Research Article

Modified Smith Predictor Based on $H_2$ and Predictive PI Control Strategy

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In this paper, a new type of modified Smith predictor based on the $H_2$ and predictive PI control strategy is proposed. The modified Smith predictor not only has $H_2$ robust performance but also has a similar predictive PI control structure. By introducing a time delay term, the modified Smith predictor controller overcomes the shortcoming that the conventional control algorithm can only use the low-order approximation of time delay term to design the control algorithm. The modified Smith predictor controller’s output is related to the current system error and related to the output in a period before the controller. Simultaneously, the modified Smith predictor controller is applied to conventional process systems based on dynamic optimization estimation in the case study to show absolute superiority over the nonpredictive control method (such as the classical PID control method).

1. Introduction

The time delay process is a kind of process widely existing in practical industrial production, such as the long-distance transmission of gas or liquid, temperature control of heating furnace, calculation delay of control action. The control problem of the time delay process is still tricky in the control field. The research on the control method and mechanism of the time delay process has attracted control researchers [1–4]. As far as the control system is concerned, the time delay refers to the control action currently applied, which can be reflected in the output after a certain period. It is often the main factor leading to the deterioration or even instability of control system quality [5–10]. For linear systems, we may use the high-order approximation method to deal with the corresponding controller. Still, for nonlinear systems with time delay, which are more common in the industry, the control difficulty will be greatly increased [11, 12].

When the ratio of the time delay to the dominant time constant of the process model is more significant than 0.5 (i.e., the model has a large time delay), the tuning strategy reported in the literature will produce poor servo performance. The conventional PID (proportional-integral-derivative) control algorithm cannot achieve satisfactory control effect [13–15]. When PID controller is used to control the process with a large time delay, differentiation $D$ is usually taken as 0 to reduce overshoot and oscillation [16–19]. Smith predictor is considered as a milestone to solve the control of time delay process. Zhang et al. [20, 21] designed a new PID controller based on $H_2/H_\infty$ method and Smith control strategy. The controller can be applied to large time delay process, but the high-order approximation method is adopted for the time delay term of process. In [22, 23], the modified Smith controller is designed based on the common industrial control strategy. The unstable term, integral term, time delay term, and other different cases are considered. The treatment of time delay term is linear approximation to design the controller. These algorithms have two defects: (1) they are susceptible to the model error, especially to the deviation of the time error; (2) the setpoint tracking performance is good; anti-interference ability is minimal.

The modified Smith controller in this paper is based on $H_2$ optimal control theory and predictive PI (proportional-integral) control strategy [24–28]. The controller has the
characteristics of predictive PI control strategy and $H_2$ robust time performance. It is especially suitable for the control of large time delay systems. The controller structure is simple, the adjustable parameters are few, and the parameters’ adjustment is convenient and intuitive. The proposed control strategy overcomes the numerical approximation of the time delay term in the previous control algorithm. Still, it introduces the time delay term into the controller, making the controller structure composed of two parts: the standard PI control term or the modified PI control term and the predictive control term. The PI control term can improve the controller’s robustness and maintain good robust performance in the presence of different disturbances and model parameter changes. The introduction of a predictive control term aims to overcome the adverse effect of a large time delay on control. It can predict the future control effect according to the control effect of a certain period in the past and eliminate the blindness of the control effect. In the controller design, although it is unnecessary to know the precise model of the process, but to know the approximate model of the process, the control is also a model-based control. There is a direct relationship between the parameters of the controller and the parameters of the actual process. Setting different parameters of the controller can meet the different control characteristics required by the object. In the process industry, setpoint changes occur less frequently than load or parameter disturbances. Therefore, interference suppression is more important than setpoint tracking. The control strategy has good closed-loop performance, especially anti-interference performance, which is more suitable for industrial applications.

