Preprints of the 3rd IFAC Conference on Advances in Proportional-
Integral-Derivative Control, Ghent, Belgium, May 9-11, 2018

ThI2S.5

A Robust PID Autotuning Method
for Steam/Water Loop in Large Scale Ships

Shiquan Zhao[1,2], Clara M. Ionescu[1], Robin De Keyser[1], Sheng Liu[2]

[1] Ghent University, Faculty of Engineering and Architecture
Research group on Dynamical Systems and Control, Technologiepark 914, B9052 Zwijnaarde, Belgium
(email: Shiquan.Zhao@UGent.be)
[2] Harbin Engineering University, College of Automation

Abstract: During the voyage of the ship, disturbances from the sea dynamics are frequently changing, and the ship's operation mode is also varied. Hence, it is necessary to have a good controller for steam/water loop, as the control task is becoming more challenging in large scale ships. In this paper, a robust proportional-integral-derivative (PID) autotuning method is presented and applied to the steam/water loop based on single sine tests for every sub-loop in the steam/water loop. The controller is obtained during which the user-defined robustness margins are guaranteed. Its performance is compared against other PID autotuners, and results indicate its superiority.

Keywords: PID autotuner, Steam power plant, Steam/water loop, Multi-input and multi-output, Modulus margin, Robustness

1. INTRODUCTION

The steam/water loop in large scale ships has the characteristics such as being a complex structure, with large number of devices and strong coupling in input-output variables. Hence, it is difficult to design a single, satisfactory controller for this system. There is few work about the control for large scale ship systems. During the voyage of the ship, the disturbance from the sea dynamics are changing and frequently the ship operation mode is also variable (Liu et a., 2016). Therefore it is meaningful to design a robust controller for steam/water loop, as this is the main energy consumer on the ship, with great impact on overall system's stability. There are mainly four sub-loops in the steam/water loop, including i) water level control loop in the drum, ii) water level control in condenser, iii) pressure and water level control in deaerator, iv) pressure control in exhaust manifold.

Most works on steam/water loop are mainly about the boiler-turbine system, in which the outputs are power output, drum water level and drum water pressure. Many advanced control strategies have been developed in this system, such as: de decentralized PID control (Dimeo and Lee,1995; Tan et al., 2004; Garrido et al., 2009; Sayed et al., 2015), sliding mode control (Ghabraei et al., 2015; Moradi et al., 2012; Mahmoodabadi et al., 2015), robust control (Kwon et al., 2014; Mathiyalagan et al., 2015), and model predictive control (Wu et al., 2014; Kong et al., 2015; Zhang et al., 2017).

To design a controller for the water level in the condenser, it is necessary to take into account the coupling influence between condenser water level and deaerator water level. (Wang et al., 2015; Zhang et al., 2005). In the sub-loop of

pressure and water level control in deaerator it is also necessary to consider the coupling effect between pressure and water level. PID neural network decoupling control was designed for the control of deaerator pressure and water level (Wang et al., 2014). Exhaust manifold is the pipeline system existing in the steam/water loop, and other auxiliary machines have to work under the pressure condition of exhaust manifold. However, the gas used in deaerator comes from the exhaust manifold. Thus, there is a strong coupling relationship between the exhaust manifold pressure and deaerator pressure which makes it difficult to develop an acceptable controller. Due to the complexity of the steam/water loop, it is difficult to obtain the model of the entire system. A PID autotuning method named KC autotuner is applied to the steam/water loop which by-passes the burden of a full modeling procedure. The KC autotuner is based on defining a 'forbidden region' for robustness in the Nyquist plane according to user-defined specifications. By designing an adequate PID controller, the Nyquist curve of the process will be changed to fulfil the robustness specified by the user.

The paper is structured as follows. The steam/water loop is descripted in section 2. In section 3, the detailed theory of KC autotuner is introduced. The results and conclusions are given in section 4 and section 5, respectively.

