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A Modified Cascade Control Strategy for Tobacco Re-Drying Moisture Control Process With Large Delay-Time

ZHIPING FAN[1,2], ZHENGYUN REN[1], AND ANGANG CHEN[1]

[1]School of Information Science and Technology, Donghua University, Shanghai 201620, China
[2]School of Electrical and Electronic Engineering, Anhui Science and Technology University, Fengyang 233100, China

Corresponding author: Zhengyun Ren (renzhengyun@dhu.edu.cn)

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ABSTRACT A novel series structure is proposed based on cascade control for dominating a class of unstable processes with large delay-times. The modified structure consists mainly of one controller that exists in the inner loop, and the inner loop controller is devised on the basis of internal model control (IMC) principles. The outer loop setpoint tracking controller and the inner loop load disturbance rejection controller are designed according to the H2 optimal performance. At the same time, the tuning parameters are selected through the experience approach. Moreover, a suitable example and real value are recommended for the inner loop controller based on a wide-ranging simulation, and the results are implemented to certify the effectiveness of the proposed method. Simultaneously, the proposed method is applied to in a real-world tobacco production line, and the test results prove that the above method is significant in terms of rapidity, robustness and residual errors.

INDEX TERMS Modified cascade control, moisture control process, large delay-time, IMC.

I. INTRODUCTION

Conventional single closed-loop control does not offer satisfactory performance for moisture control process with large delay-times and strong disturbances in chemical process control. The main reason is that the correct action for disturbance does not begin until the control variable deviates from the setpoint. This phenomenon easily causes low control accuracy and a poor control effect. Cascade control was first developed by Liu and Gao [1], Franks and Worley [2], and is usually composed of two loops, i.e., the outer(primary)and the inner (secondary) loops. The inner loop often uses common control methods such as PI to ensure the rapid control effect, even though more technologies have been advanced. A Smith predictor is commonly used in the outer loop to control integrating processes with delay-time. One of the main functions of the cascade control structure is to eliminate the load disturbance change before the system output loses the ability to follow the setpoint value well. The other function is the introduction of the inner loop, which can reduce the time constant of the control object. Generally, the inner loop can the inner loop has a quickly overcome a secondary disturbance. Meanwhile, the inner loop process dynamics are fast compared to those of the outer loop. In cascade control, the inner loop plays an important role in quick attenuation of the disturbances.

A cascade control strategy can be used to achieve better performance when the processes are not easy to control owing to large disturbances and load changes. However, if a large delay-time exists in the inner or outer loop, the cascade control may not satisfy the aim of the closed-loop response in tracking the setpoint value changes. The Smith predictor [3]is introduced to improve this problem. Therefore, references [4], [5] proposed using parallel smith predictor to substitute for the conventional method. In parallel cascade control, the structure has two controllers and a setpoint filter. The manipulated variable and the disturbances influence both the inner and outer loop outputs simultaneously [6]. Kaya and Atherton [7] reported a structure that integrate the process. The smith predictor is adopted

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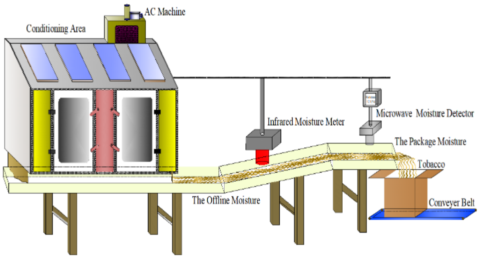

FIGURE 1. Diagram of the offline to package moisture process.

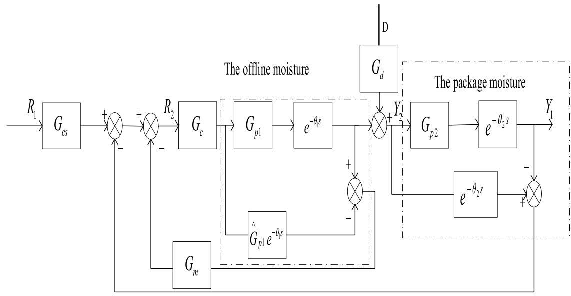

FIGURE 2. A modified cascade control structure.

in the proposed structure, which contains four controllers. Uma *et al.* [8] designed a control structure that contain four controllers. Uma *et al.* [8] designed a control structure that contains three controllers and a filter to integrate an unstable process. Semino and Brambilla [9] proposed a nonlinear filter to improve the outer-loop control performance better. Lee *et al.* [10] proposed a parallel cascade control with four controllers to enhance the system stability. Recently, Raja and Ali [11] introduced modified parallel cascade control structures (PCCS) in an integrated system. Many papers have stated the design and research of cascade control strategies for the stabilization system [12]. However, limited research has focused on a process that contains a large delay-time.