This paper is organized as follows. In Section 2, the modified Smith control based on ITAE-PI/PID numerical control strategy is compared with the Smith control strategy proposed in this paper. In Section 3, the modified Smith predictor control strategy is introduced. In Section 4, the comparison of various modified Smith predictors is presented. In Section 5, we compare different control algorithms for typical industrial processes based on dynamic optimization estimation. Finally, we give conclusions and further study in Section 6.

$$e^{-\theta s} \approx \frac{1}{1 + \theta s + \theta^2 s^2/2! + \cdots + \theta^n s^n/n!}$$

Equation (1) approximation is obtained by truncating after only a few terms.

2.1.2. $n/v$ Pade Approximation

$$e^{-\theta s} \approx \frac{P_{mv}(\theta s)}{Q_{mv}(\theta s)}$$

$$P_{mv}(\theta s) = \sum_{j=0}^{n} \frac{(n + v - j)!n!}{(n + v)!j!(n - j)!}(-\theta s)^j,$$

$$Q_{mv}(\theta s) = \sum_{j=0}^{n} \frac{(n + v - j)!v!}{(n + v)!j!(n - j)!}(-\theta s)^j.$$  (2)

In (2), $n$ and $v$ are positive integers, which are the order of the numerator and denominator of polynomial approximation, respectively. $P$ and $Q$ are the numerator polynomials and denominator polynomials, respectively. The 1/1 Pade approximation, $e^{-\theta s} \approx (1 - 0.5\theta s)/(1 + 0.5\theta s)$, is commonly used in engineering practice.

2. Modified Smith Control Based on ITAE-PI/PID Control Strategy

A large time delay plant is universal in process control, but it is not easy to control. The Smith predictor method’s greatest advantage is that the time delay is removed from the closed-loop characteristic equation. The time delay process’s design problem is transformed into the problem of no time delay so that the control quality is greatly improved. Figure 1 shows the original structure of the Smith predictor. $R(s)$ is the input signal of the system, $E(s)$ is the system error, $G_c(s)$ is the controller, $U(s)$ is the controller output, $G_p(s)$ is the actual industrial model, $G_p'(s)$ is the nominal model, $G_p(s)$ is the nominal model without time delay, $D(s)$ is the external interference signal, and $Y(s)$ is the system output.

However, the Smith predictor’s original structure still has some defects: Time delay compensation needs an accurate process mathematical model, and the control performance is sensitive to model error. When the error between the estimated model and the actual plant is large, the control performance will deteriorate significantly. It is also susceptible to external disturbances and has low robustness. It is only applicable to stable time delay plants. To overcome these shortcomings, some scholars have proposed various improved methods based on the conventional Smith predictive control strategy [15, 20, 21].

2.1. Polynomial Approximate Time Delay Process. The first difficulty in treating time delay systems is that the time delay term is represented as an irrational transfer function with infinite dimensions. However, most of the design methods proposed are based on the theory of rational functions and can only deal with finite-dimensional control objects. Therefore, it is necessary to discuss the rational approximation of delays before designing controllers [29].

The two most widely used delay polynomial approximations are as follows.

2.1.1. Taylor Series Expansion

$$Q_{mv}(\theta s) = \sum_{j=0}^{n} \frac{(n + v - j)!v!}{(n + v)!j!(n - j)!}(-\theta s)^j.$$  (2)
2.2. Modified Smith Control Based on ITAE-PI/PID Control Strategy. Most PID controllers rely on various experience tuning algorithms, and these tuning algorithms often rely on a single design index, and the overall control effect is not optimal. With the need for engineering, a comprehensive performance index can better reflect the whole control system’s performance. Common control performance indicators are shown in the following equation:

1. ITAE (integrated time absolute error) \( J = \int_{0}^{\infty} t|e(t)|dt \).
2. ISE (integral square error) \( J = \int_{0}^{\infty} e^2(t)dt \).

ISE performance index can transform the control system design problem into a purely mathematical problem, so it is widely used. The optimal design method in modern control is developed based on ISE, and the ISE performance index is also \( H_2 \) performance index in the frequency domain. ITAE cannot be analyzed and can only be calculated numerically.

