Development of an Antiwindup Technique for a Cascade Control System

Jeong Eun Bae, Kyeong Hoon Kim, Syng Chul Chu, Jaepil Heo, Sanghun Lim, and Su Whan Sung*

ABSTRACT: A cascade control system comprising the primary and secondary controllers suffers from a cascade-type integral windup problem in which the output saturation of the secondary control loop can considerably increase the integral part of the primary control loop. In this paper, we present a new predictive antiwindup technique that can completely eliminate the possibility of secondary controller output saturation, resulting in no cascade-type integral windup phenomenon. The proposed method does not require any type of process models; thus, its implementation is simple and straightforward, which is a very favorable advantage compared to the model-based antiwindup techniques from the practical viewpoint. Our simulation confirms that the proposed method can completely remove the primary controller’s cascade-type integral windup resulting from the saturation of the secondary controller output. Further, the proposed method exhibited good control performance without needing any type of process model for the various types of processes and controllers. Our experimental study successfully demonstrated that there are no problems in applying the proposed method to real plants.

1. INTRODUCTION

A proportional–integral–derivative (PID) controller has been most widely used in industry because of its simple and intuitive structure, good robustness to uncertainties, and good control performance. Until now, many efforts have been devoted to improve the control performance of the PID controller. Various autotuning methods have been proposed and applied in industry to automatically determine the tuning parameters of the PID controller.1–12 Also, enhanced controllers involving multiple PID controllers and process models (model-based PID controllers, multi-input–multi-output PID controllers, combined feedback and feedforward PID controllers, time delay compensators, and cascade controllers) have been developed and widely applied to various fields.13–15 However, less attention has been devoted to antiwindup techniques that prevent the performance degradation of the PID controller, which can be attributed to the integral windup, owing to the saturation of the actuator.16,17 Only a few antiwindup techniques have been proposed to manipulate the cascade-type integral windup phenomenon in a cascade PID control system.18–21 However, these techniques require an additional process model and cannot systematically manipulate the time delay. Furthermore, they are considerably complicated and necessitate the application of a heavy computation load, eliminating the advantage associated with the use of the PID controller. Recently, two cascade antiwindup techniques, i.e., cascade conditional integration and cascade backcalculation, have been proposed by extending local antiwindup techniques for a single-loop control system to a cascade control system. These two cascade antiwindup techniques exhibit much better performances than local antiwindup techniques.22 However, they still have limitations that an additional process model is required; further, the saturation of the secondary controller output cannot be structurally suppressed. In this paper, a new predictive antiwindup technique is developed to completely remove the possibility of saturation of the secondary controller output, resulting in no cascade-type integral windup phenomenon. The proposed method does not require any type of process model. Therefore, its implementation is simple, which is a very favorable advantage from the practical perspective. Simulation and experimental studies have successfully demonstrated that the proposed method can completely remove the cascade-type integral windup of the primary controller caused by the saturation of the secondary controller output. Furthermore, the proposed method exhibits good control performances for various types of processes and controllers, and there are no problems associated with its application to real plants.

Received: October 9, 2020
Accepted: December 2, 2020
Published: December 11, 2020
2. RESULTS AND DISCUSSION

2.1. Development of Antiwindup Techniques for a Cascade Control System. Herein, we briefly introduce the difference between cascade control and conventional single-loop control and why antiwindup techniques are required for cascade control. Figure 1a shows the control structure of the conventional single-loop control. Here, \( y_s \), \( y_r \), and \( u \) are the setpoint, process output, and process input, respectively. The control output of the PID controller is \( u_{PID} \) and \( d \) is the disturbance. Figure 1b shows the control structure of the cascade control system. There are two control loops called the primary control loop and the secondary control loop. The setpoints of the primary and secondary control loops are \( y_{s1} \) and \( y_{s2} \), respectively. \( u_1 \) and \( u_2 \) are the process outputs of the primary and secondary control loops, respectively. \( u_{PID1} \) and \( u_{PID2} \) are the control outputs of the primary and secondary PID controllers, respectively. There are two saturators: one is the primary saturator between \( u_{PID1} \) and \( u_1 \) and the other is the secondary saturator between \( u_{PID2} \) and \( u_2 \).

