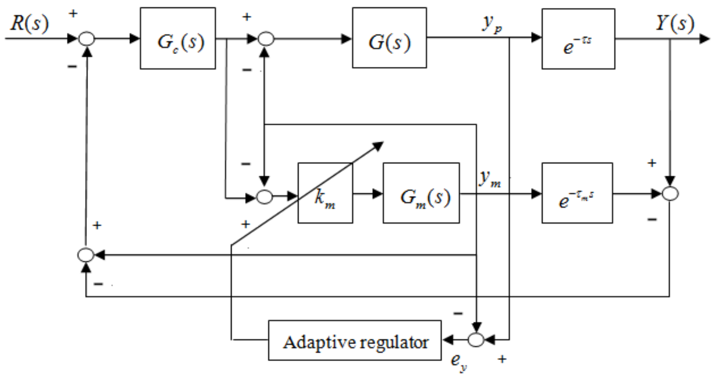


**Figure 3. Structure of the Proposed Controller**

Based on the conventional Smith predictor, a feedback loop is introduced at the front of the large delay of the system in the new scheme. The feedback signal is sent to the inputs of the model and the plant through the inner feedback loop, and makes a subtraction with the outputs of the primary controller. Then, the difference acts as the inputs of the model and the plant. The purposes of adding the inner feedback loop is to weaken the negative impact of the dynamic changes of the model and increase the stability of the system. In order to reduce the overshoot caused by the open-loop gain, the adaptive regulator, which can change the value of the proportional controller over time, is introduced. Based on the principle of Lyapunov asymptotic stability, the analysis of gain adaptive controller is given as follow [19].

Assuming $G(s)=\dfrac{k}{Ts+1}$ , $G_m(s)=\dfrac{1}{T_m s+1}$ , according to the Figure 3, gives:

$$\dot{y}_p(t) = -\frac{1}{T} y_p(t) + \frac{k}{T} u(t) \quad (7)$$

$$\dot{y}_m(t) = -\frac{1}{T_m} y_m(t) + \frac{k_m(t)}{T_m} u(t) \quad (8)$$

$$e_y(t) = y_p(t) - y_m(t) \quad (9)$$

Assuming that the model and plant match perfectly, namely, $T_m = T$ , $L_m = L$ , gives:

$$\dot{e}_y(t) = -\frac{1}{T} e_y(t) + \frac{1}{T}[k - k_m(t)]u(t) \tag{10}$$

Assuming $\Sigma$ is a two-dimensional space, which includes $e_y(t)$ and $k - k_m(t)$ . Selecting the following Lyapunov functions:

$$V(\varepsilon) = \frac{1}{2}\{T e_y^{\,2}(t) + \frac{1}{\lambda}[k - k_m(t)]^2\} \tag{11}$$

Where $\lambda > 0$ , $T > 0$ , then $V(\varepsilon) > 0$ is given.

According to Eq. (11):

$$\dot{V}(\varepsilon) = -e_y^{\,2}(t) - [k - k_m(t)][\frac{1}{\lambda}\dot{k}_m(t) - e_y(t)u(t)] \tag{12}$$

$$\text{Assuming } \dot{k}_m(t) = \lambda\, e_y(t)\, u(t) \tag{13}$$

That is:

$$k_m(t) = \lambda \int e_y(t) u(t) dt + k_{m0} \tag{14}$$

$$\text{As a result: } \dot{V}(\varepsilon) = -e_y^{\,2}(t) \le 0 \tag{15}$$

According to the theory of the Lyapunov asymptotic stability, Eq. (10) will be stable asymptotically. To simplify the calculation, it takes Eq. (14) for adaptive formula, namely, the value of the proportional controller changes with the value of the gain parameters of the plant.