The PID controller’s main characteristics are that it has a fast proportional function, eliminates the integral effect of steady-state error, and predicts the future differential effect. It is especially suitable because the process’s dynamic performance is benign, and the control performance requirements are not strict. The PID parameter tuning is always based on the analytic method to determine its parameters, leading to the PID controller not controlling the complex system. With improved computer numerical calculation technology, PID tuning is more based on a numerical optimization method to determine its parameters, which can also achieve good control effect \([30]\). The ITAE-PI/PID control structure is shown in Figure 3. Based on ITAE performance indicators, the optimization solution is shown in (4), where \( s(t) \) is the error transfer function.

\[
J = \min_{K_P, I, D} \int_{0}^{\infty} t|e(t)|dt, \quad \text{s.t.} \ e(t) = r(t) - s(t), \quad u_{\text{low}} \leq u \leq u_{\text{high}}.
\]  

### 3. Modified Smith Predictor Control Strategy

#### 3.1. Theoretical Developments. The important basis of the control system design is the mathematical model of the control plant. The mathematical model is used to describe the input, output, and internal variables of the system. Process control plants may be various equipment or devices in the production process, such as heat exchanger, dryer, and distillation column. The physical and chemical reaction principles of these control plants are different. Still, from the similarity principle of control models, a linear time-invariant model can describe a certain stage’s characteristics. An integrated process model is assumed in the control process, as shown in (5). \( K \) is the process static gain, \( T \) is the process integral constant, \( \tau \) is the process time constant, and \( \theta \) is the process pure time delay.

\[
G(s) = \frac{K}{Ts(\tau_0s - 1)(\tau_1s + 1)(\tau_2s + 1), \ldots, (\tau_n s + 1)}e^{-\theta s}.
\]  

(5)

The process model \( G(s) \) contains an integral part \( 1/Ts \) and an unstable part \( 1/\tau_0s - 1 \). Therefore, the system process model needs to be stabilized as a stable plant \( \tilde{G}_p(s) \) (see (6)), and then the system controller is designed. The advantage of this method is that the structure of the controller is simpler and the adjustable parameters are less, which is convenient for engineering practice.

\[
\tilde{G}_p(s) = \frac{Ke^{-\theta s}}{bns^n + \cdots + b_2s^2 + b_1s + 1}.
\]  

(6)

When the process model \( \tilde{G}_p(s) \) is established, the influence of input signal on system output is considered. The
input signals $u(t)$ of process control system are divided into two types: setpoint value signal $R(s)$ and interference signal $D(s)$. If the input signal $u(t)$ is known and bounded, it can be nominal to pulse signal by $W(s)$, and $W(s) = u(s)$. The system’s output norm, such as (7)–(10), is derived by using the bounded norm theorem.

$$y(t) = \tilde{G}_p(t) * u(t) = \int_{-\infty}^{\infty} G(t - \tau)u(\tau)d\tau$$

$$= \tilde{G}_p(t) * \delta(t),$$

$$\|y(t)\|_2 = \|\tilde{G}_p(t)\|_2,$$  \hspace{1cm} \text{(7)}

$$\|\tilde{G}_p(j\omega)\|_2 = \left(\frac{1}{2\pi} \int_{-\infty}^{\infty} |\tilde{G}_p(j\omega)|^2 d\omega\right)^{1/2},$$

$$\tilde{G}_p(j\omega) = \int_{-\infty}^{\infty} \tilde{G}_p(t)e^{-j\omega t} dt$$

$$= \left(\int_{-\infty}^{\infty} |\tilde{G}_p(t)|^2 dt\right)^{1/2} = \|\tilde{G}_p(t)\|_2,$$  \hspace{1cm} \text{(8)}

$$\|y(t)\|_2 = \|\tilde{G}_p(t)\|_2 = \|\tilde{G}_p(j\omega)\|_2.$$  \hspace{1cm} \text{(9)}