The dynamics of the process output becomes considerably sluggish when \( u_{PID} \) is greater than the upper limit of the saturator or less than the lower limit of the saturator (i.e., \( u \) is saturated), resulting in an abnormal increase in the integral part of the PID controller (called integral windup) and significant control performance degradation. Several antiwindup techniques called conditional integration and backcalculation have been used for conventional single-loop control in industry to prevent the occurrence of the integral windup phenomenon. There are three different integral windup phenomena associated with cascade control. The first phenomenon is the local integral windup of the primary controller because of primary saturation. The second phenomenon is the local integral windup of the secondary controller because of secondary saturation, whereas the third phenomenon is the cascade-type integral windup of the primary controller because of secondary saturation. The first and second local integral windup phenomena in cascade control are similar to those associated with single-loop control. Thus, the local integral windup phenomena can be effectively eliminated using local antiwindup techniques developed for single-loop control. However, the cascade-type integral windup phenomenon cannot be manipulated by local antiwindup techniques developed for single-loop control.
because this phenomenon originated from the secondary control loop rather than from the primary control loop. Thus, the integral part of the primary controller is abnormally accumulated through secondary loop saturation and not through primary loop saturation. Several types of cascade antwindup techniques for cascade control have been proposed to overcome the cascade-type integral windup. These techniques can effectively remove the cascade-type integral windup phenomenon considerably better than the previous local approaches for single-loop control. However, they suffer from several problems because some of them are considerably complicated and computationally heavy for applying to a real PID control system and require process models, which is a major disadvantage from the practical perspective.

In this paper, a new cascade antiwindup technique called predictive antiwindup is proposed, as shown in Figure 2. This technique is designed to remove the cascade-type integral windup by adjusting the upper and lower limits of the primary saturator based on the prediction of the secondary PID controller’s behavior to remove the possibility of secondary saturation. The control output of the secondary PID controller for the given limits of the primary saturator can be formulated for the given PID controller. Subsequently, the upper limit and lower limit of the primary saturator corresponding to the upper limit and the lower limit of the secondary saturator can be easily estimated, indicating that secondary saturation can be entirely removed by considering the estimates.

Let us assume that the noise-suppressing PID controller that has been widely used in industry is used for the primary and secondary PID controllers. Then, the control outputs of the primary and secondary PID controllers in the time domain can be formulated similarly to that in eqs 1–17. Refer to Sung et al.1 for details.

\[ u_{p1}(k) = k_i(y_i(k) - y(k)) \]  
\[ u_{d1}^f(k) = k_i \frac{(y_i(k) - y(k)) - (y_i(k-1) - y(k-1))}{\Delta t} \]  
\[ u_{d2}(k) = \exp\left(-\frac{\Delta t}{\alpha_i \tau_{d2}}\right) u_{d2}(k-1) + \left(1 - \exp\left(-\frac{\Delta t}{\alpha_i \tau_{d2}}\right)\right) u_{p2}(k) \]  
\[ u_{PID1}(k) = u_{p1}(k) + u_{d1}(k) + u_{D1}(k) \]  
\[ u_{PID2}(k) = u_{p2}(k) + u_{d1}(k) + u_{D2}(k) \]

If \( u_{PID1}(k) > u_{max1,f} \), then \( u_i(k) = u_{max1,f} \)

If \( u_{PID1}(k) < u_{min1,f} \), then \( u_i(k) = u_{min1,f} \)

If \( u_{min1,f} \leq u_{PID1}(k) \leq u_{max1,f} \), then \( u_i(k) = u_{PID1}(k) \)

\[ y_{i2}(k) = u_i(k) \]

\[ u_{d1}(k) = k_i (y_{i2}(k) - y_i(k)) \]

\[ u_{d2}^f(k) = k_i \frac{(y_{i2}(k) - y_i(k)) - (y_{i2}(k-1) - y_i(k-1))}{\Delta t} \]

\[ u_{max2} = \exp\left(-\frac{\Delta t}{\alpha_i \tau_{d2}}\right) u_{max2}(k-1) + \left(1 - \exp\left(-\frac{\Delta t}{\alpha_i \tau_{d2}}\right)\right) u_{d2}(k) \]