## 4. Experimental Verification

Simple models and clear to understand control structures are very important in the process indpustry. So, most production process can be simplified into a first-order transfer function plus a dead-time, which is given by

$$G(s) = \frac{K}{(Ts + 1)} e^{-\tau s} \tag{16}$$

Selecting an industrial electric furnace as the controlled object whose transfer function is

$$G(s) = 1 \cdot e^{-40s} \big/ (60s + 1) \tag{17}$$

This object is the long time delay system because the time constant *T*=60s, time delay $\tau$ =40s, and $\tau/T$ =0.67. In order to validate the outstanding performance of the improved fuzzy adaptive PID-Smith predictor controller, the comparative experiment with the fuzzy self-tuning PID-Smith predictor controller and the conventional Smith predictor controller is conducted.

The system responses are shown in Figure 4. When the model matches with the plant perfectly. The dotted (blue) line is the response of the conventional Smith control and the dash (green) line is the response of fuzzy self-tuning PID-Smith control and the solid (red) line is the response of proposed method. It can be seen that the solid (red) line has no overshoot without increasing the regulating time, however, the other two kinds of methods exist 4.4 %and 3.1% overshoot, respectively. It implies that under the effect of the fuzzy self-tuning PID controller, the overshoot of the fuzzy self-tuning PID-Smith controller is smaller than the conventional Smith controller, and the proposed controller, which combines the advantages of the fuzzy self-tuning PID controller and the gain adaptive regulator, has a better ability to overcome overshoot than the other two. As a result, the proposed method has better performance when the model matches with the plant perfectly.

 

