Improve Performance of Multivariable Robust Control in Boiler System

Mehdi Parsa, Ali Vahidian Kamyad and M. Bagher Naghibi Sistani

Abstract — *Optimal operation of an industrial boiler-turbine system is obtained with properly control of drum pressure, drum water level and the output load (MW) parameters. In boiler system, multi loop (decentralized) proportional-integral (PI) control is used because of its implementational advantages. PI controller under normal conditions of boiler has suitable performance but by changing this normal conditions, retuning is required. An useful method to overcome this problems is using multivariable robust control. This method of designing, causes to pole zero cancelation between plant and controller at all the stable poles of the uncompensated plant, and any unstable open-loop poles reappear in the closed-loop reflected in the imaginary axis. In this paper for reaching to proper performance and robustness in boiler control system and overcome mentioned problem; bilinear transformation and H_∞ Synthesis is used that in comparison by using common multivariable robust control, settling and rise time and damping of system is improved. In fact by using bilinear transformation, the performance of system in significant parameter control improves remarkably .*

Key Words — boiler, robust control, bilinear transform.

I. INTRODUCTION

One of the main part in thermal power plant is boiler that plays main role in steam generation. The boiler-turbine system is a typical nonlinear multivariable control system. Currently, power plant controllers are designed mainly based on classical SISO control strategies. though implementational advantages of this control strategy we cannot ignore the following problems:

1) The tuning of each PID controller is very difficult, no efficient and systematic methods are available for MIMO systems.

2) Even if each PID controller's parameters can be tuned at the nominal operation point, the whole controller cannot guarantee to work well at other operation points. Usually the PID controllers are retuned to have certain robustness against the variations of the operation points.

This work was supported by Department of research and development (R&D), Isfahan Steel company, Isfahan, Iran.

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So in order to make full use of the potentials of the boiler-turbine unit, multivariable control strategies should be taken. In fact, the need for simultaneous controlling of the strongly interacting variables of the boiler-turbine system makes the boiler-turbine control an ideal application for multivariable control .

Direct application of multivariable control theories in the boiler-turbine system has reported in several literature, e.g., [1]. However, these methods usually need an accurate plant model and the designed controllers are usually very complex. For a boiler-turbine unit, an accurate model is hardly possible to build, therefore, the robustness against modeling error is a prerequisite for a practical power plant controller. So robust control can find its application here. In this paper, loop shaping H_∞ control is applied to the same power plant considered in [2-4], then by considering condition of system and to improve performance of system (reduce rise and settling times and overshoot), we design H_∞ control based on loop shaping and bilinear transformation techniques. Performance of bilinear transformation technique [5] in reduce rise and settling times and overshoot is demonstrated by simulation.

A. Properties of system

The boilers in the plant are usually watertube drum boilers. This type of boiler usually comprises two separate systems. One system is the steam–water system, which is also called the water side of the boiler. In this system preheated water from the economizer is fed into the steam drum, then flows through the downcomers into the mud drum. The mud drum distributes the water to the risers, where the water is heated to saturation conditions. The saturated steam-water mixture then reenters the steam drum in which the steam is separated from the water and exits the steam drum into the primary and secondary superheaters. In between the two superheaters is an attemperator which regulates the temperature of the steam exiting the secondary superheater by mixing water at a lower temperature with the steam from the primary superheater.

The other system is the fuel–air–flue gas system, which is also called the fire side of the boiler. In this system, the fuel and air are thoroughly mixed and ignited in a furnace. The resulting combustion converts the chemical energy of the fuel to thermal or heat energy. The gases resulting from the combustion, known as the flue gases, pass through the superheaters, the risers, and the downcomers, and leave the boiler. A schematic diagram of this type of boiler is shown in Fig. 1.

