Rational approximations to design controllers for unstable processes, including dead-time

Marko Bošković, student
Faculty of Electrical Engineering
University of East Sarajevo
East Sarajevo, Bosnia and Herzegovina
boskovic.marko.etf@gmail.com

Tomislav B. Šekara
Faculty of Electrical Engineering
University of Belgrade
Belgrade, Serbia
tomi@etf.rs

Milan R. Rapaić
Boris Jakovljević
Faculty of Technical Sciences,
University of Novi Sad,
Novi Sad, Serbia
rapaja@uns.ac.rs
bjakov@uns.ac.rs

Abstract – **This paper addresses the problem of designing complex controllers for unstable industrial processes with transport delay under constraints on robustness and performance. The solution to the control design problem is obtained in a non-rational form which is rationalized by using various methods. The paper also presents a comparative analysis of different approximation techniques. By means of numerical simulations it has been shown that the proposed methods lead to adequate performance and robustness indices.**

Keywords – Rational approximations, Complex controller, Robustness, Frequency domain.

I. INTRODUCTION

The paper considers the problem of designing complex controllers of unstable industrial processes including transport delays, observing the restrictions on performance and robustness. When designing complex controllers for unstable processes with transport delays, a time-delay may also appear within the transfer function of the controller $C(s)$. Thus, after the design phase, the controller transfer function is not rational and one often encounters internal instability. This internal instability in the controller appears as one or more unstable dipoles, i.e. pairs of poles and zeros at the same points at the right half-plane of the s-plane. Elimination of the intrnal instability by means of suitable rational approximations of the controller transfer function is an intrinsic step in solving the control problem under consideration, and thus represents a key motivator for the present paper. Several methods of rational approximation of $C(s)$ are considered in the present paper.

It is well known that nearly 94% of feedbacks in industry is realized by PI/PID controllers [1], while this percentage is over 97% in petrochemical industry [2, 3]. Owing to this high significance of PI/PID, the efficient and simple procedures for tuning of parameters of industrial controllers have been developed [4, 5], as well as the optimization procedures [6-19] for designing PI/PID with minimum *IAE*, observing the restrictions on robustness, which meets the criterion presented in [22].

In addition to the previously mentioned methods, there are methods for designing PID controllers derived from IMC controller [23-25]. For IMC method of designing controllers there is one adjustable parameter λ which, for a narrow class of processes, directly influences the time constant of the closed loop system. Response to a Heaviside disturbance of the process controlled by a controller obtained by IMC method is dependent on the dominant dynamics of the process. E.g. if the process has dominant oscillatory dynamics, responces to any disturbance will be oscillatory.

The problem of control of complex processes (multiple instabilities, multiple astatisms, dominant time delay) can not be solved adequately by applying PID controller, the basic reason for developing methods of designing complex controllers. For the purpose of accomplishing adequate indices of robustness and performance for a wide class of stable and unstable processes new methods [26-29] have been developed for determination of complex controllers based on modified IMC structure. However, the rules of design of complex controllers by applying these methods have not been defined for the general form of process transfer function $G_p(s)$, but they are defined for specific classes of processes $G_p(s)$ [26-29]. Controller $C(s)$ and its rational approximation defined in [31] is designed for the general form of the process transfer function $G_p(s)=H(s)\exp(-\tau s)/Q(s)$ under restrictions on robustness and sensitivity to measurment noise.

Adjustable parameters of a complex controller $C(s)$ are time constant λ and factor of relative damping ζ of dominant poles of the process in closed loop with controller $C(s)$, as in [6]. Adjusting of parameter ζ allows achieving compromise between indices of robustness and performance, which is not possible for complex controllers designed by IMC [23-25] or by modified IMC [26-29].

Through a series of simulations of a wide class of industrial processes a comparison of different methods of rational approximation of $C(s)$ in order to achieve an adequate index performance/robustness and internal stability of the controller has been obtained.