The cascade control system performs better than single-loop control regardless of where the disturbance enters the control system [13]. Owing to the simple implementation and potentially large control performance improvement, cascade control has been applied extensively for several decades [14], and it can be used in the process control industries for moisture, temperature, and flow control. A typical application example is the moisture control of the tobacco re-drying process. The process diagram is shown in Fig.1.

The process of the offline to package moisture process belongs to the condition periods of the tobacco re-drying industry. The tobacco sheets in the conditioning area increase the moisture to decrease the broken rate, and the tobacco sheets are then sent to the conveyor for moisture testing. The offline moisture is detected by an infrared moisture meter, and the sample velocity of the infrared moisture meter is one second. Although, the velocity is fast, the accuracy is not yet high. Meanwhile, a microwave moisture detector is used to detect the package moisture, and the sample velocity of the microwave moisture detector is 2-3 minutes. Although it has perfect sample accuracy, the velocity is low, which can easily cause a large delay-time [15].

When disturbances such as noises and vibrations are brought into the offline to package process, they may evoke moisture content changes in the package process. At the same time, due to the detection time in the re-drying process, a large delay-time is produced during this process. The traditional method is to manually tune the offline moisture directly or alter the setting value of the offline moisture and reset it to one. However, these methods have obvious defects. The manual method increases the amount of labor, and meanwhile, the alignment accuracy depends on the skill level of workers. Altering the setting value often results in a negative effect of the re-baking tobacco leaves. Using the dynamic delay compensation concept can result in improved performance. A structure with dynamic compensation is distinct from the cascade system, but it is a supplement to cascade control. The modified structure is a transport delay system that exists in the chemical part of the transport process, for example, from the offline to package parts of the re-drying process.

In the proceeding study, diagrams and equations, the subscripts ‘ci’ and ‘pi’ are used to denote the inner and outer loops, respectively. R is the reference value, D is the disturbance in the inner or outer loop, Y is the output of the control system, and τ is the transport delay-time, an important element in this paper which exists in many chemical industrial processes. The causes of the delay-time include several situations, such as the transport time, measurement time, and computation time. In this paper, we focus mainly on the transport time and measurement time.

For clear interpretation, the organization of this article is as follows: Section 2 offers a particular review of the proposed modified cascade control structure. In section 3, the controller design methods are discussed in detail, and the selection of the tuning parameters is given. The simulation results are presented in section 4. Finally, conclusions are drawn in section 5.

II. METHOD FORMULATION

A modified cascade control scheme is shown in Fig.2, where both the manipulated variable and the disturbance influence the inner and the outer loop. The structure consists of one controller and manipulates an object in the inner loop, and the outer loop is mainly composed of the dynamic compensation. The output of the outer loop is compared with the setpoint value to achieve the aim of placing the output near the setpoint value. The primary difference between the modified cascade control and conventional cascade control is that the modified cascade control has dynamic compensation in the outer loop. In general, the inner loop dynamics response should be much faster than the outer loop response. When the disturbances enter the inner loop, the delay-time of the manipulated object in the inner loop is shorter than that in the outer loop, and the inner loop controller is regulated before the outer loop can act. Therefore, the inner loop controller is tuned first, and then the outer loop controller is regulated soon afterwards. The introduction of dynamic compensation can eliminate the large delay of the outer loop. Meanwhile, it can be used to achieve better disturbance rejection, and obtain a perfect control result.

A. MODIFIED CASCADE CONTROL STRUCTURE

A novel modified cascade control structure is proposed for a stable, unstable and integrating system with a large delay-time, and the structure comes from actual industrial fields, especially processes that involve a large delay-time.

Generally, the response rate of the inner loop is faster than that of the outer loop, hence, the corresponding control effect is swift, but the dynamic performance is poor. Therefore, the control mode of the outer loop is complex compared with that of the inner loop.

In Fig.2, G_{cs} is a first-order element, and the function of which is to slow down the tracking speed. The function of the inner loop controller G_c is to control the inner loop control object. The output of the inner loop is set as that of the outer loop, and the output value of the outer loop controller is sent to the control valve. The stability of the loop is related to the controllers and controlled objects.

