International Journal of Smart Electrical Engineering, Vol.12, No.1, Winter 2023
ISSN: 2251-9246
EISSN: 2345-6221
pp. 61:68

Comparison Analysis of Model Reference Adaptive Control, Sliding Mode and PID Controller On Drum-Boiler Level

Mohammad Maghsoudi [1], Roohollah Barzamini [1*], Mehdi Siahi[2], Payam Rabbanifar[1]

[1]Department of Electrical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[3] Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
Corresponding author: r.barzamini.eng@iauctb.ac.ir

Abstract

Demand for electricity generation is increasing day by day, and power stations must be able to meet these demands. There are several ways to generate power, such as thermal power plants. There are many variables in a thermal power plant boiler unit (steam unit), but the boiler drum level is one of the most important variables that has a very complex dynamics and it is necessary that the control system can keep it in a safe range. In this paper, two time-varying transfer functions are considered for the drum level (output) to water and steam (inputs). In the presence of parametric uncertainties in the model, the three controllers, Sliding Mode Controller (SMC), Model Reference Adaptive Control (MRAC) and PID Controller are compared to track the desired level of the drum-boiler to different inputs. The results show that the SMC has relatively better tracking results, but the control signal in MRAC is more optimal than the other two controllers and is more suitable for practical applications.

Keywords: Sliding Mode Control, Adaptive, MRAC, Uncertainty Model, Power Plant, Drum level
Article history: Submitted 17-Jun-2022; Revised 26-Feb-2022; Accepted 04-Aug-2022. Article Type: Research paper

https://doi.org /10.30495/ijsee.2022.1961266.1211

1. Introduction

Figure 1 shows the general loop of natural circulation drum-boilers. The inlet heat supplied to the heated tubes inside the boiler, causing the liquid (water-steam) to boil inside the heated tubes. Then the liquid enters the drum through the risers tubes. The steam flows out at the top of the drum level and the liquid goes down again through the downcomers tubes, and this natural circulation continues.

A change in the inlet heat causes a change in pressure and the result is a change in the size of the steam bubbles below the drum level and finally the oscillation of the drum level, which is called the shrink-and-swell phenomenon and makes level control difficult. On the other hand, changes in the steam output from the drum (inlet to the steam turbine) and the water inlet to the drum change the drum level [1].

In [1] a fourth-order model from drum boiler dynamics is investigated that the drum pressure, the total volume of water in the system, the quality of the steam output from the risers and the volume of steam under the drum level are considered as state variables. Figure 1 shows the general structure of the drum-boiler cycle [2].

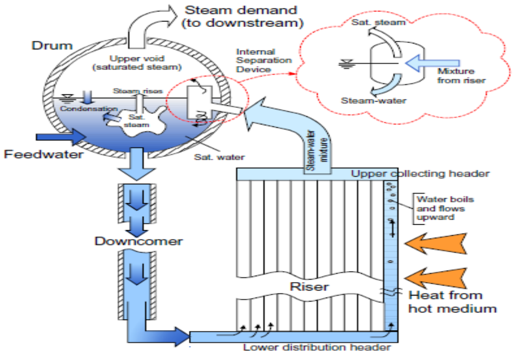

Fig. 1. General drum-boiler loop [2]

In [2], which is referred to [1], the volume of the drum is divided into three parts: steam above the drum level, steam below the level and liquid (water), and considering the dynamics of the bubbles, then new variables are added to the system. To control the drum-boiler level of the combined cycle power plant, especially in the trip conditions and closing the diverter damper (due to disturbance in the gas unit), a cascade controller with two PID has been used and practical results show improved level control [3]. A fuzzy logic controller is used to adjust the proportional-integral-derivative controller coefficients in [5]. SMC has been used to track the drum level and a comparison with H∞ robust control approach has been performed [6]. In [7], a robust H∞ sliding mode observer has designed to estimate states despite uncertainty and turbulence. In [8], SMC is used to control the boiler drum level and pressure, dynamic model [1] is used. A second-order sliding mode fault-tolerant control is used for a heat recovery steam generator boiler [9]. In fact, the state space model [1] obtained in [4] has been used.

In [10], as in [6], an industrial boiler is analyzed by comparing the sliding mode control and H∞ robust control approach. In [11], as in [10], a time-varying model is used and a robust multivariate controller for an industrial boiler is investigated. An experimental study has been performed to identify a model with time-varying parameters for a boiler drum in laboratory dimensions [12]. Coordinated control with respect to energy consumption separation for a boiler drum unit is also proposed [13]. In [14], an adaptive neural network-based PID controller for water level control is investigated.