II. COMPARATIVE ANALYSIS OF SEVERAL METHODS OF RATIONAL APPROXIMATION OF INTERNALLY UNSTABLE CONTROLLERS

The control structure with $C(s)$ controller is presented in Fig. 1. $G_{ff}(s)$ describes the feed forward from the set point y_{sp} to control signal u and will not be considered here. For a wide class of transfer functions of industrial processes is $G_p(s)=H(s)e^{-\tau s}/Q(s)$, where $Q(s)$ and $H(s)$ are polynomials

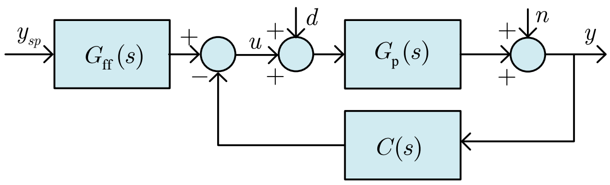

Figure 1. Control structure with controller C(s)

of the order $\deg Q(s) = n \geq \deg H(s) = 0$ and $H(0) \neq 0$. Complementary sensitivity function of the controlled process $G_p(s)$ of Fig. 1 is given by relation $T_p(s) = L(s)/(1+L(s))$ [32], the function of feedback transfer being of the form $L(s) = C(s)G_p(s)$. Let the desired complementary sensitivity function $T(s)$ is given by

$$T_p = T(s) = \frac{N(s)e^{-\tau s}}{P(s)}, \tag{1}$$

where: $N(s) = 1 + \sum_{j=1}^{n} \eta_j s^j$, $P(s) = (\lambda^2 s^2 + 2\zeta\lambda s + 1)^n$, $\zeta \in O(1)$, $n \in \mathbb{N}$ and adjustable parameteris $\lambda > 0$, $\eta_j \in \mathbb{R}$, $j = \overline{1,n}$, determined on the basis of desired peerformance of the closed loop system. From relation (1) controller $C(s)$ for process transfer function $G_p(s)$ for maximum attenuation of disturbance d or n is defined as

$$C(s) = \frac{1}{G_p(s)} \frac{T(s)}{1-T(s)} = \frac{1}{H(s)} \frac{N(s)Q(s)}{F(s)}, \tag{2}$$

where $F(s) = P(s) - e^{-\tau s}N(s)$, [30].

In general, parameters $\overline{\eta_1, \eta_n}$ are determined to achieve cancelling of poles of process $G_p(s)$ and zeros of function $F(s)$, [29], where for unstable processes an internal instability arises in complex controller (2).

Free parameters of complex controller (2) are time constant $\lambda > 0$ and factor of relative damping $\zeta > 0$ of the closed loop system, as in [6,30]. Damping factor introduced in the complex controller design plays a significant role in accomplishing a compromise between the performance and robustness indeces. It should be mentioned that parameter ζ affects sensitivity to the measurement noise at high frequencies M_n,

$$M_n = \lim_{\omega \to \infty} \left| \frac{C(i\omega)}{1 + C(i\omega)G_p(i\omega)} \right|, \tag{3}$$

In order to accomplish a compromise between the desired performance IAE and $M_s = \max_{\omega} |1/(1+L(i\omega))|$, time constant λ should fullfil condition

$$\max_{\omega,\lambda} \left| 1/(1 + C(i\omega)G_p(i\omega)) \right| = M_s . \tag{4}$$

Given ζ and M_s (4), time constant λ is determined by solving two nonlinear algebraic equations

$$\left| 1 + C(i\omega)G_p(i\omega) \right|^2 - 1/M_s^2 = 0, \tag{5}$$

$$\partial\left(\left| 1 + C(i\omega)G_p(i\omega) \right|^2 \right) / \partial\omega = 0, \tag{6}$$

as in [6, 30]. The initial choice of parameter ζ should be ζ=1 and parameter λ from the vicinity of the estimated transport delay. By determining time constant λ for different values of parameter ζ, one achieves compromise between values IAE, M_n, and $M_p = \max_{\omega} |L(i\omega)/(1+L(i\omega))|$, under condition that in the case of an unstable process $G_p(s)$ the unstable dipole in controller $C(s)$ is removed.

In order to remove the unstable dipole, if it exists in the controller, several methods found in the literature reduce to application of Padé approximation.