III. CONTROLLER DESIGN

The modified cascade control system has one controller that exists in the inner loop. If the dynamics of the inner loop are fast compared with the dynamics of the outer loop, the inner loop controller needs to be designed first [16] according to the design principle. In the present work, the dynamic performance of the inner loop controllers is considered pre-emptively, and the inner loop is designed first. Only the inner loop controller is designed, and the overall process can be obtained. In the following section, the design of the inner loop is considered first.

A. DESIGN OF THE INNER LOOP CONTROLLER

As stated in section 2, based on the analysis of the modified cascade control structure, we simplify the Fig.2. The inner loop is designed in accordance with the IMC [17], and the inner loop controller G_c is designed as an IMC controller.

The closed-loop transfer function of the inner loop can be gained from Fig.3.

$$\frac{Y_2(s)}{R_2(s)} = \frac{G_c(s)G_{p1}(s)}{1 + G_c(s)G_{p1}(s) - G_c(s)\,\hat{G}_{p1}(s)} \tag{1}$$

Here, G_{p1} is the inner-loop controlled process, and the transfer function is assumed as a first order plus delay- time (FOPDT), the transfer function is assumed to be,

$$G_{p1} = \frac{1}{\tau_1 s + 1} e^{-\theta_1 s} \tag{2}$$

where, θ_1 is the delay-time, τ_1 is the time constant.

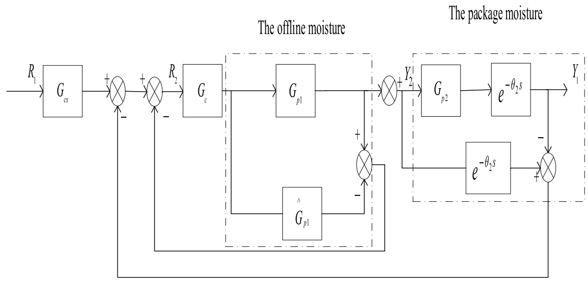

FIGURE 3. Simplify of the modified cascade control structure.

In practice, the controlled process has high-order situation, and we assumed that the high-order process can be approximated satisfactorily by the FOPDT [18].

Simultaneously, in nominal situation, under the perfect model conditions $G_{p1} = \hat{G}_{p1}$, according to design principle and general form of the IMC, the inner loop controller G_c is written as the following form,

$$G_c(s) = \frac{e^{-\theta_2 s}}{\alpha_c s + 1} \tag{3}$$

Here, α_c is the tuning parameter of the inner loop. To gaining good performance, an appropriate value α_c should be selected. Under the condition of stable output and no disturbance entering into the inner loop, the smaller the value of α_c is, the better the performance of the system [19]–[21]. Usually, α_c is related to the delay-time of the inner loop. Yin *et al.* [16] and Padhan and Majhi [17] suggested that α_c should be chosen as one-half the delay-time of the inner loop in order to obtain a faster dynamic response.

Under the ideal situation, equation (1) takes the following form,

$$\frac{Y_2(s)}{R_2(s)} = \frac{e^{-\theta_2 s}}{\alpha_c s + 1} \tag{4}$$

B. DESIGN OF THE OUTER LOOP CONTROLLER

1) DESIGN OF THE SETPOINT TRACKING CONTROLLER G_{CS}

Overshoot usually appears in the closed-loop response, which causes the system adjustment severe and oscillation serious. A setpoint tracking controller is recommended to eliminate or decrease the overshoot. In this paper, the ISE performance index [13] is adopted to design the setpoint tracking controller G_{cs}. Based on the studying of the Internal Model Control (IMC) method, the H_2 optimal performance objective [22] min $\| \; W(1 - Y_{r1}(s)) \; \|_2^2$ is designed as an optimal setpoint tracking controller. Here $W(s)$ is setpoint input weight function and usually $W(s)$ is selected as $^1/_s$ for a step change in a system.

$$Y_{r1}(s) = \frac{Y_1(s)}{R_1(s)}$$
$$Y_{r1}(s) = G_{cs}G_{c1}G_{p1}G_{p2} \tag{5}$$

In Fig.3, we assume the controlled object G_{p1} and G_{p2} have the following transfer function form.

$$G_{p1} = \frac{k_1\,[A_{1+}(s)A_{1-}(s)]}{(\tau_1 s+1)}e^{-\theta_1 s} \tag{6}$$

$$G_{p2} = \frac{k_2\,[A_{2+}(s)A_{2-}(s)]}{(\tau_2 s+1)}e^{-\theta_2 s} \tag{7}$$