If \( u_{PID2}(k) > u_{max2} \), then \( u_i(k) = u_{max2} \)

If \( u_{PID2}(k) < u_{min2} \), then \( u_i(k) = u_{min2} \)

If \( u_{min2} \leq u_{PID2}(k) \leq u_{max2} \), then \( u_i(k) = u_{PID2}(k) \)

In these equations, the subscripts 1 and 2 indicate the primary controller and secondary controller, respectively. \( \Delta t \) is the sampling time of the PID controllers, and \( k \) denotes the \( k \)th sample. The proportional gain, integral time, and derivative time of the PID controller are denoted as \( k_i, \tau_i \), and \( \tau_d \) respectively. \( \alpha \) denotes the weight for noise-suppressing that usually ranges from 0.05 to 0.20.1 With the increasing \( \alpha \) value, better robustness to noise can be obtained; however, the control performance deteriorates. \( \tau_i \) denotes the tracking time constant for local back-calculation in the case of the antiwindup technique. The recommended range of the tracking time constant is \( \tau_d \leq \tau_i \leq \tau_r \).1 Equations 1 and 3 can be used to calculate the proportional part and the derivative part of the primary PID controller, respectively. Equation 16 can be used to calculate the integral part of the primary PID controller when considering the local back-calculation antiwindup technique. Equation 4 represents the control output of the primary PID controller, whereas eqs 5–7 provide the output of the primary saturator; thus, we can obtain the setpoint of the secondary PID controller. \( u_{max1,f} \) and \( u_{min1,f} \) denote the final upper and final lower limits of the primary saturator, respectively. Equations 9 and 11 can be used to calculate the proportional and derivative parts of the secondary PID controller, respectively. Equation 17 can be used to calculate the integral part of the secondary PID controller when considering the local back-calculation antiwindup technique. Equation 12 represents the control output of the secondary PID controller. Equations 13–15 represent the output of the secondary saturator. \( u_{max2} \) and \( u_{min2} \) are the upper and lower limits of the secondary saturator, respectively.

Thus, it is possible to estimate the upper limit of the primary controller that makes the secondary control output become the upper limit of the secondary saturator by obtaining the setpoint of \( y_{i2}(k) \) as shown in eq 8 after the secondary control output of eq 12 is replaced by the upper
limit of the secondary saturator as $u_{\text{PID2}}(k) = u_{\text{max2}}$. Similarly, it is possible to estimate the lower limit of the secondary saturator by obtaining the setpoint of $y_2(k)$ as shown in eq 8 after the secondary control output of eq 12 is replaced with the lower limit of the secondary saturator as $u_{\text{PID2}}(k) = u_{\text{min2}}$. Further, the predictive antiwindup can be summarized as follows. Equations 18–26 are used to calculate the limits of the primary saturator of $y_{S,\text{max}}$ and $y_{S,\text{min}}$, corresponding to the limits of the secondary saturator for different types of controllers. Equations 27–30 are used to calculate the final limits of the primary saturator selected using the predictive antiwindup technique by combining the estimates of $y_{S,\text{max}}$ and $y_{S,\text{min}}$ and the primary saturator’s limits of $u_{\text{max1}}$ and $u_{\text{min1}}$.

If the secondary controller is a $P$ controller, the limits of the primary saturator of eqs 19 and 20 corresponding to the limits of the secondary saturator of eq 18 can be calculated as follows.

$$u_{\text{min2}} \leq k_c(y_t(k) - y_s(k)) \leq u_{\text{max2}}$$ (18)

$$y_{t,\text{max}}(k) = \frac{u_{\text{max2}}}{k_c} + y_s(k) \text{ from eq. (18)}$$ (19)

$$y_{t,\text{min}}(k) = \frac{u_{\text{min2}}}{k_c} + y_s(k) \text{ from eq. (18)}$$ (20)

If the secondary controller is a $PI$ controller, the limits of the primary saturator of eqs 22 and 23 corresponding to the limits of the secondary saturator of eq 21 can be calculated as follows.