A. Padé approximation of controller C*(*s*)*

Padé approximation is one od the most frequent rational approximations met in the control systems and wider. It can be calculated as follows [26,31]

$$C(s) \approx \hat{C}_{N/N}^{\mathrm{LZG}}(s) = \frac{\sum_{j=0}^{N} d_j s^j}{s\sum_{i=0}^{N-1} c_i s^i}, \tag{7}$$

where N is the user-specified controller order to achieve the desirable performance specification for the load disturbance rejection, and c_i and d_j are determined by the following two linear matrix equations.

$$\begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_N \end{bmatrix} = \begin{bmatrix} b_0 & 0 & 0 & \cdots & 0 \\ b_1 & b_0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots & \vdots \\ b_N & b_{N-1} & b_{N-2} & \cdots & b_1 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ \vdots \\ c_{N-1} \end{bmatrix}, \tag{8}$$

$$\begin{bmatrix} b_N & b_{N-1} & b_{N-2} & \cdots & b_2 \\ b_{N+1} & b_N & b_{N-1} & \cdots & b_3 \\ \vdots & \vdots & \ddots & \cdots & \vdots \\ b_{2N-2} & b_{2N-3} & b_{2N-4} & \cdots & b_N \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_{N-1} \end{bmatrix} = -\begin{bmatrix} b_{N+1} \\ b_{N+2} \\ \vdots \\ b_{2N-1} \end{bmatrix}, \tag{9}$$

where $b_i = f^{(i)}(0)/i!, i = \overline{1, 2N-1}$ are the Maclaurin coefficients of $f(s) = sC(s)$ and c_0 should be taken as $c_0 = \begin{cases} 1, & \text{if } c_i \geq 0 \\ -1, & \text{if } c_i < 0 \end{cases}$. In this way, under certain conditions on parameters λ, ζ, and N, the internal instability of controller $C(s)$ can be removed. However, the obtained controller $\hat{C}_{N/N}^{\mathrm{LZG}}(s)$ is not always an adequate approximation of $C(s)$ thus index robustness/performace could be impaired. For this reason in [29, 30] other methods of rational approximation are met.

The method of rational approximation of $C(s)$ applied in [29] in essence also makes use of Padé approximation in the following way. The obtained controller $C(s)$ from (2) is first decomposed in the form

$$C(s)=\frac{N(s)Q^{-}(s)}{H(s)P(s)}\frac{Q^{+}(s)}{\left(1-\dfrac{N(s)e^{-\tau s}}{P(s)}\right)}, \qquad (10)$$

where: $Q^{+}(s)$ and $Q^{-}(s)$ are polynomials whose roots represent poles of process $G_p(s)$ in the right and left half planes of the s-plane respectively. Then, Padé approximation is applied only to a part of the preceeding expresion $D(s)=Q^{+}(s)/\left(1-\dfrac{N(s)e^{-\tau s}}{P(s)}\right)$, taking care that the obtained controller is causal, ie.

$$\hat{C}^{\mathrm{LG}}(s)=\frac{N(s)Q^{-}(s)}{H(s)P(s)}\hat{D}_{N/M}(s)\,,\ \hat{D}_{N/M}(s)=\frac{\sum_{j=0}^{N}b_j s^j}{s\sum_{i=0}^{M}a_i s^i}\,. \qquad (11)$$

Similarly in [30], in order to avoid calculation of Padé approximation of complex functions, the use is made of the known Padé approximation of function $e^{-\tau s}$ in controller $C(s)$ followed by factorization and elimination of unstable dipoles to remove internal instability of the controller. Since Padé approximation of function $e^{-\tau s}$ in the vicinity of $s=0$ is given in the form

$$e^{-\tau s}\approx\frac{B_M(s)}{A_N(s)}=\frac{\sum_{k=0}^{M}\dfrac{(M+N-k)!M!}{(M+N)!k!(M-k)!}(-\tau s)^k}{\sum_{k=0}^{N}\dfrac{(M+N-k)!N!}{(M+N)!k!(N-k)!}(\tau s)^k}, \qquad (12)$$

and on the basis of relation (2) it follows

$$\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{L/L}(s)=\underbrace{\left(\frac{1}{H(s)}\frac{A_N(s)N(s)Q(s)}{(P(s)A_N(s)-N(s)B_M(s))}\right)}_{\text{factorization and elimination of unstable dipoles}}, \qquad (13)$$

therefore in the obtained controller $\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{L/L}(s)$ there are no unstabile dipoles.