In the present paper, the time-varying model [15] is used to model the drum level and also the SMC [6] is used to control the drum level. Then the MRAC and PID controller are implemented. Stability analysis of SMC and MRAS controllers are based on Lyapunov stability theory.

First, trajectories including step, ramp and ramp-step combinations are considered as the desired trajectory of the drum level and the tracking results of SMS [6] and PID controller are compared. Second, a Second-Order Reference Model (SORM) is considered and the results of the three controllers SMC, MRAS and PID are compared.

The results show that the SMC has relatively better tracking results, but the control signal in MRAS is much better than the other two controllers and is more suitable for practical applications.

2. Time-varying model of system

In this paper, as in [6], the time-varying model [15] is used. This model includes two transfer functions for drum level h (output) under steady state conditions as described in (1):

$$\begin{aligned} G_1(s) &= \frac{H(s)}{U_1(s)} = \frac{\alpha_1}{s(1+\tau_1 s)} \\ G_2(s) &= \frac{H(s)}{U_2(s)} = \frac{\beta}{1+\tau_2 s} - \frac{\alpha_2}{s} \end{aligned} \tag{1}$$

Where *G_1 (s)* is the transfer function of the drum level relative to the feedwater to the drum *U_1 (s)* and *G_2 (s)* is also the transfer function of the drum level to the steam output from the drum *U_2 (s)*. τ_1 and τ_1 are time constants and α_1, α_2 and β are time-varying constants with known boundaries.

3. Sliding mode controller

Sliding mode control is one of the popular controllers that despite its simplicity, has many capabilities. It is used in various systems such as drum-boiler [6], Congestion Control of Differentiated Services Networks [16] and others. In this paper, sliding mode controller [6] is used. Consider a dynamic system with one input:

$$y^{(n)} = \phi(\bar{y}) + \psi(\bar{y})u \tag{2}$$

where *u* is the input (water or steam), *y* is the output (drum level), and $\bar{y}$ is the state variable vector. For simplification, $\bar{y}$ is used instead of $\bar{y}(t)$ that $(\bar{y} = [y \ \dot{y} \ ...y^{(n-1)}])$. Also, $\phi(\bar{y})$ and $\Psi(\dot{y})$ are nonlinear functions of time and variables. A sliding surface can be defined by (3):

$$s(y;t) = (\frac{d}{dt} + \lambda)^{n+1} \ \hat{y}(t) \tag{3}$$

where $\tilde{y}(t) = y(t) - y_d(t)$ is tracking error and *$y_d(t)$* is the desired state for tracking and λ is a positive constant. To guarantee Lyapunov stability, the control law *u* in equation (2) must be expressed such that:

$$\frac{1}{2}\frac{d}{dt}s^2 = s\,\dot{s} \le -\eta|s| \tag{4}$$

where η is a positive constant (for simplicity, *s(y, t)* is denoted by *s*). See [6] for more details.

Equation (1) is expressed by a second-order differential equation, so in general we have a

$$\ddot{y} = \Phi(y, \dot{y}) + \delta u \tag{5}$$

second-order dynamic system (5):

where the nonlinear dynamic function $\Phi(y, \dot{y})$ is not exactly known but can be estimated by $\hat{\Phi}(y,\dot{y})$ and the control gain δ is in the range $0<\delta_{\min}<\delta<\delta_{\max}$.The estimation error Φ is assumed to be bounded by some known function $\Upsilon(y,\dot{y})$ such that:

$$\hat{\Phi}(y,\dot{y})\leq\Upsilon \tag{6}$$

to track $y_d(t)$ by $y(t)$, sliding surface s is defined by (7) and the time derivative of s by (8):

$$s=(\frac{d}{dt}+\lambda)\tilde{y}=\dot{\tilde{y}}+\tilde{y} \tag{7}$$

$$\begin{aligned}\dot{s}&=\ddot{y}-\ddot{y}_d+\lambda\dot{\tilde{y}}=\\&=(y,\dot{y})+\delta u-\ddot{y}_d+\lambda\dot{\tilde{y}}\end{aligned} \tag{8}$$