$$u_{\text{min2}} \leq \left\{ k_c(y_t(k) - y_s(k)) + u_t(k - 1) + \frac{k_c}{\tau_c}(y_t(k) - y_s(k))\Delta t \right\} \leq u_{\text{max2}}$$ (21)

$$y_{t,\text{max}}(k) = \frac{u_{\text{max2}} + \left( k_c + \frac{k_c}{\tau_c}\Delta t \right)y_s(k) - u_t(k - 1)}{\left( k_c + \frac{k_c}{\tau_c}\Delta t \right)} \text{ from eq. (21)}$$ (22)

$$y_{t,\text{min}}(k) = \frac{u_{\text{min2}} + \left( k_c + \frac{k_c}{\tau_c}\Delta t \right)y_s(k) - u_t(k - 1)}{\left( k_c + \frac{k_c}{\tau_c}\Delta t \right)} \text{ from eq. (21)}$$ (23)

If the secondary controller is a $PID$ controller, the limits of the primary saturator of eqs 25 and 26 corresponding to the limits of the secondary saturator of eq 24 can be calculated as follows.

![Figure 3. Control performances of the proposed methods for the first process. (a) Primary process output, (b) integral part of the primary controller output, and (c) secondary controller output.](https://dx.doi.org/10.1021/acsomega.0c04927)
Figure 4. Control performances of the proposed methods for the second process. (a) Primary process output, (b) integral part of the primary controller output, and (c) secondary controller output.

Figure 5. Control performances of the proposed methods for the third process. (a) Primary process output, (b) integral part of the primary controller output, and (c) secondary controller output.
Figure 6. Control performances of the proposed methods for the fourth process. (a) Primary process output and (b) integral part of the primary controller output.

\[
\begin{align*}
\text{If } u_{\text{max}} &> y_{2,\text{max}}(k), \text{ then } u_{\text{max},f} = y_{2,\text{max}}(k) \\
\text{If } u_{\text{max}} &\leq y_{2,\text{max}}(k), \text{ then } u_{\text{max},f} = u_{\text{max}} \\
\text{If } u_{\text{min}} &< y_{2,\text{min}}(k), \text{ then } u_{\text{min},f} = y_{2,\text{min}}(k) \\
\text{If } u_{\text{min}} &\geq y_{2,\text{min}}(k), \text{ then } u_{\text{min},f} = u_{\text{min}}
\end{align*}
\]

In summary, the proposed antiwindup technique eliminates the possibility of saturation of the secondary saturator by selecting limits of the primary saturator as shown in eqs 23, 25, and 27 for the PI-type secondary controller, and eqs 26, 29, and 30 for the PID-type secondary controller. Therefore, the cascade-type integral windup phenomenon cannot occur from the structural perspective. Also, the proposed method does not require any type of process models; thus, its implementation is simple and straightforward, which is a great advantage when compared with the model-based antiwindup techniques from a practical perspective.

2.2. Simulation Study. Various types of processes and controllers have been simulated to demonstrate the performance of the proposed predictive antiwindup technique and compare the proposed method with previous approaches.

In the first case, the secondary controller is a P controller. The primary process is a third-order plus time delay model, whereas the secondary process is a first-order plus time delay model, as shown in eqs 31 and 32.

\[
G_p = \frac{1.0 \exp(-0.4s)}{s^3 + 3s^2 + 3s + 1}
\]

\[
G_{f2} = \frac{2.0 \exp(-0.1s)}{s + 2}
\]
The tuning parameters of the primary and secondary PID controllers were tuned based on the ITAE-2 tuning rules (primary controller: \( k_c = 1.375 \), \( \tau_i = 6.884 \), and \( \tau_d = 1.367 \) and secondary controller: \( k_c = 15.085 \), \( \tau_i = 0.346 \), and \( \tau_d = 0.331 \)). The upper and lower limits of the secondary saturator were 1.17 and 0, respectively. The tracking time constants of the primary and secondary PID controllers remained the same with integral time. As shown in Figure 4a, the proposed method shows superior control performance compared to the previous approaches, i.e., cascade conditional integration and no cascade antiwindup techniques, in terms of overshoot and the rising time. Although the cascade back-calculation technique shows a performance similar to that of the proposed method, the proposed method is definitely preferred from the actual implementation perspective because the cascade back-calculation technique requires a process model, whereas the proposed method does not use any type of process model, thereby ensuring simplicity.

