International Journal of Engineering and Advanced Research Technology (IJEART)
Volume-1, Issue-1, July 2015

Tuning of a Novel Second-order Compensator for Use with a Highly Oscillating Second-order-like Process

Galal Ali Hassaan

***Abstract*— A novel second-order compensator is presented to control one of the difficult processes having highly oscillating characteristic with maximum overshoot of above 85 %. The proposed compensator has three parameters, one of them is used to adjust the steady-state characteristics of the control system and the other two parameter are tuned to adjust the performance of the control system during step-input tracking. The compensator is tuned using MATLAB control and optimization toolboxes through using five error-based objective functions. To examine the effectiveness of the proposed compensator, it was compared with three controllers investigated before to control the same process. The proposed compensator can compete well with the other controllers and generate an overshoot free response with good transient and steady state characteristics.**

***Index Terms*—Novel second-order compensator, Compensator tuning, second-order-like process, set-point tracking, control system performance.**

I. INTRODUCTION

A large class of industrial processes can be assigned as a second-order-like process. The control of such a process requires more attention specially if the process has bad dynamics such as highly oscillating or very slow characteristics. In such a case the control engineer has to spend some time in selecting, first of all, a suitable controller or compensator and second tuning this controlling unit. Here, I present a new novel compensator which is a second-order feedforward compensator for possible set-point tracking control of a highly oscillating second-order-like process Basilio and Matos (2002) proposed tuning methods for PI and PID controllers using parameters from the process step response. They designed PID controllers for processes with underdamped step response for transient performance specifications [1]. Hongdong, Guanghun and Huihe (2005) proposed a modified disturbance observer based control scheme to control processes with inverse response and dead-time. They discussed the robustness of the closed-loop control system and used simulation and experimental work to demonstrate the effectiveness of their proposed controller [2]. Manjunath (2007) studied the design of moving sliding surface in a variable structure plant for a second-order system. He demonstrated the powerful control technique applied for second-order systems [3].

David and Macku (2011) studied the modeling and control of semi-batch reactor. They compared three process control approaches. They developed a 2DOF controller for the reactor control and compared two control strategies using PID controllers [4]. Oliveira and Vrancic (2012) proposed a new technique to control the overshoot of second-order systems. Their technique was based on Posicast control and PID control performing switching between two controllers [5]. Jalau, Paik and Kalpana (2013) designed an optimization based compensator for closed-loop linear time invariant system. The compensator was designed such that the control system meats the desired system specifications [6].

Hassaan, Al-Gamil and Lashin (2013) used a PIDF controller to control a highly oscillating second-order process having 85.4 % maximum overshoot. They tuned the PIDF controller and compared with classical PID controller [7]. Hassaan (2014) proposed PID with first-order lag controller, PD-PI controller, feedforward lag-lead compensator, Sallen-Key compensator and notch compensator to control a highly oscillating second-order process. He tuned each controller/compensator for accepted performance of the closed-loop control system [8]-[12]. Hassaan (2015) presented a novel third-order feedforward compensator to control underdamped second-order-like processes for damping ratio between 0.05 and 0.20. He investigated using five error-based objective functions to tune the compensator with functional constraints on the maximum overshoot and the steady-state error [13].

II. PROCESS

The process dynamics can be represented by an equivalent second-order-like process model having the transfer function, $G_p(s)$:

$$G_p(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \qquad (1)$$

Where:

ω_n = process natural frequency = 10 rad/s
ζ = process damping ratio = 0.05

This process has a maximum percentage overshoot of 85.4 % and a settling time of 5.975 s. The large maximum percentage overshoot represents a challenge for the control engineer and the selected controller or compensator has to succeed in eliminating this large overshoot.

III. COMPENSATOR

The compensator is a second-order feedforward compensator having the transfer function, $G_c(s)$:

$$G_c(s) = K_c / (s^2 + a_1 s + a_2) \qquad (2)$$

Galal Ali Hassaan, Emeritus Professor of System Dynamics and Automatic Control.