2. DESCRIPTION OF THE STEAM/WATER LOOP

The steam/water loop is shown in Fig. 1, where the red line indicates steam loop and the green line indicates water loop. Major equipment in this loop includes boiler, condenser, deaerator, exhaust manifold and pumps. The steam/water loop works as follows. Firstly, the feed water is supplied into the boiler after being heated in the economizer. Secondly, due
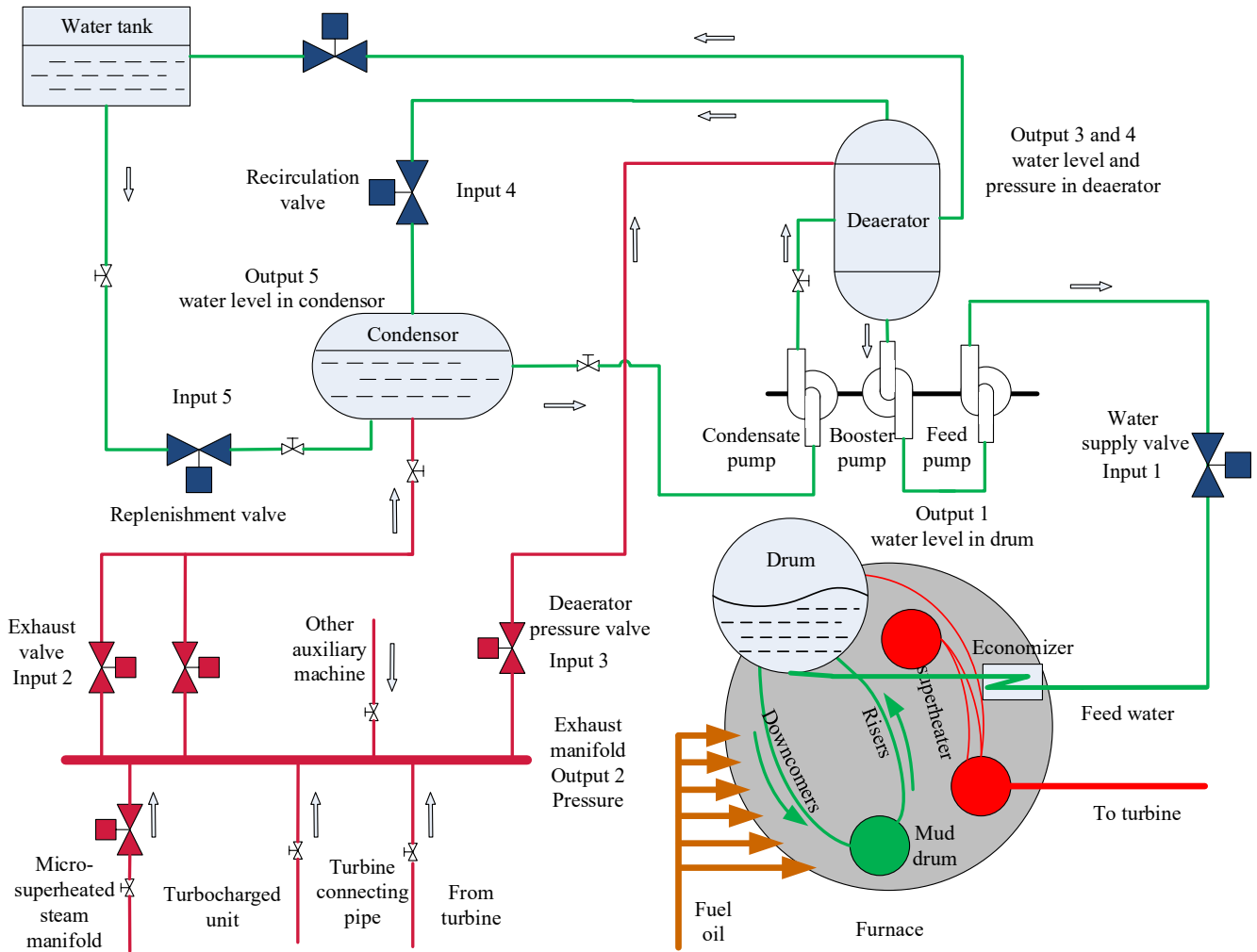
Fig. 1. Scheme of steam/water loop

to the higher density of the feed water, it will flow into the mud drum. Then, after being heated in risers under the burning of the fuel, the feed water turn into saturated mixture of water and steam. Thirdly, after the steam is separated from the mixture, the steam will be heated in superheater and used in steam turbine. Finally, the used steam will be condensed, deoxygenated and pumped to the boiler once again (Drbal et al., 2012). In this system, the interaction exists in many loops, i) drum water level and deaerator water level ii) deaerator pressure and deaerator water level; iii) deaerator pressure and exhaust manifold pressure; iv) deaerator water level and condenser water level.