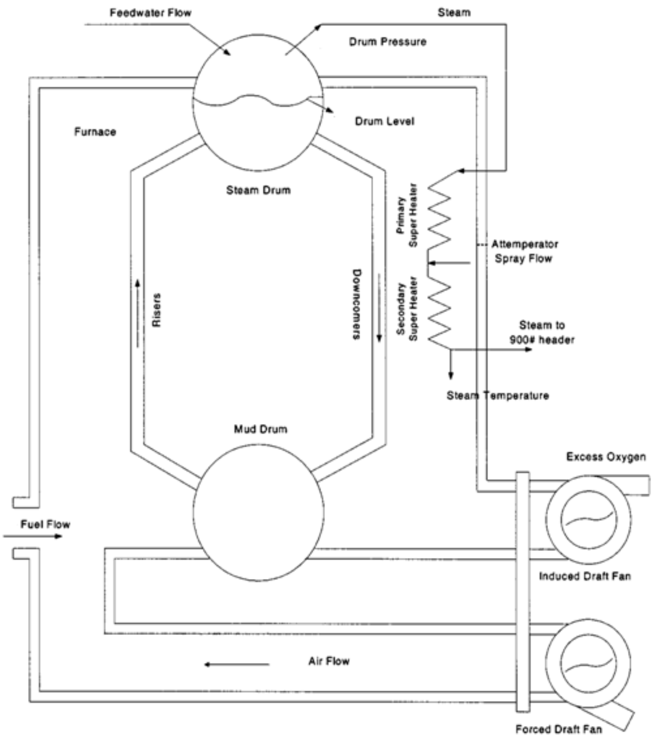


Fig. 1. Schematic of watertube boiler

II. NONLINEAR BOILER-TURBIN MODEL

The boiler-turbine control system can be modeled as a 3 x 3 system. The variables to be regulated are the electrical output, the drum pressure, and the drum water level, and the variables to regulate are the fuel actuator position, the control valve position, and the feedwater actuator position. The main objective of the boiler-turbine control system is to make the electrical output follow the load command rapidly while maintaining the water level and steam pressure in drum within the allowed limits (for the sake of safety).

The system we consider is a 160MW fossil fueled power generation unit. The model for the unit was studied extensively in the past [2,4]. It was generally regarded to model the real plant well enough. The nonlinear model is given by the equations (1):

$$\begin{cases} \dot{x}_1 = -0.0018 u_2 x_1^{9/8} + 0.9 u_1 - .015 u_3 \\ \dot{x}_2 = (0.073 u_2 - 0.016) x_1^{9/8} - 0.1 x_2 \\ \dot{x}_3 = (141 u_3 - (1.1 u_2 - 0.19) x_1)/85 \\ y_1 = x_1 \\ y_2 = x_2 \\ y_3 = 0.05(0.1307 x_3 + 100 a_{cs} + \frac{q_e}{9} - 67.975) \end{cases} \quad (1)$$

where the variables x_1 , x_2 , x_3 denote the drum steam pressure (Kg/cm2), the electrical output (MW), and the density of fluid in the system (Kg/m3), respectively. The control inputs, u_1 , u_2 , u_3 denote the fuel actuator position, the control valve position, and the feedwater actuator position, respectively. The output y_3 is the drum water level (m) and q_e , a_{cs} are the quality factor of steam and the evaporation mass flow rate (Kg/s), respectively and expressed by (2)

$$a_{cs} = \frac{(1 - 0.001538 x_3)(0.8 x_1 - 25.6)}{x_3 (1.0394 - 0.0012304 x_1)} (\frac{kg}{s}) \quad (2)$$

$$q_e = (.854 u_2 - 0.147) x_1 + 45.59 u_1 - 2.51 u_3 - 2.096 \, (\mathrm{Kg/s})$$

Note that the control inputs are saturated, i.e., they are normalized as (3):

$$0 \le u_i \le 1 \quad i = 1,2,3 \quad (3)$$

This fact puts additional nonlinearity in the system.

