Temperature Control Based on Fuzzy Logic Two-degree-of-freedom Smith Internal Model

WANG Zhigang[1,2], HE Meng[1,2]

(1. *Tianjin Key Laboratory for Advanced Mechanical System Design and Intelligent Control*, *Tianjin University of Technology*, *Tianjin* 300384, *China*;
2. *National Demonstration Centre for Experimental Mechanical and Electrical Engineering Education*, *Tianjin University of Technology*, *Tianjin* 300384, *China*)

Abstract: According to the characteristics of the large time delay, nonlinearity and the great inertia of temperature control system in biomass pyrolysis reactor, a two-degree-of-freedom Smith internal model controller based on fuzzy control is proposed. Firstly, the mathematical model of the temperature control system is established by using the step response method, and then the two-degree-of-freedom Smith internal model controller is designed, and the good tracking performance and disturbance suppression performance can be obtained by designing the set value tracking controller and interference rejection capability. Secondly, the fuzzy control algorithm is used to realize the on-line tuning of the control parameters of the two-degree-of-freedom Smith internal model algorithm. The simulation results show that, compared with the traditional internal model control, fuzzy internal model PID control and two-degree-of-freedom Smith internal model control, the algorithm proposed in this paper improves the influence of lag time on the control system, realizes the separation control of set point tracking and anti-jamming performance and the self-tuning of control parameters, and improves the control performance of the system.

Key words: Smith Predictive Controller, Internal Model Control, Two Degrees of Freedom, Fuzzy Control Algorithm

1 Introduction

The pyrolysis reactor is the core component of the biomass pyrolysis unit, and its temperature affects the type of product and its yield, so the temperature control of the reactor is extremely important. In this paper, the biomass pyrolysis device adopts resistive heating furnace, and its temperature control system has the characteristics of non-linearity, large inertia and large time delay[1], and the working environment is complex and vulnerable to external disturbance. The stability and dynamic performance of the control system cannot be guaranteed, so the research on this kind of system controller has become the focus of many scholars.

PID control technology is widely used in various industrial control systems because of its simple control structure and easy realization[2-3]. However, the traditional PID has some shortcomings in the control of time-delay and model mismatch systems[4-5]. As a result, researchers have done a lot of research and put forward many solutions. For example, using adaptive state space predictive function PID controller based on extreme optimization method[6], combining optimization method with PID controller[7], a model-based parameter tuning rule of PID controller is proposed[8], but for large time-delay systems, the control effect is not satisfactory.

Smith predictive controller is often used in time-delay systems. It can move the time delay out of the closed loop and make predictive compensation in the feedback loop, which can eliminate the adverse effects of delay time on the dynamic performance of the control system and improve the response speed. Therefore, the Smith predictor can be successfully applied to time-delay control systems[9-11]. However, it needs to completely match the control object with the prediction model in order to achieve the ideal control effect[5]. In the actual production, it is difficult to obtain an accurate mathematical model and there will be the influence of unknown disturbances, which makes the Smith controller difficult to be widely used in complex industrial control objects. In order to enhance the robustness and anti-jamming ability of the control system, many scholars improve it. In [11], the improved Smith controller is applied to the parallel cascade control structure to improve the performance of the closed-loop control system. A simplified filtered Smith predictor is proposed for the state space system, which improves the influence of model mismatch on the control effect[12]. Compared with the traditional PID control, the fuzzy Smith control method can better solve the problems of nonlinearity, large inertia and large time delay[13]. For the network time delay system, the fuzzy model predictive control method is combined with the improved Smith predictor[14]. However, these methods cannot guarantee the stability of the control system.