Table 1. Parameters used in steam/water loop

Output variables	Operating point	Range	Units
Drum water level	1.774	[1.2-2.2]	m
Exhaust manifold pressure	0.132	[0.12-0.14]	MPa
Deaerator pressure	30.51	[24.2-37.4]	KPa
Deaerator water level	0.6839	[0.49–0.88]	m
Condenser water level	0.4979	[0.35-0.66]	m

In the steam/water loop, there are five variables (the water level in drum, pressure in exhaust manifold, water level and pressure in deaerator and water level in condenser) that need to be controlled by manipulating five variables (the opening of water supply valve, exhaust valve, deaerator pressure valve, recirculation valve and replenishment valve). The ranges of the input variables are all 10%~100%, and the operating point are all 50%. The outputs used in this paper are shown in Table 1 (including ranges and initial operating point of output variables).

3. CONTROL DESIGN FOR STEAM/WATER LOOP

In this part, the detailed theory about KC autotuner is introduced (De Keyser et al, 2017). Fig. 2 illustrates the main idea of this autotuner as to move a point B on the Nyquist curve of process $P(j\omega)$ to another point A on the Nyquist curve of the loop $L(j\omega)=P(j\omega)C(j\omega)$ through the PID controller indicated by $C(j\omega)$. The "forbidden region" in Fig. 2 is obtained according to system performance requirements, for example a specific robustness or loop minimum phase and gain margin. In order to have a good performance, the Nyquist curve of loop $L(j\omega)$ should be tangent to this "forbidden region". Hence, the slope of 'forbidden region' and slope of loop $L(j\omega)$ should be the same. The tuning
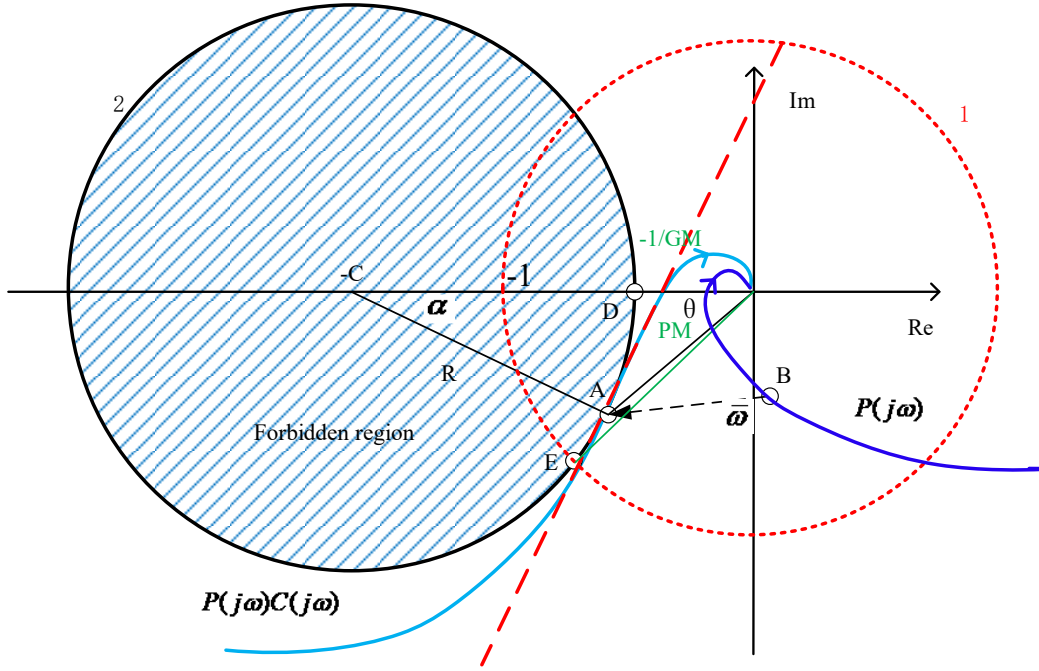
Fig. 2. Graphic illustration of autotuning principle. See text for description.

procedure can be summarized as follows.