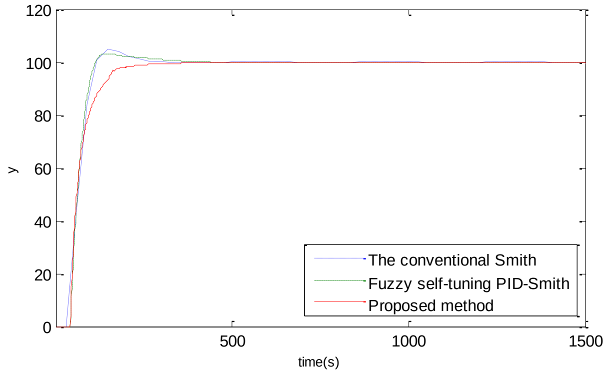


**Figure 4. Performance of Perfectly Matched System (K=1,T=60s, $\tau$ =40s)**

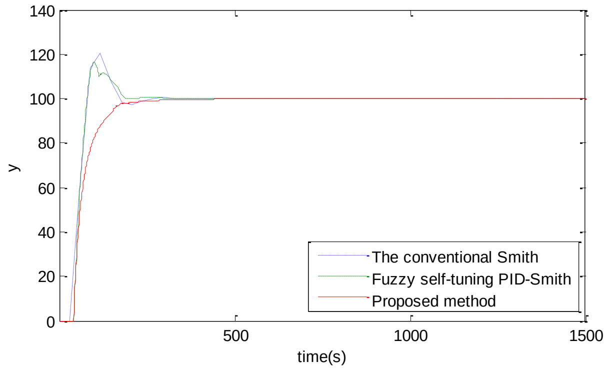


**Figure 5. Performance of +40% Change in Process Gain (K=1.4,T=60s, $\tau$ =40s)**

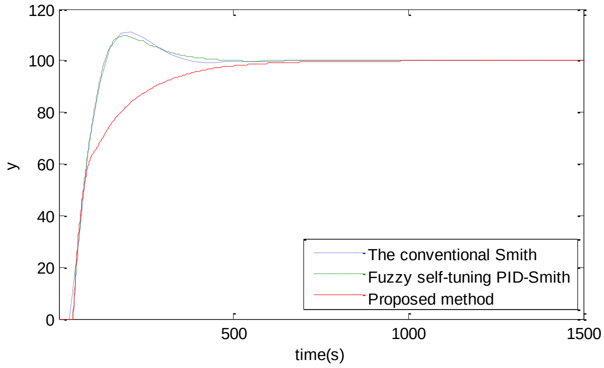


**Figure 6. Performance of +40% Change in Time Constant (K=1,T=84s, $\tau$ =40s)**

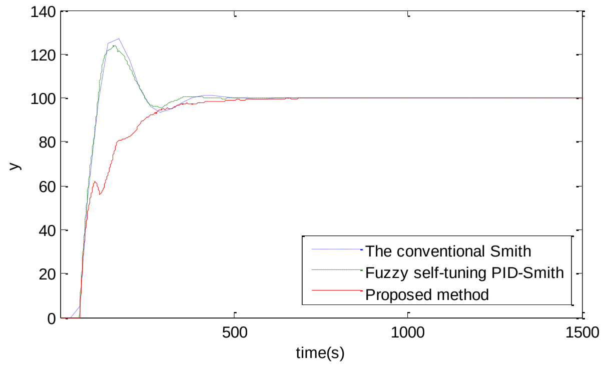


**Figure 7. Performance of +40% Change in Time Delay (K=1,T=60s, $\tau$ =56s)**

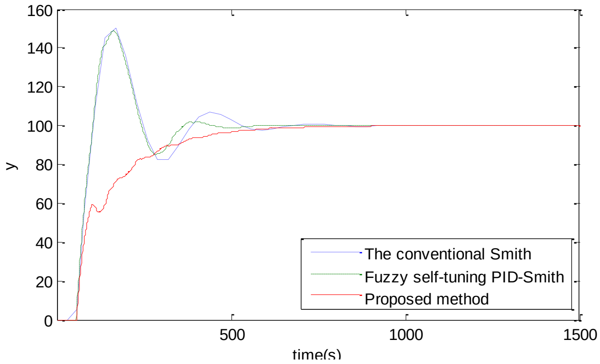


**Figure 8. Performance of +40% Change in Process Gain, Time Constant and Time Delay (K=1.4,T=84s, $\tau$ =56s)**

As we know there are three main parameters in the transfer function of the model. They are the gain parameter, the time constant and the time delay. Different changes in different parameters will lead to a variety of changes of performance. When there is 40% change in gain parameter *K*, the time constant *T*, and the time delay, respectively, the system responses are shown in Figure 5 to Figure 7. The responses are shown in Figure 8 when all of the parameters change 40%. In each figure, the dotted (blue) line is the response of the conventional Smith control and the dash (green) line is the response of fuzzy self-tuning PID-Smith control and the solid (red) line is the response of proposed method.

According to the simulation results of Figure 5 to Figure 8, some important performance indicators are given and they are listed in Table 2. It can be seen that both the fuzzy self-tuning PID-Smith control and the conventional Smith control exist large overshoot, and the maximum overshoot is up to 50.5% in the dotted (blue) line of Figure 8. It indicates that the effect of the fuzzy self-tuning PID controller is small when the model mismatch comes to 40%. Compared with the other lines, the solid (red) line only has a little overshoot in each figure from Figure 5 to Figure 8. It implies that the proposed method has significant effects in dealing with the problem of overshoot. What's more, there is large oscillation amplitude in dash (green) and dotted (blue) line in each figure because the Smith predictor is too sensitive to model mismatch, which results in a weak system stability. However, the solid (red) line has shortened the adjustment time and has small oscillation amplitude in each figure because of the effect of the inner feedback loop and the gain regulator. This suggests that proposed method holds stronger stability and robustness than the other two methods. As a result, the proposed method not only can solve the large overshoot of the long time delay system, but also holds a better stability and adaptive capacity.

**Table 2. Performance Indicators**

| | Maximum overshoot (%) | Maximum adjustment time (s) | Stability |
|---|---|---|---|
| The conventional Smith | 50.5 | 1000 | stable |
| The fuzzy self-tuning PID-Smith | 48.9 | 1000 | stable |
| Proposed method | 0.1 | 875 | stable |

## 5. Conclusion

In order to solve the difficulties for industrial control processes with time-varying parameters and long time delays, a new fuzzy self-tuning PID-Smith predictor controller, which combines the fuzzy self-tuning PID controller and the gain adaptive regulator, is proposed in this paper. This method holds excellent stability and adaptability, eliminates the steady-state error, and has improved the dynamic performance of the system, even when the model mismatch rate comes to 40%.The simulation results show that the proposed predictor controller is effective for long time delay processes, so it has great practical value.

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