The approximation $\hat{u}$ of a continuous control law (which reaches $\dot{s}=0$) is

$$\hat{u}=-\hat{\Phi}(y,\dot{y})+\ddot{y}_d-\lambda\dot{\tilde{y}} \tag{9}$$

to satisfy the sliding condition, a discontinuous term as:

$$\begin{aligned}u&=\hat{\delta}^{-1}+[\hat{u}-K\ \mathrm{sgn}(s)]\\\hat{\delta}&=(\delta_{\min}\,\delta_{\max})^{1/2}\end{aligned} \tag{10}$$

across the surface s=0 is added. Where *sgn* is the sign function. By (11):

$$\begin{aligned}K&\geq\rho(\Upsilon+\eta)+(\rho-1)|\hat{u}|\\\rho&=(\delta_{\max}\,\delta_{\min})^{1/2}\end{aligned} \tag{11}$$

where ρ is the gain margin of the design, Condition in equation (4) will be satisfied.

The control discontinuity must be smoothed around the switching surface, for this reason, the saturation function is used instead of the sign function.

So control signal u:

$$\begin{aligned}&u=\hat{\delta}^{-1}[\hat{u}-K\,.sat(s/\xi)]\\&sat(s/\xi)=\begin{cases}s/\xi & |s|\leq\xi\\\mathrm{sgn}(s) & otherwise\end{cases}\end{aligned} \tag{12}$$

where $\varepsilon=\xi/\lambda^{n-1}$is the width of the boundary layer and ξ is the thickness of the boundary layer.

We design a sliding mode controller for the G₁ (s) transfer function. This trend is similar for G₂ (s), which is not discussed in this article. According to Equation (1), G₁ (s) can be represented in space-time by (16).

$$\ddot{h}=-\frac{1}{\tau_1}\dot{h}+\frac{\alpha_1}{\tau_1}u_1 \tag{13}$$

Comparison of (16) with (5) concludes that $\delta=\alpha_1/\tau_1$ and $\Phi=-\dot{h}/\tau_1$. Approximation of functions are $\hat{\Phi}=-0.09\dot{h}$ and $\Phi=-\dot{h}/\tau_1$. To satisfy (6), the function $\Upsilon=0.025|\dot{h}|$ is considered.

For nominal performance, the level is *h = 0.8 m*. For the best performance of the system, the sliding mode controller parameters (η,λ,ξ), are selected as follows [6].

$$\eta=0.05,\lambda=0.1,\xi=0.01 \tag{14}$$

4. MRA Controller

A block diagram of the MRAC is shown in figure 2 [17]. In this structure, the controller parameters change based on the error between the plant and the reference model.

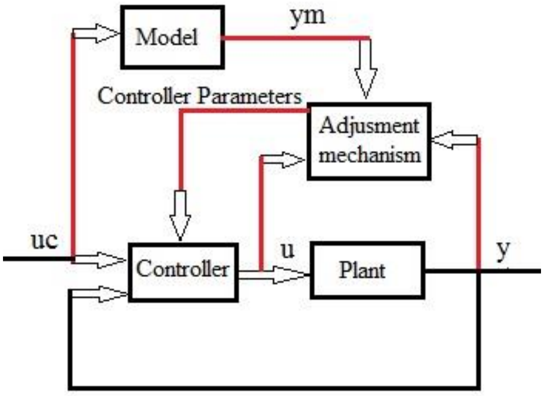

Fig. 2. Block diagram of the MRAC [17]

Adaptive control has a wide range of applications, for example in [18], an adaptive generalized minimum variance (AGMV) is suggested based on minimizing the output variance to overcome the effects of measurement noise and modeling errors. Now consider a second-order system with parametric uncertainties and reference model in Eq.15.. Now, Consider the control signal as follows [19] and the close loop system:

$$G(s)=\frac{b_0}{s^2+a_1s+a_2} \tag{14}$$

$$G_m(s)=\frac{b_m}{s^2+a_{1m}s+a_{2m}} \tag{15}$$

$$u=f\ u_c-q_0\dot{y}-q_1y \tag{16}$$

$$y=\frac{f\ b_0}{s^2+(a_1+b_0q_0)s+(a_2+b_0q_1)}u_c \tag{17}$$

where the f, q_0 and q_1 are control parameters. The adaptive system error is defined as follows

$$e = y - y_m \tag{18}$$

and the parameters error is as follows:

$$\begin{aligned} \tilde{b}_0 &= f\, b_0 - b_m \\ \tilde{a}_1 &= a_1 + b_0 q_0 - a_{m1} \\ \tilde{a}_2 &= a_2 + b_0 q_1 - a_{m2} \end{aligned} \tag{19}$$