### 3.2. Smith Predictor Based on $H_2$ and Predictive PI Control Strategy

In this section, the input signal $r(t)$ is known, a filter weight function $W(s) = R(s)$ can be introduced first to normalize the input of the system to an impulse signal, and the system error $e(t)$ is obtained according to the Section 3.1. Based on the $H_2$ optimal control strategy, the system square error integral is minimized, $\min_{e(t)}\|e(t)\|_2$. Equivalent frequency domain minimized weighted sensitivity performance index is shown in the following equation:

$$\min_{0} \int_{0}^{\infty} e^2(t)dt = \min_{e(t)}\|e(t)\|_2 \Rightarrow \min_{e(t)}\|e(t)\|_2 = \min_{W}\|W(s)S(s)\|_2 < 1.$$  \hspace{1cm} \text{(10)}

The Smith control structure shown in Figure 1 is transformed into the Youla parameterized control structure shown in Figure 4 for controller design. $Q(s) = G_c(s)/(1 + G_c(s) * G_p(s))$ is the lumped controller, and $G_f(s)$ is the filter to deal with the nonregularization problem of the controller.
\( \tilde{G}_p(s) \) has been stabilized as a stable object. To facilitate calculation, we transform \( \tilde{G}_p(s) \) into another form shown in the following equation:

\[
\tilde{G}_p(s) = \frac{K e^{-\theta s}}{b_n s^n + \ldots + b_2 s^2 + b_1 s + 1},
\]

(12)

\[ M(s) = b_n s^n + \ldots + b_2 s^2 + b_1 s + 1, \quad b_1 > 0. \]

Because of the existence of pure time delay, it is challenging to design the controller analytically. Many algorithms use low-order polynomial functions to approximate pure time delay term. In this section, \( H_2 \) optimal control theory and \( n/n, (n \rightarrow \infty) \) give a better method to deal with time delay term as shown in the following equation:

\[
e^{-\theta s} = \frac{Q_m(-\theta s)}{Q_m(\theta s)},
\]

(13)

\[
\tilde{G}_p(s) = \frac{KQ_m(-\theta s)}{M(s)Q_m(\theta s)}.
\]

Assuming that the input of the system is a unit step signal and the filter weight function is \( W(s) = 1/s \), in order to realize unbiased control of the system, the set of \( Q(s) \) satisfies the following equation:

\[
\lim_{s \rightarrow 0} (1 - \tilde{G}_p(s)Q(s)) = 0,
\]

(14)

\[
Q(0) = \frac{1}{G_p(0)} = \frac{1}{K},
\]

\[
Q(s) = \frac{1}{K} + \frac{s}{Q_1(s)},
\]

\( Q_1(s) \in \text{stable} \).

The integral sum of square error of the system is derived as the following equation:

\[
\|W(s)S(s)\|_2^2
\]

\[
= \left\| W(s) \left[ 1 - \tilde{G}_p(s) \left( \frac{1}{K} + \frac{s}{Q_1(s)} \right) \right] \right\|_2^2
\]

\[
= \left\| \frac{1}{s} \left[ 1 - \frac{Q_m(-\theta s)}{M(s)Q_m(\theta s)} - \frac{KQ_m(-\theta s)}{M(s)Q_m(\theta s)Q_1(s)} \right] \right\|_2^2
\]

\[
= \left\| \frac{1}{s} \left[ \frac{M(s)Q_m(\theta s) - Q_m(-\theta s)}{sM(s)Q_m(\theta s)} - \frac{KQ_m(-\theta s)}{M(s)Q_m(\theta s)Q_1(s)} \right] \right\|_2^2
\]

\[
= \left\| \frac{Q_m(-\theta s)}{Q_m(\theta s)} \left[ \frac{M(s)Q_m(\theta s) - Q_m(-\theta s)}{sM(s)Q_m(\theta s)} - \frac{K}{M(s)Q_1(s)} \right] \right\|_2^2
\]