B. Simulation analysis

Comparison of the proposed methods for removal of internal instability in controller $C(s)$, (2), will be analyzed through four representative typical dynamic characteristics of unstable industrial processes including transport delay:

$$G_{p1}=\frac{4e^{-2s}}{4s-1},\qquad G_{p2}=\frac{e^{-1.2s}}{(s-1)(0.5s+1)},$$

$$G_{p3}=\frac{e^{-0.2s}}{s(s-1)},\qquad G_{p4}=\frac{2e^{-0.3s}}{(3s-1)(s-1)}.$$

The obtained controllers are:

Process G_{p1}.

$$\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{4/4}(s)=\frac{2.0488(s^2+3.6778s+6.4594)(s+2.3222)(s+0.0711)}{(s^2+0.3444s+6.8416)(s+8.7177)},\ \hat{C}^{\mathrm{LZG}}_{4/4}(s)=\frac{28.7970(s+2.7760)(s+0.0711)(s^2+4.5789s+9.0689)}{s(s+220.299)(s^2+0.1638s+6.3867)}$$

$$\hat{C}^{\mathrm{LG}}_{6/6}(s)=\frac{9.6209(s+2.6822)(s+0.3818)(s+0.3815)(s^2+4.3998s+8.6936)(s+0.0711)}{s(s+0.3817)^2(s+68.06)(s^2+0.1873s+6.3972)}$$

Process G_{p2}.

$$\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{4/4}(s)=\frac{6.4835(s+0.0154)(s^2+5s+8.3333)(s+2)}{s(s^2+0.0370s+12.6343)(s+7.7176)},\ \hat{C}^{\mathrm{LZG}}_{4/4}(s)=\frac{92.2837(s+1.9890)(s+0.0155)(s^2+7.2907s+17.0647)}{s(s+279.8)(s^2-0.4117s+10.099)}$$

$$\hat{C}^{\mathrm{LG}}_{7/7}(s)=\frac{242.8705(s^2+1.1839s+0.3505)(s^2+7.4912s+17.5525)(s+0.5807)(s+2)(s+0.0155)}{s(s+0.5882)^3(s+760.46719)(s^2-0.4209s+10.1131)}$$

Process G_{p3}.

$$\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{3/3}(s)=\frac{31.1548(s+10)(s^2+0.5542s+0.2037)}{s(s^2+17.3492s+127.1133)},\ \hat{C}^{\mathrm{LZG}}_{2/2}(s)=\frac{0.19065(2911.0054s^2+2309.2295s+1108.7320)}{s(s+190.6494)},\ \hat{C}^{\mathrm{LG}}_{N/N}(s)\ \text{none}$$

Process G_{p4}.

$$\hat{C}^{\check{\mathrm{S}}\mathrm{TG}}_{4/4}(s)=\frac{100.7255(s^2+0.4604s+0.2583)(s^2+20s+133.3333)}{s(s+23.0066)(s^2+6.4890s+144.1208)},\ \hat{C}^{\mathrm{LZG}}_{3/3}(s)=\frac{54.8760(s^2+0.4762s+0.2695)(s+12.8684)}{s(s^2+2.4488s+172.6147)}$$

$$\hat{C}^{\mathrm{LG}}_{7/7}(s)=\frac{49.2861(s^2+0.4604s+0.2583)(s+14.6555)(s^2+4.4854s+5.170)(s^2+3.6172s+3.2987)}{s(s+2.0408)^4(s^2+1.9056s+175.3277)}$$

On the basis of Table 1 and transfer functions of the obtained controllers, it can be concluded that controllers $\hat{C}^{\mathrm{LG}}(s)$ are of higher orders compared to those obtained by other methods, all having the same M_s. In addition, in the third example by applying LG method it was not possible to determine the controller for the given M_s. Controllers of type $\hat{C}^{\mathrm{LG}}(s)$ and $\hat{C}^{\mathrm{LZG}}(s)$ obtained for the second process contain double unstable pole, but in control systems it is not recommendable that the controller itself is unstable since this impairs robustness of the control loop. Controller of type

$\hat{C}^{\text{ŠTG}}(s)$ gives better results for processes having dominant transport delays compared to other two controller types. In design of the controller it is possible to include parameter ζ, as in [30], in order to achieve better indices of peformance and robustness.

TABLE I. THE RESULTS OBTAINED BY THE PROPOSED METHODS OF RATIONAL APPROXIMATION OF CONTROLLER C(S) FOR THE SAME VALUE OF M_s AND ζ=1.