The parameter adjustment of the internal model controller is simple and easy to implement, which has attracted the attention of many scholars. The parameters of the internal model controller are easy to adjust and easy to implement, which has attracted the attention of many scholars. Based on internal model control, the IMC-PID controller is designed. This kind of controller has only one adjusting parameter, and the approximate treatment is usually used for the time-delay link, which leads to the approximate error. In large time-delay systems, the control performance is greatly affected[15]. And the internal model controller is an one-degree-of-freedom controller, which has strong set point tracking performance and slow response to disturbance, so it can only make a compromise choice when adjusting the parameters[16-17], so the system with high control performance cannot be realized. As a result, the researchers propose that the two-degree-of-freedom internal model control can be used to solve this problem, and realize the separate control of tracking performance and anti-jamming performance[18-23]. In large time-delay systems, the control effect of Smith predictor is good, but if the prediction model is inconsistent with the actual control object or the disturbance is very large, it cannot get the ideal effect and may cause system oscillation. Internal model control does not need accurate mathematical model, but also can get better robustness and dynamic control performance. Therefore, the Smith internal model controller can be obtained by combining the internal model control with the Smith predictor.

In this paper, a novel two-degree-of-freedom Smith internal mode control based on fuzzy logic (FTDF-SIM) is proposed to improve the control performance of biomass pyrolysis temperature control system. Moreover, the controller can reduce delay effect on system, and adjust time constant of filter online when model mismatch improves robustness of system. Compared with other methods, it has good control performance.

2 Mathematic Model

The temperature control of biomass pyrolysis has the characteristics of non-linearity, large time delay, large inertia, and strong disturbance, which is very complex, so it is difficult to establish mathematical model by mechanism method. Therefore, the experimental modelling method is widely used in practical production. According to the characteristics of the heating process of the pyrolysis furnace, the mathematical model can be expressed as equation (1), that is, the first-order inertia plus lag link[24]. Based on this, the mathematical model is established by using the step response curve method.

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

In the formula, T is the time constant, K is the gain, τ is the time delay constant.

According to the experimental data, the rising curve of the temperature of the pyrolysis system is shown in Fig.1.

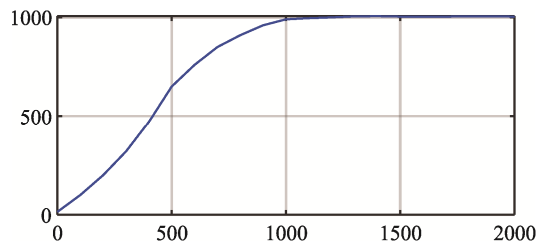

Fig.1 Temperature Response Curve

The mathematical model of the system is obtained from Cohn-Coon formula.

$$\begin{cases} K=\frac{\Delta C}{\Delta M} \\ T=1.5\left(t_{0.632}-t_{0.28}\right) \\ \tau=1.5\left(t_{0.28}-\frac{1}{3}t_{0.632}\right) \end{cases} \quad (2)$$

In formula (2), ΔC is the output response, ΔM is the input response, $t_{0.632}$ is the time of the control object when the response curve is $0.632\Delta C$, and $t_{0.28}$ is the time of the control object when the response curve is $0.28\Delta C$.

As a result, the transfer function of the temperature control system of the pyrolysis reactor can be calculated.

$$G(s)=\frac{2.63}{335s+1}e^{-155s} \quad (3)$$

3 Controller

In this paper, according to the characteristics of large time delay, large inertia and strong disturbance of biomass pyrolysis temperature control system, a two-degree-of-freedom Smith internal model control based on fuzzy logic is adopted.

3.1 Two-degree-of-freedom Smith Internal Model Control

Smith predictive controller performs well in time-delay systems, but when the model mismatch or disturbance is large, the Smith controller will lose its control effect and even lead to system instability. Internal model control can be regarded as an extension of Smith control, and a low-pass filter is added to improve the robustness of the system. The SIM controller combines the advantages of the two control methods, which not only reduces the influence of time delay, but also improves the robust performance of the system. There is only one adjustable parameter in this control method, that is, the time constant of the filter. In order to obtain good tracking performance and anti-jamming performance at the same time, a two-degree-of- freedom Smith internal model controller is used, as shown in Fig.2.