The subscript "−" refers to the roots in the left-plane and the subscript "+" refers to the roots in the right-plane [22]. y/y order all pass Pade approximation of delay-time is used to solve the equations (6) and (7), then after calculation and substitution, we obtain the following equation,

$$G_{p1} = \frac{k_1\,[A_{1+}(s)A_{1-}(s)]}{(\tau_1 s+1)}\cdot\frac{Q_{yy}(-\theta_1 s)}{Q_{yy}(\theta_1 s)} \tag{8}$$

$$G_{p2} = \frac{k_2\,[A_{2+}(s)A_{2-}(s)]}{(\tau_2 s+1)}\cdot\frac{Q_{yy}(-\theta_2 s)}{Q_{yy}(\theta_2 s)} \tag{9}$$

Here, $Q_{yy}(\theta_2 s) = \sum_{j=0}^{y}\frac{(2y-j)!y!}{(2y)!j!(y-j)!}(\theta_2 s)^j$ and y is set large enough to guarantee that the approximation error can be ignored compared with the process model mismatch in practice [23].

$$\begin{aligned}
&\| W(1-Y_{r1}(s)) \|_2^2 \\
&= \| \frac{1}{s}(1-G_{CS}(\frac{\tau_2 s+1}{\alpha_c s+1})\cdot\frac{K_1 A_{1+}(s)A_{1-}(s)Q_{yy}(-\theta_1 s)}{(\tau_1 s+1)Q_{yy}(\theta_1 s)} \\
&\quad \cdot\frac{K_2 A_{2+}(s)A_{2-}(s)Q_{yy}(-\theta_2 s)}{(\tau_2 s+1)Q_{yy}(\theta_2 s)} \|_2^2 \\
&= \| \frac{Q_{yy}(\theta_1 s)Q_{yy}(\theta_2 s)A_{1+}^*(s)A_{2+}^*(s)}{sQ_{yy}(-\theta_1 s)Q_{yy}(-\theta_2 s)A_{1+}(s)A_{2+}(s)} \\
&\quad - G_{CS}(\frac{\tau_2 s+1}{\alpha_c s+1})\cdot\frac{K_1K_2A_{1+}^*(s)A_{2+}^*(s)A_{1-}(s)A_{2-}(s)}{s(\tau_1 s+1)(\tau_2 s+1)} \|_2^2
\end{aligned} \tag{10}$$

Here, $A_{1+}^*(s)$ and $A_{2+}^*(s)$ are complex conjugates of $A_{1+}(s)$ and $A_{2+}(s)$ [23]. Adopting the orthogonality property of H_2 norm, we get (11), as shown at the bottom of the next page.

Let the second term in equation (11) be zero, minimize the right part of equation (11). Thus, we obtain the optimal controller (12) and (13), as shown at the bottom of the next page.

The theoretical controller $G_{CS(\text{opmin})}(s)$, is not physically. Therefore, a low-pass filter is added to the system, with a form similar to the following $f_{CS(\text{opmin})}(s) = \frac{1}{(\lambda_{CS}+1)^{m_{CS}}}$, where λ_{CS} is the time constant of a filter. Therefore, the setpoint tracking controller $G_{CS(\text{opmin})}(s)$ in practice is physically feasible, and the following controller is obtained,

$$\begin{aligned}
G_{CS}(s) &= G_{CS(\text{opmin})}(s)\cdot f_{CS(\text{opmin})}(s) \\
&= \frac{(\tau_1 s+1)^2}{K_1K_2A_{1+}^*(s)A_{2+}^*(s)A_{1-}(s)A_{2-}(s)(\lambda_{CS}+1)^{m_{CS}}}
\end{aligned} \tag{14}$$

Here, λ_{CS} is the tuning parameter of the closed-loop and always is positive. When λ_{CS} tends to zero, G_{cs} tends to optimal performance. That is, the tracking performance has better effect.

The value of m_{cs} depends on the order of numerator polynomials, and which aims at making the controller G_{cs} in practice. The selection of λ_{CS} should focus on the intermediate value between the nominal performance of the setpoint response and the corresponding actuator. In general, λ_{CS} is related to the process delay-time. Yin [16] et.al point out the starting value of λ_{CS} can be set $0.5(\theta_1+\theta_2)$. The recommended range of λ_{CS} is selected as $0.5(\theta_1+\theta_2) \sim 0.8(\theta_1+\theta_2)$. Usually, it is an empirical value.