Where: K_c = compensator gain.

a_1 and a_2 = compensator polynomial parameters.

The compensator has three parameter that have to be adjusted to produce a satisfactory performance for the control system in response to reference set-point tracking.

IV. CLOSED-LOOP TRANSFER FUNCTION

The closed-loop control system incorporates the feedforward second-order compensator in cascade with the second-order process as shown in Fig.1.

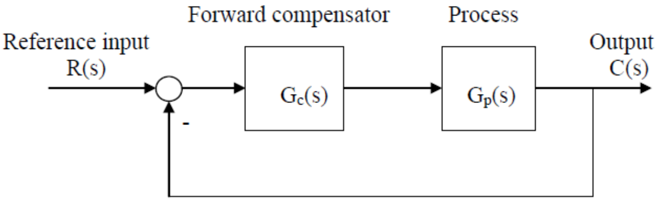

Fig.1 Control system block diagram.

The transfer function of the closed-loop transfer function of Fig.1 for a feedforward second-order compensator of a transfer function given by Eq.2 and a second-order process of a transfer function given by Eq.1 is:

$$C(s) / R(s) = b_0 / (c_0 s^4 + c_1 s^3 + c_2 s^2 + c_3 s + c_4) \tag{3}$$

Where:

$b_0 = K_c \omega_n^2$
$c_0 = 1$
$c_1 = a_1 + 2\zeta\omega_n$
$c_2 = a_2 + 2\zeta\omega_n a_1 + \omega_n^2$
$c_3 = 2\zeta\omega_n a_2 + \omega_n^2 a_1$
$c_4 = \omega_n^2 (a_2 + K_c)$

V. COMPENSATOR TUNING

The tuning process is a vital process for any controller or compensator to achieve stable control and optimal performance of the closed-loop control system. The procedure used to tune the proposed second-order compensator is as follows:

1. The compensator has three parameters: K_c, a_1 and a_2.
2. The compensator gain K_c is used to control the steady-state characteristics of the control system as it affects directly the steady-state response and steady-stare error of the system. Therefore, it is set at specific levels and its effect on the control system performance is investigated.
3. The other 2 parameters a_1 and a_2 are tuned for specific objective functions based on the error between the time response of the control system to a unit step input and the desired steady-state response.
4. The MATLAB control toolbox is used to get the time response of the control system using the command ‘*step*’ [14].
5. Five error-based objective functions are used to optimize the performance of the control system: ITAE, ISE, IAE, ITSE and ISTSE [15] – [17].
6. The MATLAB optimization toolbox is used to minimize each objective function and tune the compensator parameters a_1 and a_2 [18].
7. The results of the tuning process for K_c = 100 using the five objective functions are given in Table 1.

Table 1: Compensator tuning for K_c = 100.

Function	a_1	a_2	OS_{max} (%)	T_s (s)	e_{ss}
ITAE	499.848	-1.160	0	15.12	-0.012
ISE	1022.9	-9.900	0	34.00	0.110
IAE	499.96	-3.162	0	15.44	-0.032
ITSE	475.58	-5.305	0	15.02	-0.056
ISTSE	494.67	-1.491	0	15.02	-0.015

8. The time response of the control system to a unit reference input using the five objective functions is shown in Fig.2.

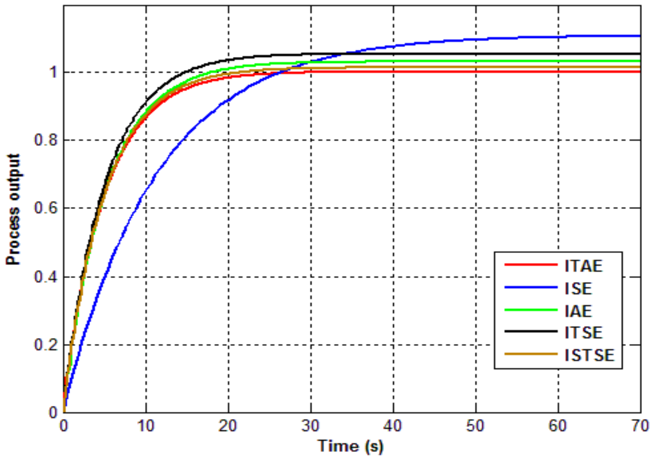

Fig.2 Unit step input time response using 5 objective functions for K_c = 100.