1) Select a frequency $\bar{\omega}$ ($\bar{\omega}$ is usually critical frequency, but might be different)

2) Perform sine tests on the steam/water loop

3) Define a 'forbidden region' in the Nyquist plane according to the loop minimum phase and gain margin

4) For each point on the region border (for α from 0° to 90°), calculate PID controller

5) Find the point where the loop $L(j\omega)$ is tangent to the 'forbidden region'

6) The PID controller from step 5) is final.

In Fig. 2, the point D and point E are obtained according to loop minimum phase and gain. D is the intersection of gain margin with negative real axis. E is the intersection of phase margin with unit circle. According to points D and E, the circle can be calculated as:

$$\text{Forbidden region}: \ (\text{Re}+C)^2 + \text{Im}^2 = R^2 \tag{1}$$

$$D \Rightarrow (-1/GM+C)^2 = R^2$$
$$E \Rightarrow (-\cos PM+C)^2 + (-\sin PM)^2 = R^2 \tag{2}$$

and the centre and radius of the forbidden region are are calculated as follows:

$$C = \frac{GM^2-1}{2GM(GM\cos PM-1)}; \ R = C - \frac{1}{GM} \tag{3}$$

and the slope on the point A:

$$\left.\frac{d\,\text{Im}}{d\,\text{Re}}\right|_{\alpha} = \frac{-\text{Re}+C}{\text{Im}} = \frac{\cos\alpha}{\sin\alpha} \tag{4}$$

The derivative from $L(j\omega)$ to ω is calculated, from which the slope of loop $L(j\omega)$ can be obtained.

$$\frac{dP(j\omega)C(j\omega)}{d\omega} = P(j\omega)\frac{dC(j\omega)}{d\omega} + C(j\omega)\frac{dP(j\omega)}{d\omega}$$
$$= \frac{d\,\text{Re}_{PC}}{d\omega} + j\frac{d\,\text{Im}_{PC}}{d\omega} \tag{5}$$
$$\Rightarrow \ \Rightarrow \left.\frac{d\,\text{Im}_{PC}}{d\,\text{Re}_{PC}}\right|_{\bar{\omega}}$$

with $\bar{\omega}$ the specified frequency. At the point A, the following equation is obtained.

$$M_A e^{j\varphi_A} = M_{PC}(j\bar{\omega})e^{j\varphi_{PC}(j\bar{\omega})} \tag{6}$$

It can be rewritten as:

$$\begin{cases} M_A = M_{PC}(j\bar{\omega}) = M_P(j\bar{\omega})M_C(j\bar{\omega}) \\ \varphi_A = \varphi_{PC}(j\bar{\omega}) = \varphi_P(j\bar{\omega})\varphi_C(j\bar{\omega}) \end{cases} \tag{7}$$

According to the typical form of PID controller

$$C(j\omega) = K_P(1+\frac{1}{T_i j\omega}+T_d j\omega)$$
$$= K_P + jK_P\frac{T_d T_i \omega^2-1}{T_i\omega} \tag{8}$$

The modulus and phase of the controller are as follows.

$$M_{C(j\omega)} = K_P\sqrt{1+(\frac{T_d T_i\omega^2-1}{T_i\omega})^2} \tag{9}$$

$$\varphi_{C(j\omega)} = \text{atan}(\frac{T_d T_i \omega^2 - 1}{T_i \omega}) \qquad (10)$$

From the point A on 'forbidden region', the modulus and phase can be calculated as follows.

$$M_A = \sqrt{R^2 \sin^2 \alpha + (C - R\cos\alpha)^2}$$
$$= \sqrt{C^2 + R^2 - 2CR\cos\alpha} \qquad (11)$$

$$\tan(\varphi_C + \varphi_P) = \frac{R\sin\alpha}{C - R\cos\alpha} = \frac{\tan\varphi_C + \tan\varphi_P}{1 - \tan\varphi_C \tan\varphi_P} \qquad (12)$$

hence we have:

$$\tan\varphi_C = \frac{R\sin\alpha - \tan\varphi_P(C - R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C - R\cos\alpha)} \qquad (13)$$