2) DESIGN OF THE INNER-LOOP LOAD DISTURBANCE REJECTION CONTROLLER G_m

The IMC strategy is adopted to design an inner-loop load disturbance rejection controller. The controller is used to reject the disturbance in the inner loop.

From Fig 2, the transfer function of the closed-loop from y_2 to d can be inferred as

$$\frac{y_2}{d} = \frac{G_d}{1+G_mG_{c1}G_p} \tag{15}$$

Therefore, the complementary sensitivity function of the inner loop may be derived as,

$$T_d(s) = \frac{G_mG_{c1}G_p}{1+G_mG_{c1}G_p} \tag{16}$$

Equation (15) can be written as,

$$\frac{y_2}{d} = G_d(1-T_d) \tag{17}$$

From the H_2 optimal performance, the practically desired complementary sensitivity function of the inner loop is written as follows,

$$T_d(s) = \frac{1}{\lambda_f s+1}\cdot\frac{Q_{yy}(\theta_1 s)}{Q_{yy}(-\theta_1 s)}e^{-\theta_1 s} \tag{18}$$

Here, λ_f is a tunable parameter.

From Equation (16), we obtain the load disturbance rejection controller.

$$G_m(s) = \frac{T_d}{1-T_d}\cdot\frac{1}{G_{c1}G_p} = \frac{T_d/G_{c1}G_p}{1-T_d} \tag{19}$$

To achieve more robust stability and a good disturbance rejection performance, the selection of λ_f comes from the empirical values of many simulations in different cases. The suggested range of the tunable parameter is $0 \sim \frac{1}{2}(\theta_1+\theta_2)$. Under normal conditions, the recommended value is about $\frac{1}{4}(\theta_1+\theta_2)$.

C. THE STABILITY ANALYSIS OF THE MODIFIED CASCADE CONTROL SYSTEM

Stability is one of the key points in judging whether or not system works properly. The following work is to prove the stability of the modified cascade control system. Taking Fig.3 as a specific example to prove the stability and steady

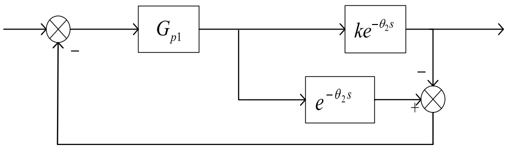

FIGURE 4. The block diagram of the proposed structure.

residual error. Here the dotted box represents the inner loop that takes IMC as its control strategy.

For ease of presentation, we assume $d = 0$ and $G_{p2} = k$. The closed-loop transfer function is given as follows,

$$\frac{Y_1(s)}{R_1(s)} = \frac{G_c(s)G_p(s)ke^{-\theta_2 s}}{1 + G_c(s)G_p(s)[1 + (k-1)e^{-\theta_2 s}]} \tag{20}$$

Substituting equation (2) and equation (3) into equation (20), and then simplifying, the following equations can be obtained,

$$Y_1(s) = \frac{G_c(s)G_p(s)ke^{-\theta_2 s}}{1 + G_c(s)G_p(s)[1 + (k-1)e^{-\theta_2 s}]}R_1(s) \tag{21}$$

$$\begin{aligned} E(s) &= R_1(s) - Y_1(s) \\ &= R_1(s)\left[1 - \frac{kG_c(s)G_p(s)e^{-\theta_2 s}}{1 + G_c(s)G_p(s)[1 + (k-1)e^{-\theta_2 s}]}\right] \\ &= \frac{1 + G_c(s)G_p(s)(1 - e^{-\theta_2 s})}{1 + G_c(s)G_p(s)[1 + (k-1)e^{-\theta_2 s}]} \end{aligned} \tag{22}$$

$$\begin{aligned} e_{ss} &= \lim_{s\to 0} S \cdot E(s) \\ &= \lim_{s\to 0} S \cdot \frac{1 + G_c(s)G_p(s)(1 - e^{-\theta_2 s})}{1 + G_c(s)G_p(s)[1 + (k-1)e^{-\theta_2 s}]} \end{aligned} \tag{23}$$

After calculation and the result can be obtained.

$$e_{ss} = \lim_{s\to 0} S \cdot \frac{1}{1+k} = 0 \tag{24}$$

There is no steady-state residual error in the system. The stability of the proposed method is described as follows. The block diagram expresses in Fig.4.