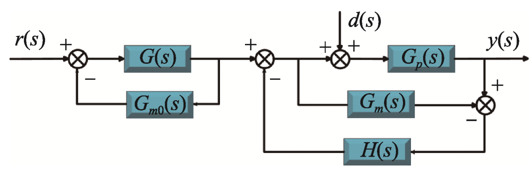

Fig.2 Two-degree-of-freedom Smith Internal Model Control Structure

The $r(s)$ is the input signal, $d(s)$ is unknown interference input, the $G(s)$ is the tracking controller and the $H(s)$ is the interference suppressor, the $G_p(s)$ is the controlled object, the $G_m(s)$ is the controlled object model, and the $G_{m_0}(s)$ is the part of the controlled object model that does not contain time delay, $y(s)$ is the system output.

The output response of the system can be obtained from Fig.2.

$$y(s)=\frac{G(s)G_p(s)}{\left[1+G(s)G_{m_0}(s)\right]\left[1+\left(G_p(s)-G_m(s)\right)H(s)\right]}r(s)+\frac{\left(1-G_m(s)H(s)\right)G_p(s)}{1+\left(G_P(s)-G_m(s)\right)H(s)}d(s) \quad (4)$$

When the model matches, that is, $G_p(s)=G_m(s)$.

$$y(s)=\frac{G(s)G_p(s)}{1+G(s)G_{m_0}(s)}r(s)+\left(1-G_m(s)H(s)\right)G_P(s)d(s) \tag{5}$$

According to the formula (5), the transfer function of the set value and interference from input to output can be obtained respectively.

$$G_r(s)=\frac{G(s)G_p(s)}{1+G(s)G_{m_0}(s)} \tag{6}$$

$$Gd(s)=\left(1-G_m(s)H(s)\right)G_p(s) \tag{7}$$

From equations (6) and (7), the controller $G(s)$ is related to the tracking performance of the system set point, and the $H(s)$ is related to the interference suppression performance. Therefore, good control performance can be achieved by designing $G(s)$ and $H(s)$ respectively, and the problem that the one-degree-of-freedom controller can only choose between the two performances is solved.

3.1.1 Set Value Tracking Controller

It can be seen from equation (6) that there is no time delay link in the closed loop of the system. For the control object $G_p(s)$, according to the Dahlin control algorithm, the desired set value tracking transfer function is set to formula (8).

$$G_r(s)=\frac{1}{\lambda_1 s+1}e^{-\tau s} \tag{8}$$

The combination of formula (6) and formula (8).

$$G(s)=\frac{Ts+1}{K\lambda_1 s} \tag{9}$$

In the formula, λ_1 is the time constant of the controller $G(s)$ filter.

3.1.2 Interference Suppression Controller

According to the internal model control method, the controller $H(s)$ is designed.

$$H(s)=G_{m0}^{-1}(s)f(s) \tag{10}$$

In this paper, the control object is a first-order time-delay system. In order to make the $H(s)$ realized, the $f(s)$ is set as a second-order filter.

$$f(s)=\frac{\delta s+1}{\left(\lambda_2 s+1\right)^2} \tag{11}$$

In the formula, δ is the coefficient and λ_2 is the filter time constant of the controller $H(s)$.

In order to improve the anti-jamming performance of the system, formula (12) can be obtained according to formula (7).

$$1-G_m(s)H(s)\Big|_{s=-\frac{1}{T}}=\left[1-\frac{(\delta s+1)e^{-\tau s}}{\left(\lambda_2 s+1\right)^2}\right]\Bigg|_{s=-\frac{1}{T}}=0 \tag{12}$$

Through the above formula, the value of δ can be obtained.

$$\delta=T\left[1-\left(1-\lambda_2/T\right)^2 e^{-\tau/T}\right] \tag{13}$$

According to the equations (10) (11) and (13), the controller $H(s)$ can be obtained.

$$H(s)=\frac{(Ts+1)(\delta s+1)}{K\left(\lambda_2 s+1\right)^2} \tag{14}$$

3.2 Fuzzy Two-degree-of-freedom Smith Internal Model Controller

According to the above analysis, good tracking performance and anti-interference can be obtained by adjusting the values of parameters λ_1 and λ_2 respectively. However, in the actual production, due to the existence of various uncertain factors, the fixed parameters often cannot get a better control effect, so in order to realize the on-line adjustment of control parameters, fuzzy control is added to the two-degree-of-freedom SIM controller, and the control system is shown in Fig.3.