Now, for the second order system, we have:

$$\begin{aligned} &\ddot{y} + (a_1 + b_0 q_0)\dot{y} + (a_2 + b_0 q_1) y = f b_0 u_c \\ &\ddot{y}_m + a_{m1}\dot{y}_m + a_{m2} y_m = b_0 u_c \end{aligned} \tag{20}$$

and the error dynamics are as follows

$$\ddot{e} + a_{m1}\dot{e} + a_{m2} e = \tilde{b}_0 u_c - \tilde{a}_1 \dot{y} - a_2 y \tag{21}$$

Consider Lyapunov's function as follows

$$V = a_{m2} e^2 + \dot{e}^2 + \frac{1}{\gamma_0}\tilde{b}_0^2 + \frac{1}{\gamma_1}\tilde{a}_1^2 + \frac{1}{\gamma_2}\tilde{a}_2^2 \tag{22}$$

where $(\gamma_0, \gamma_1, \gamma_2) \in \Re^+$ and the derivative of Lyapunov's function is as follows.

$$\begin{aligned} \dot{V} &= 2a_{m2} e\dot{e} + 2\dot{e}(-a_{m1}\dot{e} - a_{m2} e + \tilde{b}_0 u_c - \tilde{a}_1 \dot{y} - \tilde{a}_2 y) \\ &\quad + \frac{2}{\gamma_0}\tilde{b}_0 \dot{\tilde{b}}_0 + \frac{2}{\gamma_1}\tilde{a}_1 \dot{\tilde{a}}_1 + \frac{2}{\gamma_2}\tilde{a}_2 \dot{\tilde{a}}_2 \\ &= -2a_{m1}\dot{e}^2 + 2\tilde{b}_0\left[\dot{e}u_c + \frac{1}{\gamma_0}\dot{\tilde{b}}_0\right] + 2\tilde{a}_1\left[-\dot{e}\dot{y} + \frac{1}{\gamma_1}\dot{\tilde{a}}_1\right] \\ &\quad + 2\tilde{a}_2\left[-\dot{e}y + \frac{1}{\gamma_2}\dot{\tilde{a}}_2\right] \end{aligned} \tag{23}$$

$$\begin{aligned} &\dot{\tilde{b}}_0 = -\gamma_0 \dot{e} u_c \Rightarrow f = -\frac{\gamma_0}{b_0}\int_0^{t_0} \dot{e}\, u_c\, dt + f(0) \\ &\dot{\tilde{a}}_1 = \gamma_1 \dot{e}\dot{y} \quad \Rightarrow q_0 = -\frac{\gamma_1}{b_0}\int_0^{t_0} \dot{e}\, \dot{y}\, dt + q_0(0) \\ &\dot{\tilde{a}}_2 = \gamma_1 \dot{e} y \quad \Rightarrow q_1 = -\frac{\gamma_2}{b_0}\int_0^{t_0} \dot{e}\, y\, dt + q_1(0) \end{aligned} \tag{24}$$

then the derivative of the Lyapunov function becomes negative semi-definite.

5. PID controller

The most common method for control in different industries is to use a PID controller. Most power plants use a PID controller to control the drum level. The PID controller transfer function is expressed as follows.

$$C(s) = k_p + \frac{k_i}{s} + k_d\, s \tag{25}$$

where kp is the proportional coefficient, ki is the integral coefficient and kd is the derivative coefficient. A PID with a parallel structure in MATLAB Simulink is shown in figure 3.

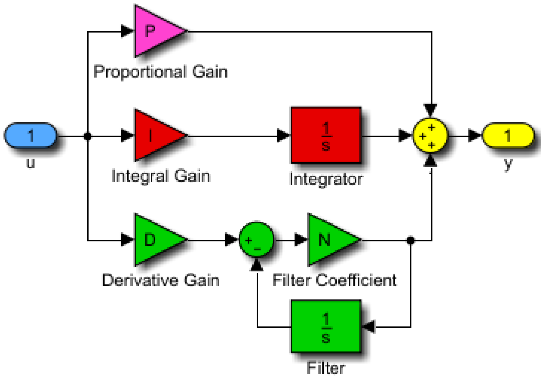

Fig. 3. PID controller

As shown in figure 3, the derivative is implemented in Equation (13) with an approximation and is expressed by (14).

$$C(s) = k_p + \frac{k_i}{s} + k_d \frac{N}{1 + N\frac{1}{s}} \tag{26}$$

In fact, the derivative part is expressed by a filter, which by increasing the number N, its behavior becomes closer to a derivative. To adjust the PID controller, the controller coefficients can be obtained using MATLAB software and experimental manipulation of parameters. It should be noted that according to the required performance, the controller coefficients can be changed to achieve the desired control objectives. It should be noted that in power plants, PID controller is also used to control the other variables. For example, in [20], the hybrid fuzzy-PID is used for boiler to obtain optimum efficiency.