The transfer function of the block diagram is obtained from Fig.4.

$$G(s) = \frac{kG_{p1}e^{-\theta_2 s}}{1 + kG_{p1}e^{-\theta_2 s} - G_{p1}e^{-\theta_2 s}} \tag{25}$$

Substituting equation (2) into equation (25), we obtain,

$$G(s) = \frac{ke^{-(\theta_1+\theta_2)s}}{(\tau_1 s + 1) + (k-1)e^{-(\theta_1+\theta_2)s}} \tag{26}$$

Let the denominator be zero,

$$(\tau_1 s + 1) + (k-1)e^{-(\theta_1+\theta_2)s} = 0 \tag{27}$$

Entering $s = a + jb$ into equation (27), then we can get the following equation,

$$(\tau_1 a + 1) + (k-1)e^{-(\theta_1+\theta_2)a}\cos(\theta_1 + \theta_2)\mathrm{b} = 0 \tag{28}$$

$$\tau_1 b + (k-1)e^{-(\theta_1+\theta_2)a}\sin(\theta_1 + \theta_2)\mathrm{b} = 0 \tag{29}$$

Here, a and b are the real part and imaginary part of a complex number. respectively, we discuss the following cases.

Case1. When a $>$ 0, if $-1 < k - 1 < 1$, the equation (28) has no solution. That is, all the roots are located at the left plane, and the system is stable under the condition of $0 < k < 2$.

Case2. When a $<$ 0, the system is stable in itself.

Case3. When a $=$ 0, the roots are located at the imaginary axis, the system is in a critical stable state.

D. ROBUSTNESS ANALYSIS OF MODIFIED CASCADE CONTROL SYSTEM

It is essential to analyze the stability and robustness of the proposed structure due to uncertainty exists in a practical process. The types of uncertainty here discussed are model and parameters uncertainties between the ideal parameters and actual parameters in the system [24]. The robustness is strongly interrelated to the nominal performance.

The closed-loop system is robust if and only if the following condition is set up. The condition $\|T_m(s)\Delta l_m(s)\|_\infty < 1$ [19] is given by the small-gain Theorem. Here, $T_m(s)$ is the

$$\begin{aligned} \| W(1 - Y_{r1}(s)) \|_2^2 &= \| \frac{1}{s}(1 - G_{CS}(\frac{\tau_2 s + 1}{\alpha_c s + 1}) \cdot \frac{K_1 A_{1+}(s)A_{1-}(s)Q_{yy}(-\theta_1 s)}{(\tau_1 s + 1)Q_{yy}(\theta_1 s)} \cdot \frac{K_2 A_{2+}(s)A_{2-}(s)Q_{yy}(-\theta_2 s)}{(\tau_2 s + 1)Q_{yy}(\theta_2 s)} \|_2^2 \\ &= \| \frac{Q_{yy}(\theta_1 s)Q_{yy}(\theta_2 s)A_{1+}^*(s)A_{2+}^*(s) - Q_{yy}(-\theta_1 s)Q_{yy}(-\theta_2 s)A_{1+}(s)A_{2+}(s)}{sQ_{yy}(-\theta_1 s)Q_{yy}(-\theta_2 s)A_{1+}(s)A_{2+}(s)} \|_2^2 \\ &\quad + \| \frac{(\tau_1 s + 1)(\tau_2 s + 1 - G_{CS}(\frac{\tau_2 s+1}{\alpha_c s+1}) \cdot K_1 K_2 A_{1+}^*(s)A_{2+}^*(s)A_{1-}(s)A_{2-}(s)}{s(\tau_1 s + 1)(\tau_2 s + 1)} \|_2^2 \end{aligned} \tag{11}$$

$$\frac{(\tau_1 s + 1)(\tau_2 s + 1) - G_{CS(\text{opmin})}(\frac{\tau_2 s+1}{\alpha_c s+1}) \cdot K_1 K_2 A_{1+}^*(s)A_{2+}^*(s)A_{1-}(s)A_{2-}(s)}{s(\tau_1 s + 1)(\tau_2 s + 1)} = 0 \tag{12}$$

$$G_{CS(\text{opmin})} = \frac{(\tau_1 s + 1)^2}{K_1 K_2 A_{1+}^*(s)A_{2+}^*(s)A_{1-}(s)A_{2-}(s)} \tag{13}$$

closed-loop complementary sensitivity function. $\Delta l_m(s)$ is the multiplicative uncertainty of the process.