9. The effect of the compensator gain K_c on the dynamics of the control system for reference input tracking is shown in Fig.3 for K_c in the range from 25 to 175.

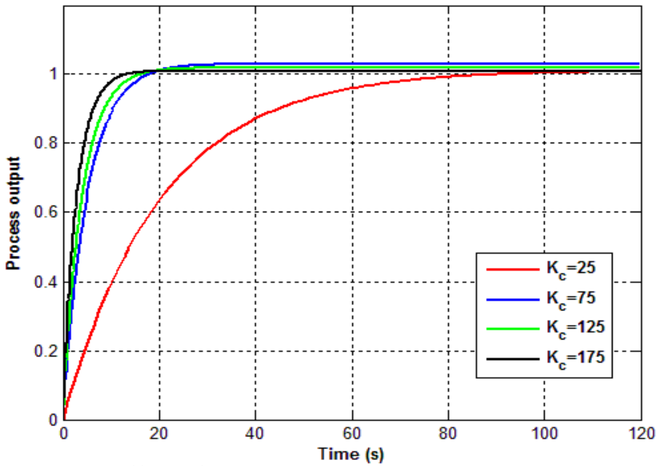

Fig.3 Effect of K_c on the control system time response.

10. The maximum percentage overshoot of the step response of the control system is zero for the K_c range investigated.
11. The effect of the compensator gain K_c on some of the performance measures of the control system response is shown in Fig.4 for the settling time T_s

and Fig.5 for the steady-state error e_{ss}.

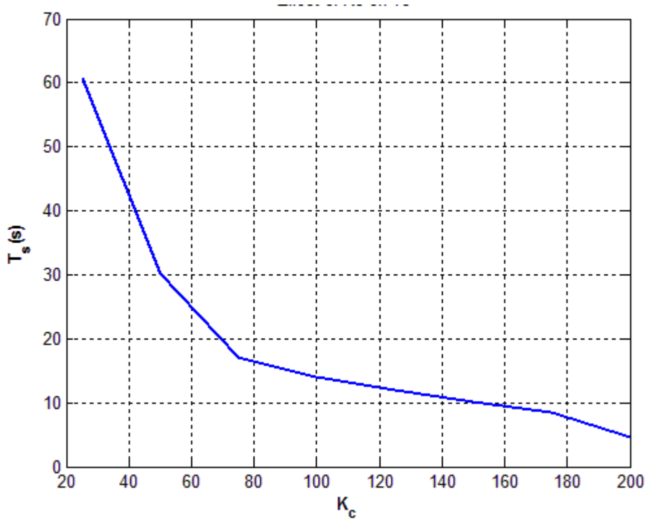

Fig.4 Effect of K_c on the settling time of the control system.

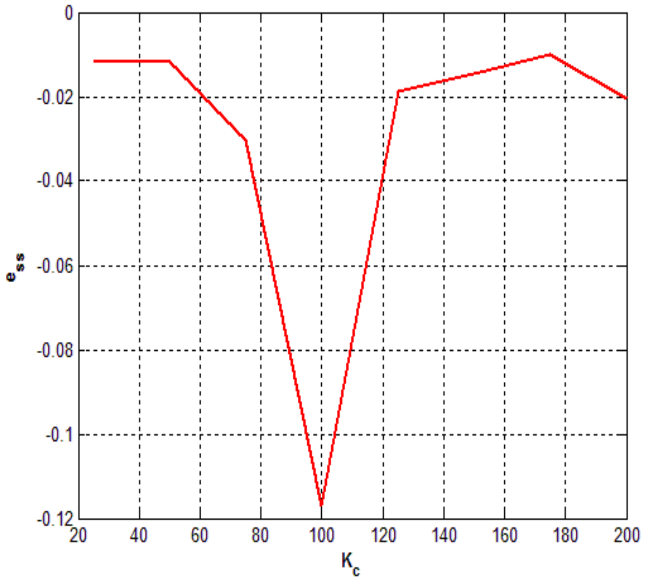

Fig.5 Effect of K_c on system steady-state error.