Let:

$$F = \frac{R\sin\alpha - \tan\varphi_P(C - R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C - R\cos\alpha)} \qquad (14)$$

And considering the relationship of $T_i = 4T_d$, the T_d can be calculated as:

$$T_d = \frac{F + \sqrt{F^2 + 1}}{2\bar{\omega}} \qquad (15)$$

Substituting T_d to equation(7), K_p can be obtained as:

$$K_p = \frac{M_A}{M_P(j\bar{\omega})\sqrt{1 + F^2}} \qquad (16)$$

Therefore the item of $C(j\bar{\omega})$ and $\left.\frac{dC(j\omega)}{d\omega}\right|_{\bar{\omega}}$ can be calculated as follows:

$$C(j\bar{\omega}) = K_p(1 + j\frac{T_d T_i \bar{\omega}^2 - 1}{T_i \bar{\omega}}) = \frac{M_A}{M_P(j\bar{\omega})\sqrt{1 + F^2}}(1 + jF) \qquad (17)$$

$$\left.\frac{dC(j\omega)}{d\omega}\right|_{\omega=\bar{\omega}} = K_p(-\frac{1}{jT_i \bar{\omega}^2} + jT_d)$$
$$= jK_p(\frac{T_d T_i \bar{\omega}^2 + 1}{T_i \bar{\omega}}) = j\frac{M_A}{M_P(j\bar{\omega})\bar{\omega}} \qquad (18)$$

The $P(j\bar{\omega})$ and $\left.\frac{dP(j\omega)}{d\omega}\right|_{\omega=\bar{\omega}}$ can be obtained according to

sine test (De Keyser et al., 2016). Hence, the $\left.\frac{d\,\text{Im}_{PC}}{d\,\text{Re}_{PC}}\right|_{\bar{\omega}}$ can

be calculated with equation(5).

By finding the angle α which minimizes the error between slope of 'forbidden region' and slope of loop $L(j\omega)$, the PID parameters can be calculated as:

$$K_p = \frac{M_A}{M_P(j\bar{\omega})\sqrt{1 + F^2}} \qquad (19)$$

$$T_d = \frac{F + \sqrt{F^2 + 1}}{2\bar{\omega}} \qquad (20)$$

$$T_i = 4T_d \qquad (21)$$

Application of the autotuner method to the steam/water loop, implies the following iterative steps.

Step 1: Select a loop and apply a sine test on the selected sub-loop while keeping other sub-loops work at operating points. From this test, obtain the magnitude and phase for the selected loop.

Step 2: Compute the PID parameters for the selected sub-loop.

Step 3: Apply the PID controller on the selected sub-loop. Perform sine test on another sub-loop, while keeping other sub-loops work at operating points.

Step 4: Repeat steps 2-3 for each loop until the output magnitude and phase do not change significantly between consecutive tests.

Step 5: After step 4 is completed, these are the final PID parameters obtained.

4. SIMULATION RESULTS

In order to validate the performance of the proposed method, other PID autotuners such as Åström-Hägglund (AH) (Åström and Hägglund, 1984), Phase Margin (PM) and Kaiser-Rajka (KR) are designed for steam/water loop. In the experiment, *GM*=2 and *PM*=45º are imposed for KC autotuning method.