6. Simulation results

In this following, the three paths of step, ramp and the combination of steps and ramps are considered for the desired trajectory of the level and we examine the performance of the three controllers. First we consider the reference trajectory for the drum surface and the SMC [6] and the PID controller are compared. Then we add a second order reference model (SORM) and compare the SMC, MRAC and PID controllers.

A) Step trajectories

The desired trajectory is considered as several step inputs as shown in figure 4. Figure 5 shows the results of level tracking by SMC and PID controllers to the step reference input for the drum level. As shown in figure 5, the sliding mode controller has better results than the PID controller, and the main reason is that the sliding mode controller is robust to changing system parameters and ensures system stability. In steam power plants, PID controller is mainly used [3].

B) Ramp trajectories

The desired trajectory is considered as several ramp inputs in figure 6. Figure 7 shows the tracking results for the desired ramp trajectory. It can be seen that the sliding mode controller has better tracking than PID. It can be seen, for example, that at 200 seconds when the situation changes, the PID controller does not respond very well. In practice, the PID controller does not respond properly in abnormal conditions, and in some cases emergency shutdown occurs.

C) Ramp and step trajectories

As in figure 8, the desired trajectory is considered as several ramp and step inputs. Figure 9 shows the tracking results of the SMC and PID controllers to the desired ramp-step trajectories. As expected, the sliding mode controller has better results than the PID. Now consider a SORM such as $G_m(s)=\frac{2}{s^2+2s+2}$. The reference signal u_c (ie the desired trajectory h_d) is applied to this system and its output is y_m. Again, we consider the reference inputs of the step, ramp, and combination of ramps and steps, as in Figures 4, 6, and 8, and apply these signals to the reference model.