\[
= \left\| \frac{M(s)Q_m(\theta s) - Q_m(-\theta s)}{sM(s)Q_m(-\theta s)} - \frac{K}{M(s)Q_1(s)} \right\|_2^2.
\]
H2 Theorem 2 (see [21]). Let L2 denote all strictly regular stable transfer functions. H2 is a subset of L2, which is resolved at Re s > 0, and \( H^2_2 \) is resolved at Re s ≤ 0, \( H^2_2 + H^2_2 = L_2 \). Then, each function in \( L_2 \) satisfies the following equation:

\[
\zeta(s) = \zeta_1(s) + \zeta_2(s), \quad \zeta_1(s) \in H^2_2, \quad \zeta_2(s) \in H^2_2, \quad \|\zeta(s)\|^2 = \|\zeta_1(s)\|^2 + \|\zeta_2(s)\|^2.
\] (16)

We use H2 Theorem 2 to derive the integral sum of square errors of the system as the following equation:

\[
\|W(s)S(s)\|^2 = \left\| \frac{Q_m(\theta_s) - Q_m(-\theta_s)}{s Q_m(-\theta_s)} + \frac{M(s) - 1}{s M(s)} - \frac{K}{M(s) Q_1(s)} \right\|^2.
\] (17)

The minimum value of the system error performance function \( \|W(s)S(s)\|^2 \) is taken as the following equation:

\[
\frac{M(s) - 1}{s M(s)} - \frac{K}{M(s) Q_1(s)} = 0,
\]

\[
Q_1(s) = \frac{K s}{M(s) - 1},
\] (18)

\[
Q(s) = \frac{1}{K} + \frac{s}{Q_1(s)} = \frac{M(s)}{K}.
\]

According to the control structure of Figure 4, the lumped controller \( Q(s) \) needs a filter \( G_f \) to regularize the parameters. The filter must be low-pass to attenuate the high-frequency characteristics. Still, because there are many low-frequency functions, this requirement does not necessarily uniquely determine the filter. Here, the filter \( G_f = 1/((\lambda s + 1)^m) \) is introduced into the controller design. \( \lambda \) is an adjustable parameter representing the bandwidth of the system’s closed-loop response. It determines the performance of the control system. Equation (19) is Zhang’s Smith control strategy, where the lumped controller \( Q(s) \) and controller structure \( G_c(s) \) are shown [20, 21]. Zhang only gives rough simulation guidance for selecting parameter \( \lambda \), and there is no specific and detailed selection method, which also leads to the effect of control algorithm not reaching reasonable optimization.

\[
Q(s) = \frac{M(s)}{K} \frac{1}{((\lambda s + 1)^m)}
\] (19)

\[
G_c(s) = \frac{1}{\lambda s + 1^m}.
\]

Predictive PI (PPI) controller proposed by Astrom [24] combines a predictive control algorithm with a PI control algorithm. PPI controller is designed based on the industrial process model with a large time delay. It consists of two parts: the standard PI controller part and the dynamic prediction part depending on the process model delay time. PPI controller inherits the PID algorithm’s thought system, and its characteristics are familiar to operators, which is conducive to playing its good control performance.

The actual plant of the process is shown in the following equation:

\[
\tilde{G}_p(s) = \frac{K_p e^{-L_0}}{s M(s) + 1}, \quad M(s) = b_0 s^0 + \cdots + b_2 s^2 + b_1 s, \quad b_i > 0,
\] (21)

Among them, \( \mu \) is an adjustable parameter. The controller transfer function of the control system is shown in the following equation:

\[
G_c = \frac{G_0}{G_p(1 - G_0)} = \frac{M_0(s) + 1}{K_p \left( \mu M_0(s) + 1 - e^{-L_0} \right)}.
\] (23)

The input and output relationship of the controller is shown in the following equation:
The Smith control structure proposed in this paper.

\[ U(s) = \frac{1}{\mu K_p} \left( 1 + \frac{1}{M_0(s)} \right) E(s) - \frac{1}{\mu M_0(s)} \left( 1 - e^{-L_0 s} \right) U(s). \]  

(24)

Term \( 1/\mu K_p (1 + (1/M_0(s))E(s) \) has the structure of PI controller, while term \( - (1/\mu M_0(s))(1 - e^{-L_0 s})U(s) \) can be interpreted as the controller’s output at time \( t \) based on the control action in time interval \( (t - L_0, t) \). Therefore, this kind of control is called predictive PI controller.