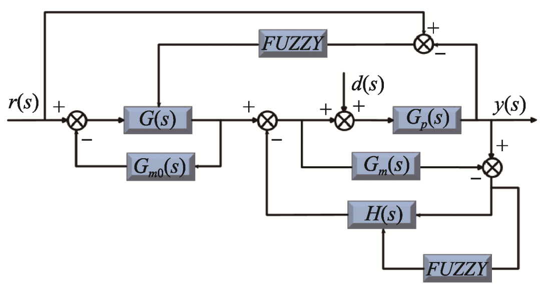

Fig.3 Two-degree-of-freedom Smith Internal Model Control Structure Based on Fuzzy Logic

It can be seen from the diagram that the two fuzzy controllers are two-dimensional inputs (system error e and error rate of change ec), one-dimensional output (parameter compensation$\Delta\lambda$), and the adjustment parameters of the controller$\mathrm{G}(s)$ and $\mathrm{H}(s)$ can be obtained.

$$\lambda_1 = \lambda_{10} + \Delta\lambda_1 \tag{15}$$

$$\lambda 2 = \lambda_{20} + \Delta\lambda 2 \tag{16}$$

Through the above two equations, λ_1 and λ_2 are modified to realize the on-line tuning of filter parameters.

Both input and output of the fuzzy controller choose the triangular membership function. In the controller $\mathrm{G}(s)$, the fuzzy subset of error e is set to $\{NB\ NM\ NS\ NZ\ PZ\ PS\ PM\ PB\}$, the fuzzy subset of error rate of change ec and output $\Delta\lambda_1$ is set to $\{NB\ NM\ NS\ ZO\ PS\ PM\ PB\}$, and the input and output domain is $[-6,6]$. In the controller $\mathrm{H}(s)$, the fuzzy subsets of input and output are all set to: $\{NB\ NM\ NS\ ZO\ PS\ PM\ PB\}$, and the input and output domain is $[-6,6]$.

The assignment of fuzzy rules is related to the control effect, so it is very important. In this paper, by drawing lessons from the experience of experts and operators, as well as continuous testing and debugging, to formulate fuzzy rules as shown in Table 1 and Table 2.

Table 1 $\Delta\lambda_1$ Fuzzy Control Rules

$\Delta\lambda_1$	ec						
e	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	*PB*	*PB*	*PB*	*PB*	*PM*	*PS*	*ZO*
NM	*PB*	*PB*	*PM*	*PS*	*PS*	*ZO*	*ZO*
NS	*PB*	*PM*	*PM*	*PS*	*ZO*	*ZO*	*NS*
NZ	*PB*	*PM*	*PS*	*ZO*	*ZO*	*NS*	*NM*
PZ	*PM*	*PS*	*ZO*	*ZO*	*NS*	*NS*	*PB*
PS	*PS*	*ZO*	*ZO*	*NS*	*NS*	*NM*	*NB*
PM	*ZO*	*ZO*	*NS*	*NS*	*NM*	*NB*	*NB*
PB	*ZO*	*NS*	*NS*	*NB*	*NB*	*NB*	*NB*