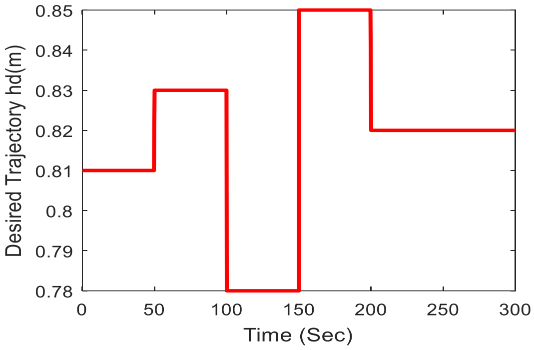

Fig. 4. Desired level trajectory – step trajectories

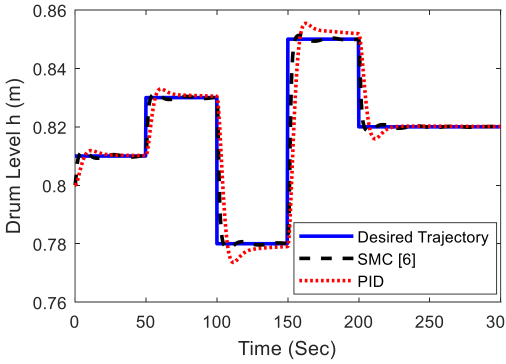

Fig. 5. Level tracking - step trajectories

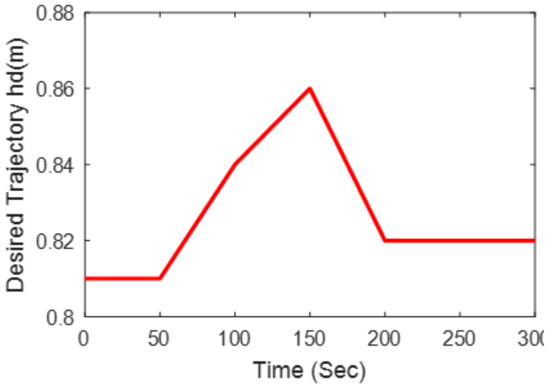

Fig. 6. Desired level trajectory – ramp trajectories

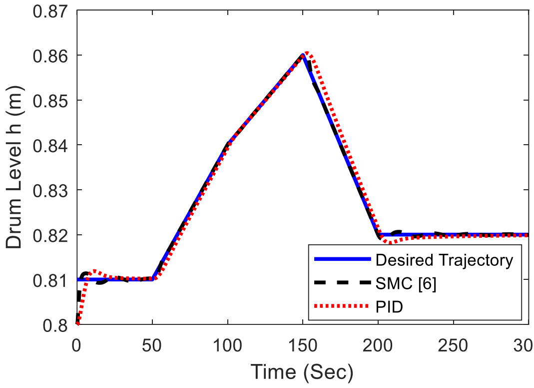

Fig. 7. Level tracking – ramp trajectories

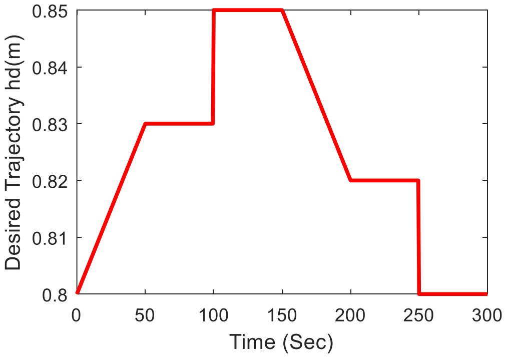

Fig. 8. Desired level trajectory – ramp and step trajectories

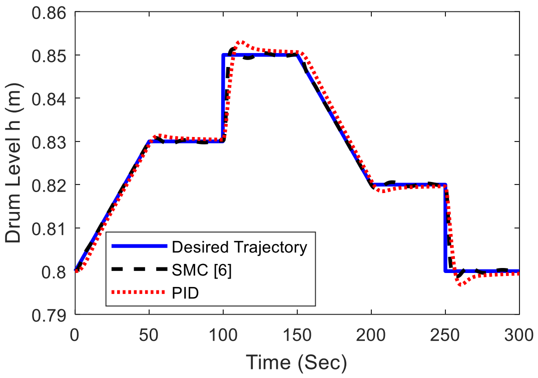

Fig. 9. Level tracking – ramp and step trajectories

D) *Reference model with step trajectories*

By applying the step reference signal as shown in Figure (4) and considering the reference model, the tracking results of the three controllers are shown in Figure 10. The sliding mode controller has better tracking results, but it should be noted that the sliding mode controller control signal in Figure 11 has large oscillations that in practice can lead to saturation or failure of the activator. The MRAS controller has acceptable tracking results but has a very good control signal that is perfectly suited for practical applications. The PID controller also has acceptable results. It can be seen that the SMC control signal [6] has a lot of fluctuations and on the other hand this control signal is not suitable for practical applications. MRAC has a good control signal but SMC tracking is better.

E) *Reference model with ramp trajectories*

Now consider the ramp reference signal as shown in Figure 6, the tracking results of the three controllers are shown in Figure 12. Although the sliding mode controller results slightly better, the MRAS controller control signal in Figure 13 is much better. The PID controller also has good control results because input changes are smooth. At 150 seconds, due to the rapid change of the reference signal, tracking is performed well in the SMC, but the control signal changes rapidly. On the other hand, MRAC has both good tracking and good control signal consumption.

F) *Reference model with ramp and step trajectories*

Consider a combination of step and ramp inputs as shown in Figure 8. As shown in Figure 14, the sliding mode controller has a better response. Adaptive controller and PID also have a good response, but the results of the control signal in Figure 15 show that the adaptive controller has a more appropriate signal. Again, the control signal in the SMC has a lot of fluctuations that can hurt the actuators.