In the third case, the response time of the secondary process is similar to that of the primary process. Both the primary and secondary processes are the second-order plus time delay models, as shown in eqs 35 and 36.

\[
G_{p1} = \frac{1.0 \exp(-3.0s)}{4s^2 + 6s + 1}
\]  

\[
G_{p2} = \frac{1.0 \exp(-0.1s)}{s^2 + 3s + 9}
\]  

The primary PID controller was tuned by the ITAE-2 tuning rule with a model reduction method (\( k_c = 1.859 \), \( \tau_i = 2.741 \), and \( \tau_d = 0.919 \)). The secondary P controller was tuned based on the ZN tuning rule (\( k_c = 4.251 \)). The upper and lower limits of the secondary saturator were 1.3 and 0, respectively. The tracking time constant of the primary PID controller remained the same with integral time. As shown in Figure 3a, the proposed method provides the best performance with a small overshoot and short rising time. The cascade control with no cascade antiwindup technique suffers from serious integral part accumulation of the primary PID controller during output saturation of the secondary P control, as shown in Figure 3b. Although previous approaches of cascade conditional integration and cascade back-calculation show relative improvement compared to the case of no cascade antiwindup techniques, they still show a longer rising time compared to the proposed method. Furthermore, the cascade back-calculation method requires a process model, complicating the implementation.

In the second case, the response time of the secondary process is considerably less than that of the primary process. Both the primary and secondary processes are the second-order plus time delay models, as shown in eqs 33 and 34.

\[
G_{p1} = \frac{1.0 \exp(-3.0s)}{4s^2 + 6s + 1}
\]  

\[
G_{p2} = \frac{1.0 \exp(-0.1s)}{s^2 + 3s + 9}
\]  

In the second case, the response time of the secondary process is considerably less than that of the primary process. Both the primary and secondary processes are the second-order plus time delay models, as shown in eqs 33 and 34.

\[
G_{p1} = \frac{1.0 \exp(-3.0s)}{4s^2 + 6s + 1}
\]  

\[
G_{p2} = \frac{1.0 \exp(-0.1s)}{s^2 + 3s + 9}
\]  

Figure 7. Liquid level control system.
The tuning parameters of the primary and secondary PID controllers were tuned based on the ITAE-2 tuning rules (primary controller: $k_c = 1.745$, $\tau_i = 6.612$, and $\tau_d = 1.107$ and secondary controller: $k_c = 2.251$, $\tau_i = 3.126$, and $\tau_d = 1.079$).\textsuperscript{1} The upper and lower limits of the secondary saturator were 1.3 and 0, respectively. The tracking time constants of the primary and secondary PID controllers remained the same with integral time, respectively. Figure 5 shows that the proposed method effectively prevents cascade-type integral windup and that it exhibits the best control performance in terms of the performance criteria of the overshoot and rising time compared with other methods. Although the performance of the previous cascade back-
calculation is close to that of the proposed method, the proposed method (model-free) is definitely better than the previous approach (model-based) when considering the implementation complexity.

In the fourth case, noise and nonlinearity are added to the process of the third case for enhancing the realistic nature of the simulation. Both the primary and secondary processes are the second-order plus time delay models with 5% nonlinearity, as shown in eqs 37 and 38. The primary and secondary process outputs are contaminated by uniformly distributed random noises exhibiting a variation of ±0.005.

\[ G_{p1} = \frac{1.0(1 - 0.05y_1) \exp(-1.0s)}{4s^2 + 6s + 1} \]  
\[ G_{p2} = \frac{1.0(1 - 0.05y_2) \exp(-0.7s)}{3s^2 + 3s + 1} \]  

The weight for the noise-suppressing of the primary and secondary PID controllers was 0.2. The tuning parameters of the primary and secondary PID controllers were tuned using the ITAE-2 tuning rules (primary controller: \( k_c = 1.745, \tau_i = 6.612, \) and \( \tau_d = 1.107 \) and secondary controller: \( k_c = 2.251, \tau_i = 3.126, \) and \( \tau_d = 1.079 \)). The upper and lower limits of the secondary saturator were 1.3 and 0, respectively. The tracking time constants of the primary and secondary PID controllers remained the same with integral time. Figure 6 shows that the proposed method effectively prevents cascade-type integral windup and that it exhibits the best control performance compared with other methods under non-linearity and noisy environments.