Table 2. PID Controller Parameters

Tuning method	Tuning method	K_p	T_i	T_d
AH	Sub-loop 1	1.97	55.26	13.82
	Sub-loop 2	67.66	6.5	1.63
	Sub-loop 3	41.63	3.15	0.79
	Sub-loop 4	76.92	12.74	3.18
	Sub-loop 5	88.76	7.04	1.76
PM	Sub-loop 1	2.32	84.93	21.23
	Sub-loop 2	79.73	9.99	2.5
	Sub-loop 3	49.06	4.84	1.21
	Sub-loop 4	90.65	19.58	4.9
	Sub-loop 5	104.6	10.83	2.71
KR	Sub-loop 1	2	77.94	19.49
	Sub-loop 2	80.31	8.75	2.19
	Sub-loop 3	15.23	7.70	1.93
	Sub-loop 4	44.89	24.9	6.23
	Sub-loop 5	63.17	13.74	3.43
KC	Sub-loop 1	3.92	83.04	20.76
	Sub-loop 2	204.17	8.12	2.03
	Sub-loop 3	125.62	3.92	0.98
	Sub-loop 4	232.12	15.88	3.97
	Sub-loop 5	267.85	8.8	2.2

Table 2 shows the PID parameters obtained for every sub-loop with different tuning methods. Sub-loop 1 to sub-loop 5 indicate drum water level control loop, exhaust manifold pressure control loop, deaerator pressure control loop, deaerator water level control loop and condenser water level control loop respectively. There are two experiments to validate the performance of the proposed method. The first one is setpoint tracking experiment, and the other one is disturbance experiment. The setpoint and disturbance imposed to every sub-loop is shown in Table 3.

Table 3. Parameters imposed in validation experiments

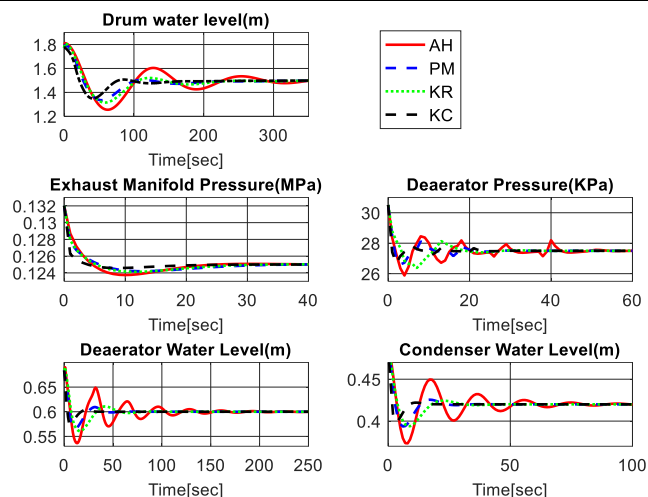| Output variables	Setpoint	Disturbance (Valve opening)
Drum water level	1.5m	+30%
Exhaust manifold pressure	0.125Mpa	-50%
Deaerator pressure	27.5Kpa	+50%
Deaerator water level	0.6m	+30%
Condenser water level	0.42m	+30%

Fig. 3. System outputs in setpoint tracking with different PID controller.
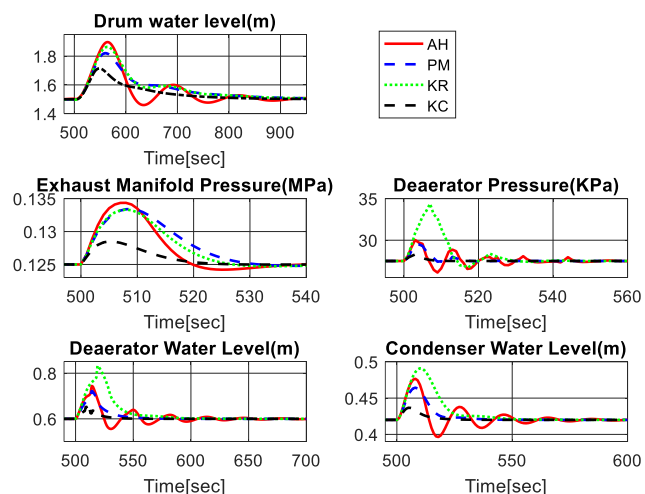

Fig. 4. System outputs in disturbance rejection with different PID controllers.

Fig. 3 and Fig. 4 show the control results in every sub-loop with different controllers. Fig. 3 indicates the setpoint tracking performance and Fig. 4 illustrates the disturbance rejection performance, respectively. From the results, the proposed method has a better performance not only in setpoint tracking but also in disturbance rejection in all sub-loops. Taking the interaction into account, the result of the whole steam/water loop with different autotuner PID controllers is shown in Fig. 5, the PID controller based on KC autotuner shows its superiority.