Using the predictive PI control strategy characteristics, we compare and analyze the two control structures’ controllers, as shown in the following equation:

\[
\begin{align*}
PPI &= \frac{M(s)/(\lambda s + 1)^m}{K(1 - G_p'(s)/K * M(s)/(\lambda s + 1)^m)}, \\
G_c &= \frac{1}{K_p (1 - G_p)}, \quad \mu = 1.
\end{align*}
\]

(25)

When \( \lim_{\lambda \to 0} M(s)/(\lambda s + 1)^m = 1 \), the modified Smith predictor controller can be equivalent to a predictive PI controller, and \( G_p'(s)/K = G_0(s) \) is the closed-loop transfer function of the control system.

By simplifying the parameters \( \lambda, \mu, \) and \( m \), the controller structure of PPI is obtained as the following equation:

\[ PPI = \frac{1}{K(1 - G_p'(s)/K)}. \]  

(26)

\( \lambda \) is an adjustable parameter when \( \mu = 1 \), and the system’s open-loop time constant is the same as the closed-loop time constant. When \( \mu > 1 \), the system’s closed-loop response speed is slower than the open-loop response speed; when \( \mu < 1 \), the system’s closed-loop response speed is faster than the open-loop response speed. From the engineering practice perspective, this control strategy can completely ignore the adjustment of \( \lambda \) and \( m \) to solve controller parameter tuning and obtain good setpoint tracking performance in terms of anti-interference robustness.

4. Comparison of Various Modified Smith Predictors

The control performance of \( H_2 \) Smith predictor proposed in this paper is compared with other modified Smith predictor control algorithms (ITAE-PI/PID and Zhang [20, 21]). Although these modified Smith predictor methods can provide better system performance and robustness than conventional Smith estimation methods, they are challenging to apply to high-order time delay processes. In this paper, the high-order time delay system is considered to reduce the order to the standard industrial first order plus time delay system (see (27)) for control comparison.

\[ G_p'(s) = \left( \frac{100}{200s + 1} \right) e^{-360s}. \]  

(27)

The parameters of ITAE-PI are \( K_p = 0.67998, K_i = 0.65448 \); the parameters of ITAE-PID controller are \( K_p = 0.9972, K_i = 0.8698, K_d = 0.0001 \); the parameters of Zhang’s Smith predictor are \( G_c(s) = (1/100)(200s + 1/0.15), \lambda = 0.1 \), and the \( H_2 \) Smith predictor parameters proposed in this paper are \( PPI = (1/100)(200s + 1/200s + 1 - e^{-360s}) \). In the nominal case, the setpoint tracking response with a value of 100 is shown in Figure 6. According to the setpoint tracking response, the modified Smith predictor algorithm can track the set value well. The \( H_2 \) algorithm proposed in this paper is slower than the other three algorithms in tracking speed.

The control performance and robust performance of the modified Smith predictor control algorithm are studied under the condition of parameter uncertainty. In the control system, four types of uncertain factors are mainly concerned to investigate the robustness of the controller system:

1. Static gain of the model: \( K \in [K_{\min}, K_{\max}] \)
2. Time constant of the model: \( \tau \in [\tau_{\min}, \tau_{\max}] \)
3. The pure time delay of the model: \( \theta \in [\theta_{\min}, \theta_{\max}] \)
4. Random interference of the model: \( d \in [d_{\min}, d_{\max}] \)
Parameter uncertainty situation 1: The amplitude of the static gain $K$ of the actual model of the system is increased from 100 to 150. According to the setpoint value tracking response in Figure 7, during the system’s dynamic process, the other three control algorithms have frequent oscillations, and the robustness of anti-interference is very poor. The steady-state tracking performance is also slower than that of the $H_2$ Smith predictor control algorithm proposed in this paper.