Process	Method	λ	M_n	IAE	M_s	M_p
$G_{p1}(s)$	$\hat{C}^{\text{ŠTG}}_{4/4}(s)$	2.62	2.05	27.3	2.9	2.7
	$\hat{C}^{\text{LZG}}_{4/4}(s)$	2.62	29.0	27.3	2.9	2.7
	$\hat{C}^{\text{LG}}_{6/6}(s)$	2.62	9.62	27.3	2.9	2.7
$G_{p2}(s)$	$\hat{C}^{\text{ŠTG}}_{4/4}(s)$	1.71	6.48	58.1	14	14.6
	$\hat{C}^{\text{LZG}}_{4/4}(s)$	1.71	92.3	58.1	14	14.6
	$\hat{C}^{\text{LG}}_{7/7}(s)$	1.71	243	58.1	14	14.6
$G_{p3}(s)$	$\hat{C}^{\text{ŠTG}}_{3/3}(s)$	0.63	31.1	2.00	2.8	3
	$\hat{C}^{\text{LZG}}_{2/2}(s)$	0.47	555	0.90	2.8	3
	$\hat{C}^{\text{LG}}(s)$	-	-	-	-	-
$G_{p4}(s)$	$\hat{C}^{\text{ŠTG}}_{4/4}(s)$	0.49	100	0.95	3.8	3.9
	$\hat{C}^{\text{LZG}}_{3/3}(s)$	0.48	54.8	0.91	3.8	3.9
	$\hat{C}^{\text{LG}}_{7/7}(s)$	0.49	49.3	0.96	3.8	3.9

III. CONCLUSIONS

Design of controllers of unstable industrial processes including transport delays with restrictions on performance and robustness is of exceptional significance from the point of view of industry. The problem of control of complex processes (multiple instabilties, multiple astatisms, dominant time delay) can not be adequatly solved by using PID controllers, which is the basic reason for development of the methods for design of complex controllers. The conditions for a complex controller are that it is stable, of relativly lower order, and of adequate structure for practical realization. In this work three methods of rational approximation in the design of complex controllers have ben analyzed. The presented comparative analysis and simulation gave the expected results.

ACKNOWLEDGMENT

The authors would like to acknowledge financial support of the Serbian Ministry of Science and Education, under grants TR33020 (T.B.Š), TR32018 and TR33013 (M.R.R).

REFERENCES

[1] S. Yamamoto and I. Hashimoto, "Present status and future needs: the view from Japanese industry", In Arkun and Ray, Eds., *Chemical Process Control-CPCIV. Proc. 4th Inter. Conf. on Chemical Process Control,* TX, 1991.

[2] L. Desbourough, R. Miller, "Increasing customer value of industrial control performance monitoring—Honeywell's experience", in: *Sixth International Conference on Chemical Process Control, AIChE Symposium* Series Number 326, Vol.. 98, 2002.

[3] K.J. Åström, T. Hägglund, "Revisiting the Ziegler-Nichols step response method for PID control", *Journal of Process Control*, vol. 14, pp. 635-650, September 2004.

[4] S. Skogestad, "Simple analytic rules for model reduction and PID controller tuning", *Journal of Process Control*, Vol. 13, pp. 291–309, 2003.

[5] M. Shamsuzzoha, M. Lee, "IMC-PID controller design for improved disturbance rejection of time-delayed processes", *Industrial & Engineering Chemistry Research*, vol. 46, no.7, pp. 2077-2091, 2007.

[6] M.R. Mataušek, T.B. Šekara, "PID controller frequency-domain tuning for stable, integrating and unstable processes, including dead-time", *J. Process Control* vol. 21, pp. 17-27, 2011.

[7] T.B. Šekara, M.R. Mataušek, "Classification of dynamic processes and PID controller tuning in a parameter plane", *J. Process Control* vol. 21, Issue 4, pp. 620-626, 2011.

[8] H. Panagopoulos, K.J. Åström and T. Hägglund, "Design of PID controllers based on constrained optimization", *IEE Proceedings-Control Theory and Applications*, vol. 149, pp. 32-40 January 2002.

[9] A. Wallén, K.J. Åström, and T. Hägglund, "Loop-shaping design of PID controllers with constant T_i/T_d ratio", *Asian Journal of Control,* vol. 4, pp. 403-409, December 2002.

[10] C. Hwang and C-Y. Hsiao, "Solution of non-convex optimization arising in PI/PID control design", *Automatica* vol. 38, pp. 1895-1904, November 2002.

[11] B. Kristiansson and B. Lennartson, "Evaluation and simple tuning of PID controllers with high-frequency robustness", *Journal of Process Control*, vol..16, pp. 91-102, February 2006.