5. CONCLUSIONS

Steam power plant is one of the most important parts of the ship. Hence, to design an adequate controller for the steam/water loop is of great significance. However, the modeling process is difficult due to the complexity. In this paper, a PID autotuning method is proposed which is free to the system model. According to the system performance requirments, a "forbidden region" is defined on the Nyquist plane. Based on sine tests performed on the steam/water loop, PID controller is obtained. The performance of the PID controller based on KC autotuner is compared with other PID controllers. According to the simulation results, the proposed autotuning method obtains better results in all sub-loops not only in setpoint tracking but also in disturbance rejection.

ACKNOWLEDGEMENT

REFERENCES

Åström, K.J. and Hägglund, T. (1984). Automatic tuning of simple regulators with specifications on phase and amplitude margins. *Automatica*, 20(5), 645-651.

De Keyser, R., Ionescu, C.M., and Muresan, C.I. (2017). Comparative evaluation of a novel principle for pid autotuning. In *11th Asian Control Conference (ASCC)*, 1164-1169.

De Keyser, R., Muresan, C.I., and Ionescu, C.M. (2016). A novel auto-tuning method for fractional order PI/PD controllers. *ISA transactions*, 62, 268-275.

Dimeo, R. and Lee, K.Y. (1995). Boiler-turbine control system design using a genetic algorithm. *IEEE transactions on energy conversion*, 10(4), 752-759.

Drbal, L., Westra, K., & Boston, P. (Eds.). (2012). *Power plant engineering*. Springer Science & Business Media.

Garrido, J., Morilla, F., and Vazquez, F. (2009). Centralized pid control by decoupling of a boiler-turbine unit. In *2009 ECC European Control Conference, , 4007-4012. IEEE.

Ghabraei, S., Moradi, H., and Vossoughi, G. (2015). Multivariable robust adaptive sliding mode control of an industrial boiler{turbine in the presence of modeling imprecisions and external disturbances: A comparison with type-i servo controller. *ISA transactions*, 58, 398-408.
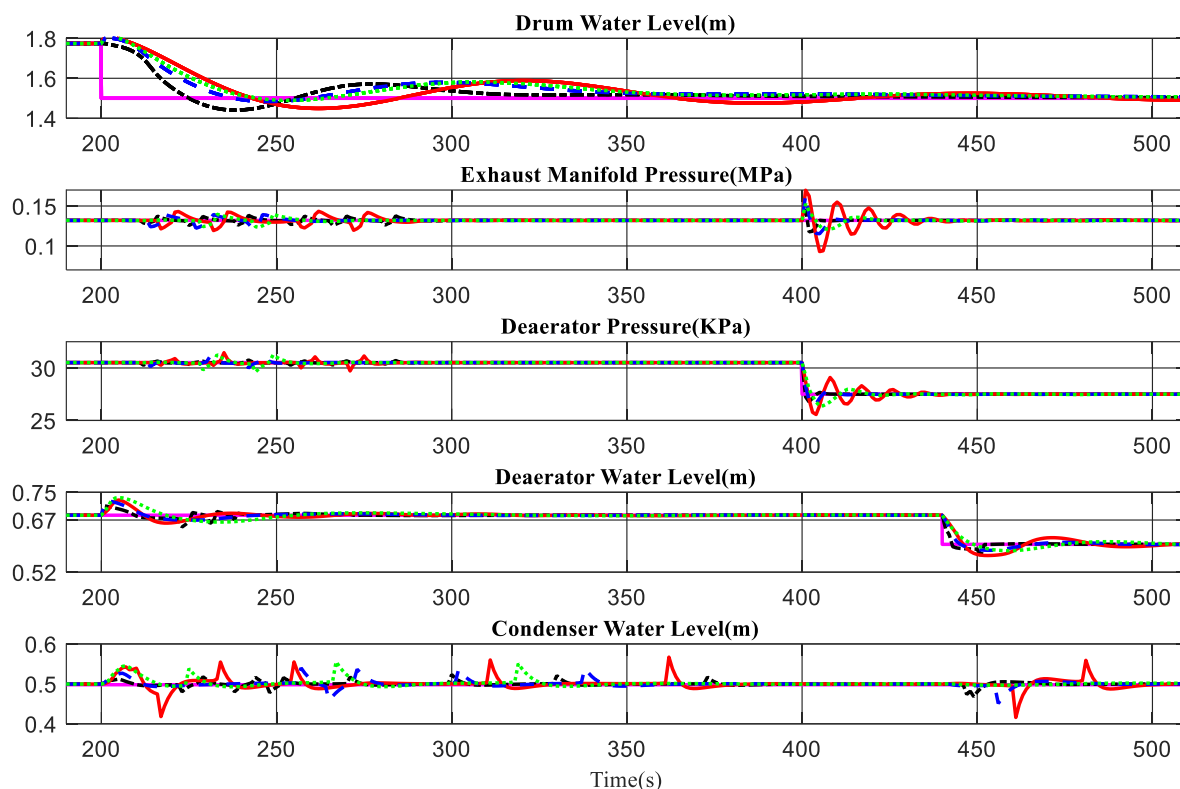
Fig. 5. System outputs with different controllers considering the interaction between sub-loops