2.3. Experimental Study. The proposed antiwindup technique was successfully commercialized by implementing it using a commercial process automation software called PROMONICON (www.tbb-automation.com). PROMONICON has been successfully applied to various processes such as single crystal, cement, adhesive, and polymer production processes.

We demonstrated the performance of the proposed method for the liquid level control system presented in Figure 7. The liquid level control system includes three tanks. The process output and input of the secondary process are the liquid level of the first tank and the opening percent of the valve, respectively. The process output and input of the primary process are the liquid level of the third tank and the output flow rate of the first tank, respectively. The tuning parameters of the primary and secondary PID controllers are \( k_c = 3.0, \tau_i = 50.0, \) and \( \tau_d = 5.0 \) and \( k_c = 1.2, \tau_i = 20.0, \) and \( \tau_d = 1.5 \), respectively. Figure 8 shows the control performance of the PID controllers with almost no limitations (i.e., the upper limit of the valve = 100% and the lower limit of the valve = 0%). The techniques of the previous local antiwindup method and the proposed predictive antiwindup method exhibit similar performances because there is nearly no valve saturation. However, the proposed method is definitely superior to the previous approach when the upper and lower limits of the valve are 70 and 45%, respectively, as shown in Figure 9. This is because the proposed method can prevent fast accumulation of the integral part of the primary PID controller owing to the saturation of the secondary PID controller output, while the previous approach cannot systematically manipulate the cascade-type integral windup phenomenon. The experimental results confirmed that the proposed predictive antiwindup technique can be successfully applied to real plants and that it exhibits better control performances compared to those exhibited by the previous approach.

Further, the proposed method was applied to control the temperature of the commercial-scale batch reactor (10 ton production per batch) for polymer production in Figure 10 by adjusting the cooling jacket water valve. Figure 11 shows the polymer plant of 10 batch reactors controlled by the proposed method. Figure 12 shows the control performance of the proposed method for the polymer manufacturing plant.
PROMONICON software, and Figure 12 shows the control performance of the proposed antiwindup technique in controlling the reactor temperature, confirming a fairly good control performance and no problems associated with the application of the proposed method to commercial-scale processes.

3. CONCLUSIONS

In this paper, we proposed a new predictive antiwindup technique for cascade control that can handle the integral windup phenomenon of the primary PID controller. The proposed method successfully prevents cascade integral windup by eliminating the possibility of secondary saturation by adjusting the upper and lower limits of the primary saturator based on the formula that describes the relationship between the limits of the secondary and primary saturators for the given PID controller. Also, the proposed method (model-free) showed a very favorable advantage compared to the previous approaches based on process models from the perspective of practical implementation because obtaining a process model is difficult and places a significant burden on the control engineer. Our simulation study confirmed that the proposed predictive antiwindup technique can effectively remove cascade integral windup and that it exhibits better control performance when compared with those exhibited by previous approaches for various types of processes and controllers. Further, our experimental study demonstrated that there are no problems in applying the proposed method to real and commercial-scale processes.

AUTHOR INFORMATION

Corresponding Author
Su Whan Sung – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; Email: suwhansung@knu.ac.kr; Fax: +82-53-950-6615

Authors
Jeong Eun Bae – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
Kyeong Hoon Kim – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
Syng Chul Chu – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
Jaepil Heo – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
Sanghun Lim – Department of Chemical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04927

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20173030018990).