[12] B. Kristiansson and B. Lennartson, "Robust tuning of PI and PID controllers: using derivative action despite sensor noise" *IEEE Control Systems Magazine***,** pp. 55-69, February 2006.

[13] A.J. Isaksson and S.F. Graebe, "Derivative filter is an integral part of PID design", *IEE Proceedings-Control Theory and Applications*, vol. 149 pp. 41-45, January 2002.

[14] A. Karimi, M. Kunze and R. Longchamp, "Robust controller design by linear programming with application to a double-axis positioning system", *Control Engineering Practice*, vol. 15, pp. 197-208, February 2007.

[15] T. B. Šekara, M. R. Mataušek, "A simple effective method to obtain a well-tuned PID controller", Proceedings of the 51st, Conference on. ETRAN, AU3.1, 2007 (in Serbian).

[16] T.B. Šekara, M.R. Mataušek, "Optimal tuning of a PI/PID controller for processes defined by a rational transfer function", INFOTEH Vol. 6, Paper A-2, p. 6-9, Jahorina, March 2007 (in Serbian).

[17] T.B. Šekara and M.R. Mataušek, "Optimization of PID controller based on maximization of the proportional gain under constraints on robustness and sensitivity to measurement noise ", *IEEE Trans. Automatic Control*, vol. 54, no.1, pp.184-189, Jan. 2009.

[18] T.B. Šekara and M.R. Mataušek, "Revisiting the Ziegler-Nichols process dynamics characterization", *J. Process Control* vol. 20, pp. 360-363, 2010.

[19] T. B. Šekara, M. R. Mataušek, "A four-parameter optimization of a PID controller", Proceedings of 52. Conf. ETRAN, Vol. 1, Palic, Junne 2008 (in Serbian).

[20] T.B. Šekara, M.R. Mataušek, "Optimal tuning of a PID controller in frequency domain,", INFOTEH , Paper A-6, p. 24-27, Bosnia and Herzegovina, Jahorina, March 2009 (in Serbian).

[21] T.B. Šekara, M.B. Trifunovic, Optimal tuning of a PID controller having a differential compensator connected in series in frequency domaine, Proceedings of INDEL, pp. 258-261, Banja Luka, 4-6 November 2010 (in Serbian).

[22] F.G. Shinskey, "How good are our controllers in absolute performance and robustness?", *Measurement and Control*, vol. 23, pp. 114-121, May 1990.

[23] Chien, I. L."IMC-PID controller design-an extension" *IFAC Proceedings Series*, vol. 6 (pp. 147-152), 1988.

[24] Fruehauf, P. S., Chien, I. L., & Lauritsen, M. D. "Simplified IMC-PID tuning rules." *ISA Transactions*, 33(1), 43-59, 1994.

[25] Lee, Y., Lee, M., Park, S., & Brosilow, C. "PID controller tuning for desired closed-loop responses for SI/SO system. " A.I.Ch.E. Journal, 44(1), 106-115, 1998.

[26] Liu T, Zhang W, Gu D. Analytical design of two-degree-of-freedom control scheme for open-loop unstable process with time delay. *J Process Control* 2005; 15:559-72.

[27] M. Shamsuzzoha, M. Lee, "Analytical design of PID controller cascaded with a lead-lag filter for time-delay processes", Korean J. Chem. Eng., vol. 26, pp. 622-630, 2009.

[28] M. Shamsuzzoha, M. Lee, "Enhanced disturbance rejection for open-loop unstable process with time delay" *ISA Transactions*, vol. 48, pp. 237-244, 2009.

[29] M. Liu, F. Gao, "Enhanced IMC design of load disturbance rejection for integrating and unstable processes with slow dynamics" *ISA Transactions*, vol. 50, pp. 239-248, 2011.

[30] T.B. Šekara, M. B. Trifunović, V. Govedarica, " Frequency Domain Design of a Complex Controller under Constraints on Robustness and Sensitivity to Measurement Noise", *Electronics*, vol. 15, pp. 40-44, 2011.

[31] A. George, J. Baker, G.M. Peter, Padé Approximants: Part I.Basic Theory, Addison Wesley, New York, 1981.

[32] K.J. Åström, T. Hägglund, Advanced PID control, ISA-The instrumentation, Systems, and Automation Society, 2006.