$$T_m(s) = \frac{G_Q(s)G_{p2}(s)}{1+G_Q(s)G_{p2}(s)} = \frac{k(\tau_1 s+1)(\tau_2 s+1)e^{-\theta_2 s}}{(\alpha_c s+1)(\tau_1 s+1)-(\tau_2 s+1)e^{-\theta_1 s}+(\tau_2 s+1)(\tau_1 s+1)ke^{-\theta_2 s}} \quad (30)$$

$$G_Q(s) = \frac{G_c(s)}{1-G_c(s)\hat{G}_p(s)} = \frac{\frac{(\tau_2 s+1)}{(\alpha_c s+1)}}{1-\frac{(\tau_2 s+1)}{(\alpha_c s+1)}\cdot\frac{e^{-\theta_1 s}}{(\tau_2 s+1)}} = \frac{(\tau_1 s+1)(\tau_2 s+1)}{(\alpha_c s+1)(\tau_1 s+1)-(\tau_2 s+1)e^{-\theta_1 s}} \quad (31)$$

If the parameters contain uncertainty elements, then $\Delta l_m(s)$ can be obtained as follows,

$$\Delta l_m(s) = \frac{G_p(s)-\hat{G}_p(s)}{\hat{G}_p(s)} \quad (32)$$

Here, $\hat{G}_p(s)$ is the model of an unstable process.

In a modified cascade control system, the delay-time includes uncertainty, and the controller should ensure the following equation must be found.

$$\|T_m(s)\|_\infty < \frac{1}{\left|e^{-\Delta\theta_1 s}-1\right|} \quad (33)$$

To ensure the robustness of the closed-loop performance, the robust stability and nominal performance must be satisfied with the following constraint,

$$\| |\Delta l_m(s)T_m(s)| + |W(s)(1-T_m(s))| \|_\infty < 1 \quad (34)$$

Here, $W(s)$ is the sensitivity weight function and usually the value is $1/s$ for step response of the load disturbance. Therefore, only a sound λ_f should be selected to satisfy the robustness stability and performance.

IV. SIMULATION EXAMPLE

The proposed structure exists in the industrial process model, especially in the condition area of the tobacco re-drying period. From offline to package, the process requires a long time and the moisture of the process will change at any moment. It needs 3-5 minutes to sample the moisture content if using an infrared moisture meter. Even microwave testing also need take 1-2 seconds. For the moisture content, this time is considered a large delay-time, and it is easy to cause a slow response. Thus, the implementation of control may cause the proper opportunity [24]. Traditional methods cannot ensure moisture content that is controlled within the required range.

The moisture content of the offline phase is usually approximately 12:5%, but during the transmission of tobacco, moisture is gradually lost. The loss of moisture content will affect the quality of tobacco. Therefore, a high-pressure sprinkler sprays pure water during the transmission process to ensure that the moisture content in the package is maintained at 12:5%. This control process adopts the modified cascade control to ensure that the system is more rapid performance, and can tend to the steady state quickly in the case of disturbance [25]. A schematic diagram of the moisture content from offline to package is shown in Fig.1. In this section, the effectiveness of the proposed method is verified through the simulation of real parameters. We consider the following style of control by analyzing different situations, and compare it in terms of the rapidity, stability and overshoot. In the tobacco re-drying process, the disturbances come mainly from the measuring devices, control valves, external interference and the process itself. Because this paper focuses on the process of tobacco re-drying, the controlled objects discussed below are all assumed to be first-order inertia plus pure delay-time.

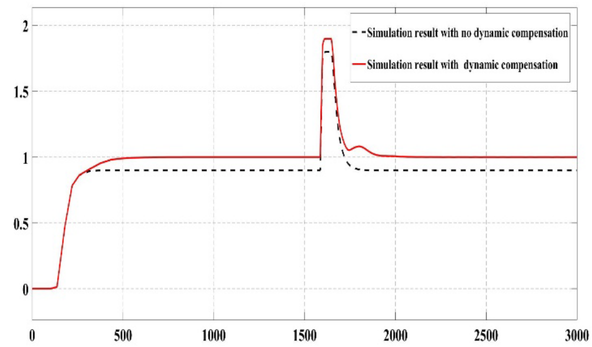

FIGURE 5. The simulation result of Case 1.