VI. COMPARISON WITH OTHER CONTROLLERS

To investigate the effectiveness of the proposed compensator, it is compared with the results of some other controllers used by the author to control the same highly oscillating process. The present compensator is compared with the PPI controller [19]. PIP controller [20] and 2DOF controller [21]. The comparison is presented in Fig.6 for the same process and the same unit step reference input.

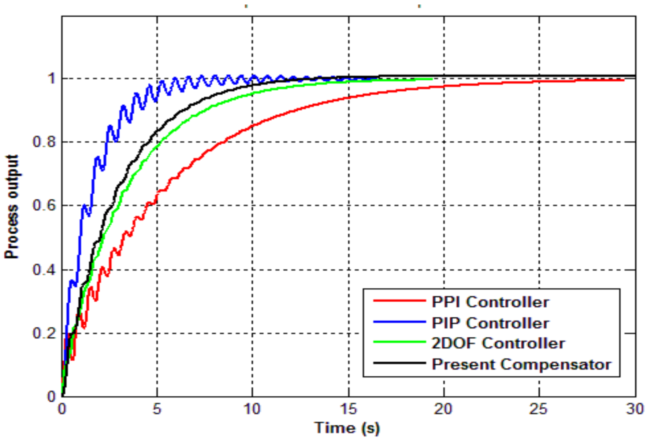

Fig.6 Comparison with other controllers.

The performance of the control system is measured by three parameters: maximum percentage overshoot, settling time and steady-state error. The comparison of the performance parameters for the three controllers and the present second-order compensator is given in Table 2.

Table 2: Performance parameters comparison.

Controller / compensator	OS_{max} (%)	T_s (s)	e_{ss}
PPI	0	16.040	0
PIP	1.110	5.670	0
2DOF	0	9.713	0
Present	0	8.577	-0.01

VII. CONCLUSION

- A novel control compensator was introduced in this work to control a highly oscillating second-order-like process.
- The compensator has three parameters, one of them was used to adjust the steady-state error of the control system in reference input tracking.
- The other two parameters were tuned using MATLAB control and optimization toolboxes.
- Five objective functions were used in the compensator tuning process to assign the best of them suitable for the process under control.
- Using the proposed compensator, it was possible to go down with maximum overshoot from 85.4 % to zero.
- It was possible to go down with the settling time to 4.6 s at a compensator gain of 200.
- The limitation of the proposed compensator is having a steady-state error. However it was possible to limit this error through the compensator gain Kc. It was as low as 0.01 at a K_c of 175.
- The performance of the control system using the proposed compensator was compared with that using other controllers investigated by the author in previous research work.
- When compared with PPI, PIP and 2DOF controllers, the present compensator could compete well with the three controllers.

REFERENCES

[1] J. Basilio and S. Matos, “Design of PI and PID controllers with transient performance specifications”, *IEEE Transactions on Education, vol.45, issue 4, 2002, pp.364-370.*

[2] Z. Hongdong, Z. Guanghun and S. Huihe, “Control of the process with inverse response and dead-time based on disturbance observer”, *American Control Conference*, Portland, OR, USA, 8-10 June 2005, pp.4826-4831.

[3] J. Manjunath, “Design of moving sliding surfaces in a variable structure plant and chattering phenomena”, *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, vol.1, issue 9, 2007, pp.573-579.