Table 2 $\Delta\lambda_2$ Fuzzy Control Rules

$\Delta\lambda_2$	ec						
e	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	*PB*	*PB*	*PB*	*NB*	*NB*	*NM*	*NM*
NM	*PB*	*PM*	*PM*	*NS*	*NS*	*ZO*	*ZO*
NS	*PM*	*PM*	*PS*	*ZO*	*ZO*	*PS*	*PS*
ZO	*PM*	*PS*	*PS*	*NS*	*NS*	*ZO*	*ZO*
PS	*ZO*	*ZO*	*NS*	*NM*	*NM*	*NM*	*NS*
PM	*NS*	*NM*	*NM*	*NS*	*NS*	*NS*	*ZO*
PB	*NB*	*NB*	*NB*	*PM*	*PM*	*PS*	*PS*

4 Simulation Analysis

In this paper, the temperature of biomass pyrolysis reactor is controlled. According to the previous expression, the transfer function of the control object is equation (3). The controller parameters $\lambda_1 = 279$, $\lambda_2 = 155$. The input $r(s)$ is a unit step signal, and an interference signal with an amplitude of 0.2 is added at $t = 3500s$. For reference and comparison, this paper selects the research methods of Qin [24] and the control methods of SIM and TDF-SIM. Among them, the parameter $\lambda = 279$ in reference [24] and traditional SIM control method is taken.

When the model is matched, the output of the control system is shown in Fig.4.

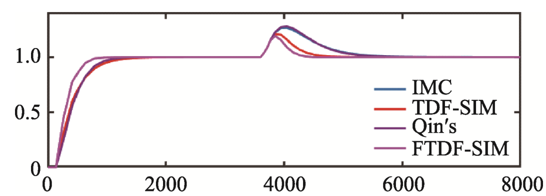

Fig.4 System Output Response When Model Matching

According to above image, when model matches, TDF-FSIM control method react quickly and improve smoothly. While the response velocity is slightly slower during heating stage but anti-jamming performance is relatively good. However, traditional IMC and document [24] control methods have longer regulation time when interference occurs and cannot recover to steady state value in time. Thus, when matching model, the algorithm improves the tracking performance and anti-jamming performance of system.

In order to verify the control performance of the proposed method when the model mismatches, the gain K, the time constant T and the lag time constant τ are reduced by 20% respectively, that is, $K = 2.1$, $T = 268$, $\tau = 124$, and the control simulation figure is shown in Fig.5, Fig.6 and Fig.7.

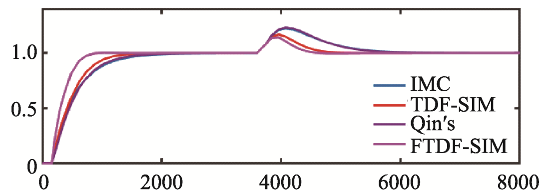

Fig.5 The Output Response of the System When the RV K Reduced by 20%

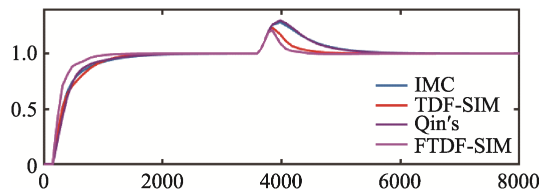

Fig.6 The Output Response of the System When the T Reduced by 20%

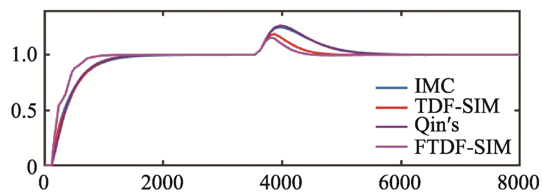

Fig.7 System Output Response When τ Reduced by 20%

According to Fig.5 when gain decreases 20% the control method used in this paper responds quickly and control process is stable. In Fig.6 and Fig.7, when time constant and delay constant decrease respectively, FTDF-SIM control algorithm has some instability during rising process, but this does not affect control system too much, and it is still the first to achieve steady state value through a period of adjustment. Through these three graphs, it can be observed that when the model mismatches the proposed method, it will have some instability in some cases but they are acceptable and relative to other methods, the adjust time is short and anti-jamming capability is strong.