Case 1: we consider the condition where dynamic compensation is not contained in the outer loop. For the tobacco re-drying process, the transfer function of the offline moisture usually is assumed as $G_{p1} = \frac{1}{60s+1}e^{-60s}$, and the transfer function of the package moisture is assumed to be $G_{p2} = 0.9e^{-90s}$ in the actual process. According to the tuning principle mentioned above, take $\alpha_c = 30$ and $\alpha_f = 75$.

With the IMC method adopted in the inner loop, the simulation is carried out in the outer loop with dynamic compensation and without dynamic compensation. The simulation results are shown in Fig.5.

Fig.5 shows that the proposed method has a better system response, in addition, it can be seen that the proposed structure has no residual-error while the system with no dynamic compensation has larger residual-error under the same situation. At the same time, when there is disturbance existing in the system, the proposed structure can quickly restore stability. But the method with no dynamic compensation still exists residual error.

Case 2: We consider the difference control method with the same dynamic compensation as well as the same value of α_c and α_f. Here, we discuss the predictive PI(PPI) and IMC of the inner loop method, these two methods are popular in the control area. The simulation results are shown in Fig6.

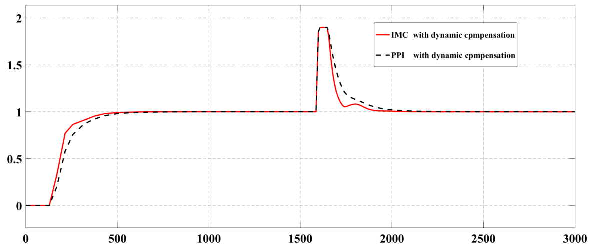

FIGURE 6. The simulation result of Case 2.

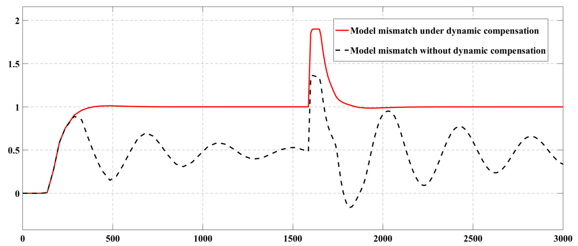

FIGURE 7. The simulation result of Case 3.

Fig.6 shows that the proposed method matching different control methods achieves a good effect in terms of stability, rapidity and residual error. The difference is that IMC has better rapidity than PPI, but PPI tends to be more stable in the presence of disturbance. The IMC can restore stable when the disturbance appears, but IMC has oscillation in the process of restoring stability. Reference [26] It is proved that the proposed method is suitable for a system with large delay-time. Moreover, the proposed method can be used in many industrial areas like tobacco re-drying.

Case 3: We consider a model that does not exactly represents the process with or without dynamic compensation under the same controller, and another parameter, adjusting only the parameter of the model. A comparison is performed under the condition of model mismatch. The simulation results are shown in Fig.7

Fig.7 shows that a large-scale model mismatch arises. The model mismatch without dynamic compensation gets out of control, and shocks severely. It cannot ultimately converge to stability. By contrast, despite a model mismatch, the proposed methods still own good control effect, well rapidity, also no overshoot [27]. When there is a secondary disturbance, the adjust speed is fast and almost unaffected by the model mismatch.

It can be observed that the proposed method ameliorates the large delay-time of the outer loop through dynamic compensation compared with the other methods, and the control action is smoother obviously. From a real simulation example, we found that the proposed methods own obvious advantages in some respects.

V. CONCLUSION

In a real tobacco re-drying production line, the quality of tobacco products is influenced by higher or lower moisture content in the package process, and moisture content control has caused wide concern. Therefore, an improved cascade dynamic compensation is proposed. The proposed method consists of only one controller in contrast to previous methods. The design and operation are relatively easy and can be performed for many processes with a large delay-time to control stable, unstable or integrating processes with a large delay-time, such as temperature and moisture control. Thus, in this manuscript, there are several innovations,(1)The conventional control methods, such as PID, PPI and IMC, usually have two or more controllers, the structure is complex and the control effect is poor for systems with a large delay-time.(2)Introducing the concept of dynamic compensation into a system with a large delay-time, and the rationality and property of the structure are proved through the H_2 optimal performance.(3)The robustness issue is resolved through small-gain theorem owing to the large-delay and dynamic compensation.

Based on the above analysis, the proposed method has better rapidity and no overshoot. The simulation results indicate that the proposed structure affords a significant improvement in the closed-loop performance. At the same time, it possesses a fine anti-disturbance ability and robustness, being especially suitable for an industrial site with a complex environment.

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 conflict of interest.

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