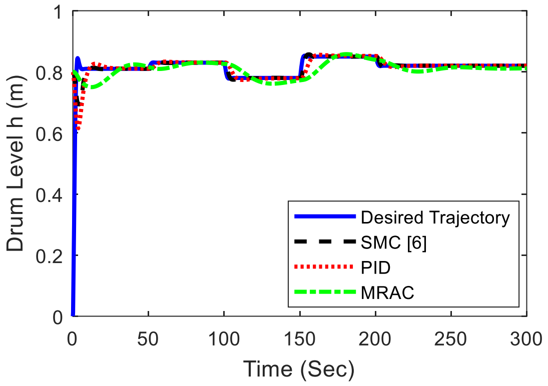

Fig. 10. Level tracking – step trajectories

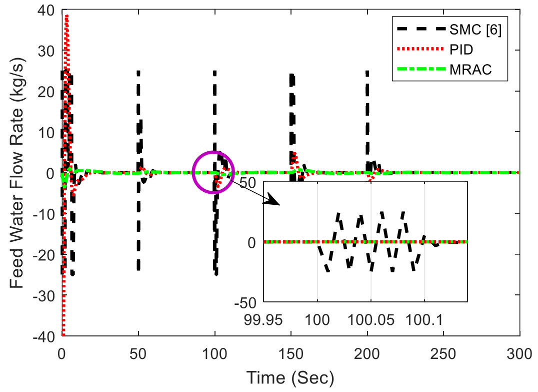

Fig. 11. Control Signal – step trajectories

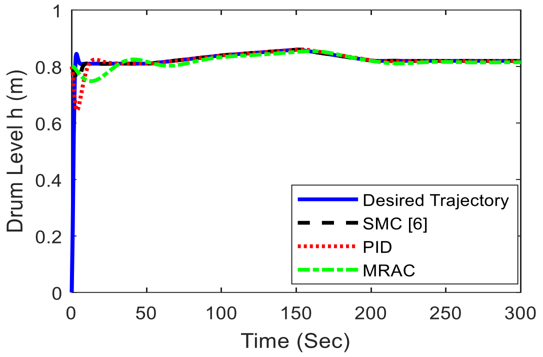

Fig. 12. Level tracking – ramp trajectories

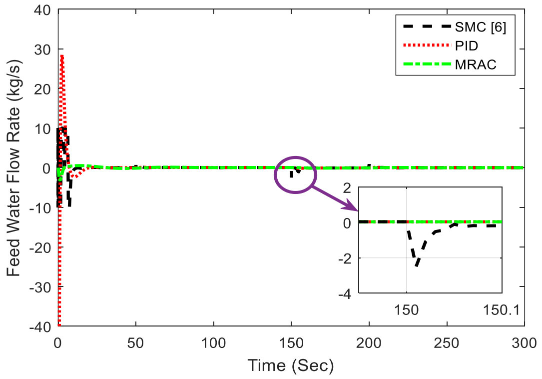

Fig. 13. Control Signal – ramp trajectories

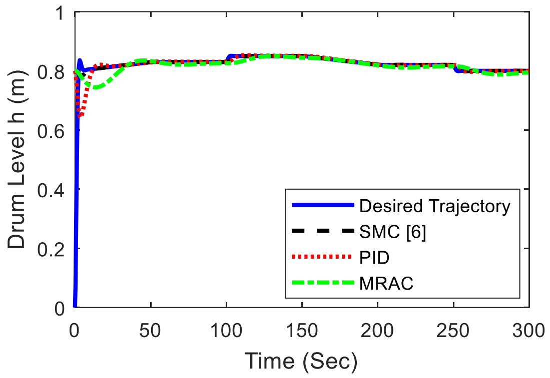

Fig. 14. Level tracking – ramp and step trajectories

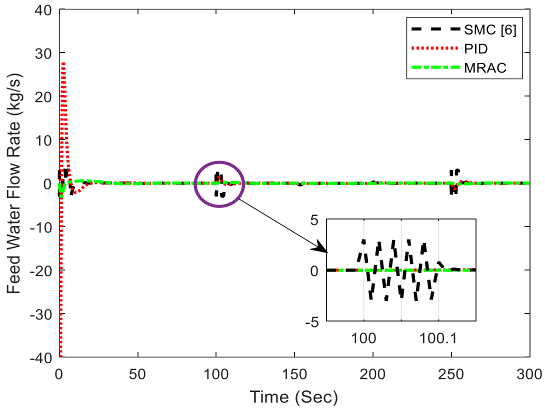

Fig. 15. Control Signal – ramp and step trajectories

Similarly, it is observed that in some times, the PID controller does not respond very well and more oscillations occur. In such cases, if the controller can't control the oscillations, then the sever swelling and shrinkage will increase the amplitude of the oscillations, and finally the protective conditions may be activated and emergency shutdown may occur.

In general, due to the increasing demand for electricity generation, which is due to population growth, industry growth, electricity theft [21], etc., it is necessary for control systems to react quickly and accurately to these changes. Here the capability of several controllers for different working conditions was examined and analyzed.