When the gain, time constant and time delay constant are all reduced by 20%, the simulation diagram is shown in Fig.8.

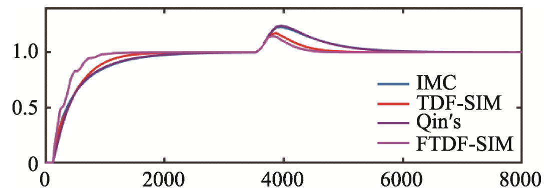

Fig.8 The Output Response of the System When All the Values of K, T, τ Reduced by 20%.

When the system is completely mismatched, the response speed of the method proposed in this paper is fast, and the set point tracking performance and anti-jamming ability are strong.

According to 5 figures above, compared with traditional IMC and document [24], it proves that two degrees of freedom controller can obtain good set tracking performance and disturbance rejection performance simultaneously. Compared with TDF-SIM method, this paper illustrates advantages of adjusting control parameters on line using fuzzy logic. Simulation results verify that the control strategy of FTFD-SIM is effective and robust.

5 Conclusion

Aiming at the temperature control system of biomass pyrolysis reactor, a two-degree-of- freedom Smith internal model control strategy based on fuzzy logic is proposed. In the system with large time delay and large inertia, good robustness can be obtained by combining Smith control with internal model control. The two-degree-of-freedom controller can adjust the set value tracking performance and anti-jamming performance respectively, and the two performances can be considered at the same time. With the addition of fuzzy logic, the on-line adjustment of control parameters is realized. Compared with other control methods, the results show that the proposed method improves the control performance of the system.

Acknowledgement

The financial support was given by Tianjin Technical Expert Project (19JCTPJC59300).

References

[1] S. S. Kuznetsov, L. P. Sebina, E. A. Ryzhkova, (2013). Regulating steam temperature in drum boilers by means of injection desuperheaters. initial investigation of the controlled object. *Fibre Chemistry*, 45(2), pp. 114-118.

[2] D. Ma, J. Chen, (2019). Delay Margin of Low-Order Systems Achievable by PID Controllers. *IEEE Transactions on Automatic Control*, 64(5), pp. 1958-1973.

[3] Q. B. Jin, Q. Liu, B. Huang, (2017). Control Design for Disturbance Rejection in the Presence of Uncertain Delays. *IEEE Transactions on Automation Science and Engineering*, 14(4), pp. 1570-1581.

[4] Y. M. Zhao, W. F. Xie, X. W. Tu, (2012). "Performance-based parameter tuning method of model-driven PID control systems," *Isa Transactions*, 51(3), pp. 393-399.

[5] S. M. Hassan, R. Ibrahim, N. Saad, et al. (2017). Adopting Setpoint Weighting Strategy for WirelessHART Networked Control Systems Characterised by Stochastic Delay, *IEEE Access*, 5, pp. 25885-25896.

[6] K. D. Lu, W. N. Zhou, G. Q. Zeng, et al. (2018). Design of PID controller based on a self-adaptive state-space predictive functional control using extremal optimization method. *Journal of the Franklin Institute-Engineering and Applied Mathematics*, 355(5), pp. 2197-2220.

[7] J. Cvejn, D. Vrancic, (2018). The magnitude optimum tuning of the PID controller: Improving load disturbance rejection by extending the controller. *Transactions of the Institute of Measurement and Control*, 40(5), pp. 1669-1680.

[8] G. G. Jin, Y. D. Son, (2019). Design of a Nonlinear PID Controller and Tuning Rules for First-Order Plus Time Delay Models. *Studies in Informatics and Control*, 28(2), pp. 157-166.

[9] M. P. Kumar, K. V. L. Narayana, (2018). Multi control scheme with modified Smith predictor for unstable first order plus time delay system. *Ain Shams Engineering Journal*, 9(4), pp. 2859-2869.

[10] D. G. Padhan, S. Majhi, (2012). An improved parallel cascade control structure for processes with time delay. *Journal of Process Control*, 22(5), pp. 884-898.