Kong, X., Liu, X., and Lee, K.Y. (2015). Nonlinear multivariable hierarchical model predictive control for boiler-turbine system. Energy, 93, 309-322.

Kwon, W., Kim, S., and Park, P. (2014). On the multivariable robust control of a boiler-turbine system. In *IFAC symposium on power systems and power plant control*, 219-223.

Liu, S., Zhao, S., & Wang, Y. (2016). Smooth Sliding Mode Control and Its Application in Ship Boiler Drum Water Level. *Mathematical Problems in Engineering*, 2016.

Mahmoodabadi, M., Taherkhorsandi, M., Talebipour, M., and Castillo-Villar, K. (2015). Adaptive robust PID control subject to supervisory decoupled sliding mode control based upon genetic algorithm optimization. *Transactions of the Institute of Measurement and Control*, 37(4), 505-514.

Mathiyalagan, K., Park, J.H., and Sakthivel, R. (2015). New results on passivity-based h control for networked cascade control systems with application to power plant boiler-turbine system. *Nonlinear Analysis: Hybrid Systems*, 17, 56-69.

Moradi, H., Saffar-Avval, M., and Bakhtiari-Nejad, F. (2012). Sliding mode control of drum water level in an industrial boiler unit with time varying parameters: A comparison with H_∞ -robust control approach, *Journal of Process Control*, 22, 1844-1855.

Sayed, M., Gharghory, S.M., and Kamal, H.A. (2015). Gain tuning pi controllers for boiler turbine unit using a new hybrid jump PSO. *Journal of Electrical Systems and Information Technology*, 2(1), 99-110.

Tan, W., Liu, J., Fang, F., and Chen, Y. (2004). Tuning of PID controllers for boiler-turbine units. *ISA transactions*, 43(4), 571-583.

Wang, P., Meng, H., and Ji, Q. (2014). Pid neural network decoupling control of deaerator pressure and water level control system. In *Robotics and Biomimetics (ROBIO), 2014 IEEE International Conference on*, 2298-2303. IEEE.

Wang, P., Meng, H., Dong, P., and Dai, R. (2015). Decoupling control based on pid neural network for deaerator and condenser water level control system. In *34th CCC Chinese Control Conference,* 3441-3446. IEEE.

Wu, X., Shen, J., Li, Y., and Lee, K.Y. (2014). Hierarchical optimization of boiler-turbine unit using fuzzy stable model predictive control. *Control Engineering Practice*, 30, 112-123.

Zhang, F., Wu, X., and Shen, J. (2017). Extended state observer based fuzzy model predictive control for ultra-supercritical boiler-turbine unit. *Applied Thermal Engineering*, 118, 90-100.

Zhang, L., Duan, Q., and Jin, Y. (2005). The Subsection Coordination Control Strategy for the Water Level Coupling Objects of the Steam Condenser and the Deaerator of Big Capacity Units. *Proceedings of 16th Chinese Process Control Conference & 4th Chinese Fault diagnosis and Safety Conference*, 1-6