Parameter uncertainty situation 2: the amplitude of the time constant $\tau$ of the actual model of the system increases from 200 to 250. According to the setpoint tracking response in Figure 8, during the system’s dynamic process, the other three control algorithms have frequent oscillations, and the robustness of anti-interference is very poor. However, the $H_2$ Smith predictor control algorithm proposed in this paper has no oscillation in the whole dynamic process, and the control performance and robustness performance are good.

Parameter uncertainty situation 3: the pure time delay $\theta$ of the actual model of the system increases from 360 to 400. According to the setpoint tracking response in Figure 9, ITAE-PI/PID control algorithm has a super large oscillation and cannot stabilize the system. Zhang’s Smith predictor control algorithm has a large and frequent oscillation in the dynamic process, and its anti-interference robustness is very poor. The $H_2$ Smith predictor control algorithm proposed in this paper has no overshoot in the whole dynamic process. The control algorithm has an excellent ability to suppress pure time delay interference.

Parameter uncertainty situation 4: the output disturbance $d$ of the system is a random signal with an amplitude of ±5. According to the setpoint tracking response in Figure 10, the ITAE-PI/PID control algorithm has a large overshoot oscillation in the dynamic process, and the overall system deviation is larger than that of the other two algorithms. Zhang’s Smith predictor control algorithm and the $H_2$ Smith predictor control algorithm proposed in this paper have no overshoot in the dynamic process. The system deviation of the $H_2$ Smith predictor control algorithm proposed in this paper is smaller than that of the Smith predictor control algorithm.

5. Case Study
Above, we have only verified that the proposed controller has good control performance and robust performance compared to other modified Smith predictor control algorithms. Here, it is compared with PID control algorithms under other control structures to verify the control algorithm’s scalability.

The industrial water tank is the storage equipment commonly used by various enterprises. Filtered and disinfected water in the industry is used for cooling equipment and other mechanical parts in the process. This water is stored in the industrial water tank, and it is crucial to keep the water of appropriate capacity in the tank at any time. Its management personnel monitor the materials stored in the tank and master the important data such as the liquid level (unit: m), reserves, and quality. To effectively manage them, it is particularly important to understand the liquid level measurement in the tank. A reasonable liquid level can ensure the safe, reliable, and efficient operation of the tank.

As shown in Figure 11, a cylindrical water tank’s inlet flow is controlled by a valve (unit: %). LT and PT are the water tank level and inlet pressure sensors. Inlet pressure is the system’s disturbance variable; LC and PC are the level controller and pressure controller, respectively, a cascade control structure.

Here, we choose to use the dynamic optimization estimation method. At the same time, the result based on the graphic method is used as the initial value of the dynamic
optimization estimation to improve the convergence and solution speed of the optimization [31]. The dynamic optimization estimation method results are shown in Figures 12 and 13. The system process model and input pressure disturbance model are obtained by dynamic optimization. The specific optimization parameters are shown in Table 1.

In the process control, the main control methods to suppress interference are feedforward and feedback and cascade control [32, 33]. Compared with the single loop control system, the cascade control system has a secondary loop connected with it in the structure. The secondary loop control is mainly used to suppress the system interference quickly. For the tank level process, we use the modified Smith predictor controller proposed in this paper, IMC-PID method [32], ZN-PID method [34], and Lambda-PID method [35], respectively. To verify the effectiveness of the control algorithm, various time domain performance indicators (such as response time, stability time, overshoot, and ITAE) are selected for comparison [36].
Figure 9: Setpoint tracking of the modified Smith predictor under parameter uncertainty situation 3.