7. Conclusions

In a thermal power plant unit, there are many variables to control. Boiler drum level control is very important. Poor control of the drum level leads to many problems, including emergency shout down. Two time-varying transfer functions are considered for the drum level (output) to water and steam (inputs). In the presence of parametric uncertainties in the model, we compared the three Sliding Mode Controller (SMC), Model Reference Adaptive Control (MRAC) and PID Controller to track the reference level relative to ramp, step, and ramp-step trajectories. The results showed that the SMC had relatively good tracking compared to the other two controllers, but the control signal in the SMC had large oscillations that could cause the actuator to malfunction. MRAC also had acceptable tracking and a very good control signal and was suitable for practical applications.

References

[1] Kim, h. And choi, s. A model on water level dynamics in natural circulation drum-type boilers. International communications in heat and mass transfer, 2005(32): 786-796.

[2] Maghsoudi m, salarizadeh e, maghfoori m. Nonlinear modelling of kerman combined cycle power plant drum-boiler and drum level control especially in trip conditions. Joc. 2020; 13 (4):37-48.

[3] Mrunalini, p. Kundu, k.k. Dutta, state space model for drum boiler system. Ie(i) journal-el, 2006(86): 260-267.

[4] Wei-jie, y. And yong-xin, l. Boiler drum level controlled by fuzzy self-adapting pid. Computational intelligence and industrial applications. Paciia. Asia-pacific conference. Ieee, 2009: 381-384.

[5] Moradi, h., saffar-avval, m. And bakhtiari-nejad, f. 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, 2012(22): 1844-1855.

[6] Alaei, h. J. And yazdizadeh, a. A new robust h∞ sliding mode observer-based state estimation and fault reconstruction for nonlinear uncertain boiler system. Soft computing, 2016: 1-12

[7] Rehan, ahmed, and ahmed al-durra. "design of sliding mode control for complex nonlinear models: a numerical approach." ieee access, 2020(8): 166347-166364.

[8] Aliakbari, s., ayati, m., osman, j. H. And sam, y. M. Second-order sliding mode fault-tolerant control of heat recovery steam generator boiler in combined cycle power plants. Applied thermal engineering, 2013(50): 1326-1338.

[9] Moradi, hamed, firooz bakhtiari-nejad, and majid saffar-avval. "robust control of an industrial boiler system; a comparison between two approaches: sliding mode control & h∞ technique." energy conversion and management, 2009 (50.6): 1401-1410.

[10] Tan w, marquez hj, chen t. Multivariable robust controller design for a boiler system. Ieee trans control syst technol, 2002(10.5):735–342.

[11] Sunil, p. U., et al. "experimental study and identification of linear model with parameter variation for drum type laboratory scale boiler." ifac-papersonline, 2020(53.1): 608-615.

[12] Gao, yaokui, et al. "research on coordinated control system of drum boiler units considering energy demand decoupling." control engineering practice, 2020(102): 104562

[13] Yazdizadeh, alireza, et al. Adaptive pid controller design with application to nonlinear water level in neka power plant. In: 2010 4th international symposium on communications, control and signal processing (isccsp). Ieee, 2010. 1-9.

[14] Y. Nanhua, m. Wentong, s. Ming, application of adaptive gray predictor based algorithm to boiler drum level control,

journal of energy conversion & management 2006(47): 2999-3007.

[15] Barzamini, r.; shafiee, m. Congestion control of differentiated services networks by sliding mode control. Elektronika ir elektrotechnika, 2013, 19.1: 83-86.

[16] Åström, karl j.; wittenmark, björn. Adaptive control. Courier corporation, 2013.

[17] Barzamini, roohollah; shafiee, masoud; dadlani, aresh. Adaptive generalized minimum variance congestion controller for dynamic tcp/aqm networks. Computer communications, 2012, (35.2): 170-178.

[18] Coman, simona; boldisor, cristian; ciusdel, costin. Combining the mit and lyapunov stability adaptive methods for second order systems. In: 2018 international conference on development and application systems (das). Ieee, 2018. 31-37.

[19] Javadi, s, & gohari, a. Hybrid fuzzy-pid application in boilers to obtain optimum efficiency. International journal of smart electrical engineering (ijsee), 2013 (2.1): 11-16.

[20] Barzamini, h., & ghassemian, m. (2019). Comparison analysis of electricity theft detection methods for advanced metering infrastructure in smart grid. International journal of electronic security and digital forensics, 11(3), 265-280.