[4] N. David and L. Macku, “Pole placement controller with compensator adapted to semi-batch reactor process”, *Proceedings of the 18th International Conference on Process Control*, Tatranska Lomnica, Slovakia, 14-17 June 2011, pp.383-387.

[5] P. Oliveira and D. Vrancic, “Underdamped second-order systems overshoot control”, *IFAC Conference on Advances in PID Control*, Brescia, Italy, 28-30 March 2012, 6 pages.

[6] G. Jalau, H. Paik and S. Kalpana, “Design and implementation of compensator for optimizing linear time invariant system parameters”, *International Journals of Engineering Research and Development*, vol.7, issue 10, 2013, pp.76-79.

[7] G. A. Hassaan, M. Al-Gamil ans M. Lashin, “Tuning of a PIDF controller used with a highly oscillating second-order process”, *Science in Countries*, vol.1, 2013, pp.15-21.

[8] G. A. Hassaan, “Tuning of a feedforward lag-lead second-order compensator used with a highly oscillating second-order process”, *International Journal of Mechanical Engineering*, vol.4, issue 3, 2014, pp.25-33.

[9] G. A. Hassaan, “Tuning of a PD-PI controller used with a highly oscillating second-order process”, *International Journal of Scientific and Technology Research*, vol.3, issue 7, 2014, pp.145-147.

[10] G. A. Hassaan, “A novel notch compensator used with a highly oscillating second-order process”, *International Journal of Advanced Research in Computer Science and Technology*, vol.2, issue 3, 2014, pp.334-338.

[11] G. A. Hassaan, “Tuning of a PID with first-order lag controller used with a highly oscillating second-order process”, *International Journal of Scientific and Technology Research*, vol.3, issue 9, 2014, pp.314-317.

[12] G. A. Hassaan, “A novel Sallen-Key compensator used with a highly oscillating second-order process”, *International Journal of Advanced Research in Computer Science and Management*, vol.2, issue 11, 2014, pp.77-83.

[13] G. A. Hassaan, “Tuning of a novel third-order feedforward compensator, Part I: used with underdamped second-order-like process”, *International Journal of Scientific Research and Technology*, vol.4, issue 5, 2015, pp.441-445.

[14] C. Houpis and S. Sheldon, *Linear control system analysis and design with MATLAB*, CRC Press, 2013.

[15] F. Martins, "Tuning PID controllers using the ITAE criterion", *International Journal of the Engineering Education*, vol.21, issue 5, 2005, pp.867-873.

[16] Y. Soni and R. Bhatt, “BF-PSO optimized PID controller design using ISE, IAE, ITAE and MSE error criteria”, *International Journal of Advanced Research in Computer Engineering and Technology*, vol.2, issue 7, 2013, pp.2333-2336.

[17] D. Maalouf et. al., “Real time experimental comparison of two depth control schemes for underwater vehicles”, *International Journal of Advanced Robotic Systems*, vol.12, 2015, pp.1-15.

[18] P. Venkataraman, *Applied optimization with MATLAB programming*, J. Wiley, 2009.

[19] G. A. Hassaan, “PPI controller tuning for use with a highly oscillating second-order-like process”, *International Journal of Science and Engineering*, vol.1, issue 3, 2015, pp.32-37.

[20] G. A. Hassaan, “Tuning of a PIP controller for use with a highly oscillating second-order-like process”, *International Journal of Research in Information Technology*, vol.3, issue 7, 2015, pp.206-213.

[21] G. A. Hassaan, “Tuning of a 2DOF for use with a highly oscillating second-order-like process”, *International Journal of Modern Trends in Engineering Research*, vol.2, issue 8, 2015, Accepted for publication.

BIOGRAPHY

Galal Ali Hassaan

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations , Mechanism Synthesis and History of Mechanical Engineering.
- Published 10’s of research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of some international journals.
- Reviewer in some international journals.
- Scholars interested in the author’s publications can visit:

http://scholar.cu.edu.eg/galal