Figure 10: Setpoint tracking of the modified Smith predictor under parameter uncertainty situation 4.
Figure 11: Scheme of the industrial water tank.

Figure 12: Continued.
Figure 12: FOPDT dynamic optimization estimation. (a) System process model step response (level (unit: m) and valve (unit: %)). (b) System process model dynamic optimization estimation (output (unit: m) and input data (unit: %)).

Figure 13: Continued.
5.1. Case 1. For the nominal process model and disturbance model that we have established, we control the process object through the modified Smith predictor controller proposed in this paper (proposed method), IMC-PID method, ZN-PID method, and Lambda-PID method. Figure 14 shows that these four control algorithms have a good control effect for the process model with a large time delay. With the change of the setpoint value, the tracking performance is good, but the proposed method’s response speed is faster than that of the other three control algorithms without any overshoot phenomenon. From Table 2, we can see that the proposed method performs well in ITAE error.

5.2. Case 2. Apply disturbance to the nominal system: add a disturbance model of \(\frac{1}{s+1}\) in 385 s, with the input being step signal; add a disturbance with a constant value of 1 in 1000 s; add a disturbance with a constant value of \(-1\) in 1700 s.

In the whole dynamic process, the system is subject to different output disturbances in three time periods, and the overall robust performance of the four control algorithms is acceptable. From Figure 15, when the proposed method suppresses interference, its response speed and overshoot are better than those of the other three control algorithms. At the same time, it can be seen from the ITAE error performance index of each control algorithm in Figure 16 that the proposed method is hugely smaller than the other three algorithms.

5.3. Case 3. When the system gets a wrong model due to data acquisition error or sensor equipment damage, there is model adaptation. In this case, we assume that there is no mismatch in the disturbance model of the system and that the process model of the system changes from the FOPDT model to the SOPDT (second order plus dead time) model, which is also a large time delay system: \(G_p(s) = k_p/(\tau_0 s + 1)(\tau_p s + 1)e^{-\theta r}\), \(\tau_0 = 8\).

For the model mismatch of the system, the four controller parameters have not changed to investigate each control algorithm’s robust performance. Figure 17 shows that each control algorithm has overshoot. The proposed method’s response speed is still faster than that of other control algorithms, and the response time of the other three algorithms is slower than that of the nominal case. From ITAE error performance in Table 3, the error convergence speed and amplitude of the proposed method control algorithm are better than those of the other three algorithms.
Figure 14: Setpoint tracking of the four control algorithms under a nominal condition.

Figure 15: Setpoint tracking of the four control algorithms under different output disturbances.

| ITAE             | 0–600 s | 600–1300 s | 1300–2000 s |
|------------------|---------|------------|-------------|
| Proposed method  | 1485    | 6.761e+04  | 1.375e+05   |
| IMC-PID          | 5294    | 1.258e+05  | 2.503e+05   |
| ZN-PID           | 5000    | 1.034e+05  | 2.04e+05    |
| Lambda-PID       | 3045    | 9.343e+04  | 1.818e+05   |
6. Conclusion

In this paper, a new type of modified Smith predictor is proposed, and its application and characteristics in systems with large time delay are explained. By comparing it with some other modified Smith predictors and with the conventional PID controller in cascade control strategy in the case study, the simulation results show that the proposed controller has some superior characteristics and indicators. The proposed controller has both robust performances from \( H_2 \) and a control structure similar to predictive PI. As mentioned above, the proposed design controller’s important property is that it introduces the time delay term into the controller, which overcomes the adverse effect of
traditional algorithms on the low-order approximation of the time delay term.

At present, the control strategy in this paper is only designed for linear time delay systems, and it may need further expansion for nonlinear time delay systems. In the following research work, the controller’s parameter adjustment with the time delay term is based on the controller’s output data in the past time domain, which can be extended to a moving horizon controller based on optimization. In general, the controller provides a more flexible framework to replace traditional controllers.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare no conflicts of interest.

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