[11] G. L. Raja, A. Ali, (2017). Smith predictor based parallel cascade control strategy for unstable and integrating processes with large time delay. *Journal of Process Control*, 52, pp. 57-65.

[12] B. C. Torrico, M. P. de Almeida, T. A. Lima, et al. (2019). New simple approach for enhanced rejection of unknown disturbances in LTI systems with input delay. *Isa Transactions*, 94, pp. 316-325.

[13] H. C. Huang, S. Q. Zhang, Z. Yang, et al. (2018). Modified Smith fuzzy PID temperature control in an oil-replenishing device for deep-sea hydraulic system. *Ocean Engineering*, 149, pp. 14-22.

[14] A. Sakr, A. M. El-Nagar, M. El-Bardini, et. al. (2018). Improving the performance of networked control systems with time delay and data dropouts based on fuzzy model predictive control. *Journal of the Franklin Institute-Engineering and Applied Mathematics*, 355(15), pp. 7201-7225.

[15] A. R. Pathiran, P. Jagadeesan, (2018). Design of internal model control dead-time compensation scheme for first order plus dead-time systems. *Canadian Journal of Chemical Engineering*, 96(12), pp. 2553-2563.

[16] M. Shamsuzzoha, M. Lee, (2008). Design of advanced PID controller for enhanced disturbance rejection of second-order processes with time delay. *Aiche Journal*, 54(6), pp. 1526-1536.

[17] J. P. Sutikno, B. A. Aziz, C. S. Yee, et al, (2013). A New Tuning Method for Two-Degree-of-Freedom Internal Model Control under Parametric Uncertainty. *Chinese Journal of Chemical Engineering*, 21(9), pp. 1030-1037.

[18] T. Kobaku, S. C. Patwardhan, V. Agarwal, (2017). Experimental Evaluation of Internal Model Control Scheme on a DC-DC Boost Converter Exhibiting Nonminimum

Phase Behavior. *IEEE Transactions on Power Electronics*, 32(11), pp. 8880-8891.

[19] W. Tan, (2010). Unified Tuning of PID Load Frequency Controller for Power Systems via IMC, *IEEE Transactions on Power Systems*, 25(1), pp. 341-350.

[20] W. Zhang, Y. G. Wang, W. D. Zhang, (2017). Optimal disturbance rejection controller design for integrating processes with dead time based on algebraic theory. *International Journal of Systems Science*, 48(6), pp. 1266-1280.

[21] M. J. Li, P. Zhou, Z. C. Zhao, et al. (2016), Two-degree-of-freedom fractional order-PID controllers design for fractional order processes with dead-time. *Isa Transactions*, 61, 147-154.

[22] J. Singh, K. Chattterjee, C. B. Vishwakarma, (2018). Two degree of freedom internal model control-PID design for LFC of power systems via logarithmic approximations. *Isa Transactions*, 72, pp. 185-196.

[23] T. N. L. Vu, M. Lee, (2013). A unified approach to the design of advanced proportional-integral-derivative controllers for time-delay processes. *Korean Journal of Chemical Engineering*, 30(3), pp. 546-558.

[24] X. Qin, H, (2019). Temperature Control of Hot Sealing Cutter of Packaging Machine Based on Fuzzy Internal Model - PID. *Packaging Engineering*, 40(11), pp. 166-171.

Author Biographies

WANG Zhigang, received his B.Sc. degree in 2000 from Harbin Institute of Technology, received his M.Sc. degree in 2005 from Tianjin University, received his Ph.D. degree in 2010 from Tianjin University. Now he is an associate professor in Tianjin University of Technology. His main research direction is intelligent control.

Email: taylor@tjut.edu.cn

HE Meng, received her B.Sc. degree in 2018 Tang Shan College. Now she is a M.Sc. candidate in Tianjin University of Technology. Her main research interest is control of biomass pyrolysis reactor.

Email: hm950928@163.com