REFERENCES

(1) Sung, S. W.; Lee, J.; Lee, I. B. Process Identification and PID Control; John Wiley & Sons, 2009.
(2) Seborg, D. E.; Mellichamp, D. A.; Edgar, T. F.; Doyle, F. J., III Process Dynamics and Control; John Wiley & Sons, 2010.
(3) Cheon, Y. J.; Sung, S. W.; Lee, J.; Je, C. H.; Lee, I. B. Improved frequency response model identification method for processes with initial cyclic-steady-state. AIChE J. 2011, 57, 3429–3435.
(4) Kim, K.; Cheon, Y. J.; Lee, I. B.; Lee, J.; Sung, S. W. A frequency response identification method for discrete-time processes with cyclic steady state conditions. Automatica 2014, 50, 3260–3267.
(5) Ryu, K. H.; Lee, S. N.; Nam, C. M.; Lee, J.; Sung, S. W. Discrete-time frequency response identification method for processes with final cyclic-steady-state. J. Process Control 2014, 24, 1002–1014.
(6) Jin, C. Y.; Ryu, K. H.; Sung, S. W.; Lee, J.; Lee, I. B. PID auto-tuning using new model reduction method and explicit PID tuning rule for a fractional order plus time delay model. J. Process Control 2014, 24, 113–128.
(7) Berner, J.; Hagglund, T.; Aström, K. J. Asymmetric relay autotuning – Practical features for industrial use. Control Eng. Pract. 2016, 54, 231–245.
(8) Lee, J.; Sung, S. W.; Lee, F. Y.; Baldea, M.; Edgar, T. F. Full closed-loop tests for the relay feedback autotuning of stable, integrating, and unstable processes. ACS Omega 2019, 4, 18760–18770.
(9) Park, B. E.; Kim, K. H.; Kang, H. S.; Sung, S. W.; Lee, I. B. Improved relay feedback method under noisy and disturbance environments. J. Chem. Eng. Jpn 2019, 52, 430–438.
(10) Nikita, S.; Lee, M. Control of a wastewater treatment plant using relay auto-tuning. Korean J. Chem. Eng. 2019, 36, 505–512.
(11) Ponglai, J.; Angeli, C.; Shi, P.; Su, X.; Assawinchaichote, W. Optimal PID controller autotuning design for MIMO nonlinear systems based on the adaptive SLP algorithm. Int. J. Control Autom. Syst. 2020, 19, 1–12.
(12) Zhao, S.; Liu, S.; Keyser, R. D.; Jonescu, C. M. The application of a new PID autotuning method for the steam/water loop in large scale ships. Processes 2020, 8, 196.
(13) Morari, M.; Zafiriou, E. Robust Process Control; Prentice Hall, 1989.
(14) Jia, B.; Mikalsen, R.; Smallbone, A.; Zao, Z.; Feng, H.; Roskilly, A. P. Piston motion control of a free-piston engine generator: A new approach using cascade control. Appl. Energy 2016, 179, 1166–1175.
(15) Yin, C.; Wang, H.; Sun, Q.; Zhao, L. Improved cascade control system for a class of unstable processes with time delay. Int. J. Control Autom. Syst. 2019, 17, 126–135.
(16) Jail, M. H. A.; Salan, N. M.; Hamdan, R.; Ngadengon, R.; Kadir, H. A.; Noh, F. H. M.; Kasuan, N. Integration of back calculation anti windup and smith predictor on PID controller for varying time delay system with input constraint. Appl. Modell. Simul. 2019, 3, 95–101.
(17) da Silva, L. R.; Flesch, R. C.; Normey-Rico, J. E. Analysis of anti-windup techniques in PID control of processes with measurement noise. IFAC-PapersOnLine 2018, 51, 948–953.
(18) Aström, K. J.; Hagglund, T. PID Controllers: Theory, Design, and Tuning; Instrument Society of America, 1995.
(19) Rehan, M.; Ahmad, A.; Iqbal, N. Static and low order anti-windup synthesis for cascade control systems with actuator saturation: An application to temperature-based process control. ISA Trans. 2010, 49, 293–301.
(20) Mehdi, N.; Rehan, M.; Malik, F. M.; Bhatti, A. I.; Tufail, M. A novel anti-windup framework for cascade control systems: An application to underactuated mechanical systems. ISA Trans. 2014, 53, 802–815.

(21) Adegbege, A. A.; Heath, W. P. A framework for multivariable algebraic loops in linear anti-windup implementations. Automatica 2017, 83, 81–90.

(22) Bae, J. E.; Kim, K. H.; Chu, S. C.; Heo, J.; Lim, S.; Sung, S. W. Development of anti-windup techniques for cascade control system. Korean Chem. Eng. Res. 2020, 58, 430–437.