We consider the nominal operating point as the half load point where $x_1^0 = 108, x_3^0 = 428, u_2^0 = 0.69$. From the system, we can obtain the values of other variables and then the nominal operating point is given by (4)

$$x^0 = \begin{bmatrix} 108 \\ 66.65 \\ 428 \end{bmatrix}, u^0 = \begin{bmatrix} 0.34 \\ 0.69 \\ 0.436 \end{bmatrix}, y^0 = \begin{bmatrix} 108 \\ 66.65 \\ 0 \end{bmatrix} \quad (4)$$

At this point, a linearized model can be obtained, and the system matrices are given by

$$A = \begin{bmatrix} -2.509e^{-3} & 0 & 0 \\ 6.94e^{-2} & -0.1 & 0 \\ -6.69e^{-3} & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 6.34e^{-3} & 0 & 4.71e^{-3} \end{bmatrix}, D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.235 & 0.512 & -0.14 \end{bmatrix}$$

Our aim is to design a robust controller for the nonlinear boiler-turbine system. Various control techniques have been applied to boiler or boiler–turbine controller design, e.g., inverse Nyquist array [1], QFT and Sliding Mode [6], mixed-sensitivity approach [7] and predicative control [8]. Here, we will adopt the bilinear transformation that used in the design to prevent the pole-zero cancellation of the poorly damped poles and to improve the control system performance. Simulation results show satisfactory performance of the proposed method for a wide range of operating conditions and good stability margin as compared to the conventional H_∞ loop shaping technique**.**

III. DESIGN CONTROLLER

The loop shaping H_∞ method is first to specify a desired loop shape by the designer (ignoring closed-loop stability considerations at this stage), and then the 'shaped' plant is further compensated by a controller using the normalized LCF robust stabilization method. In this case, the guaranteed stability properties of the H_∞ method ensure close- loop stability.

Given a plant model *G,* the design approach consists of three steps:

A. Loop Shaping

Use pre- and/or post-compensators W_2 and W_1, to shape the singular values of the original plant G (See Fig.2a). This step contains all of the ingredients of the classical techniques. The shaping functions W_1 and W_2 are controlled by the designer and the properties of the resulting controller depend upon these functions in an essential manner. Guidelines for choosing W_1 and W_2 may be found in [7].

B. Robust Stabilization

A feedback controller which robustly stabilizes the shaped plant ($\tilde{G} = W_1 G W_2$) is found. More explicitly (See Fig.2b), we solve the following H_∞ optimization problem (5):

$$\varepsilon_{max}^{-1} = inf \left\| \begin{bmatrix} (I+\tilde{G}\tilde{K})^{-1} & (I+\tilde{G}\tilde{K})^{-1}\tilde{G} \\ \tilde{K}(I+\tilde{G}\tilde{K})^{-1} & \tilde{K}(I+\tilde{G}\tilde{K})^{-1}\tilde{G} \end{bmatrix} \right\|_\infty \quad (5)$$

The importance of this minimization is the following:

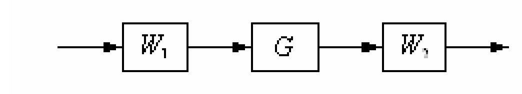
Suppose that $\tilde{G} = \tilde{M}^{-1}\tilde{N}$ is a normalized left coprime factorization of . It can be shown [9] that the controller obtained in (5) will guarantee stability of any plant G^* which belongs to the family of plants G_Δ defined as follows:

$$G_\Delta = \{ M_\Delta^{-1} N_\Delta : \left\| M_\Delta - \tilde{M}, N_\Delta - \tilde{N} \right\|_\infty < \varepsilon_{\max} \}$$

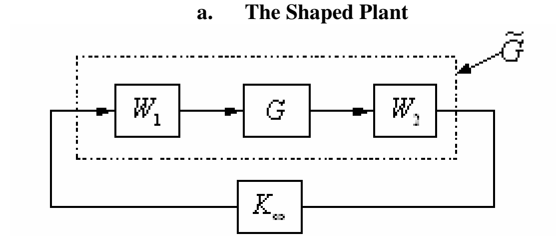
This also guarantees that the loop shape we selected in the previous step can be well approximated with good robust stability if $\varepsilon_{\max}$ is sufficiently large. The value $\varepsilon_{\max}$ is used as a design indicator; usually it should be between 0.3 and 0.5. (Notice, also, that the H_∞ optimization problem in (2) can be solved explicitly without iteration, using only two Riccati equations).

C. Final Controller

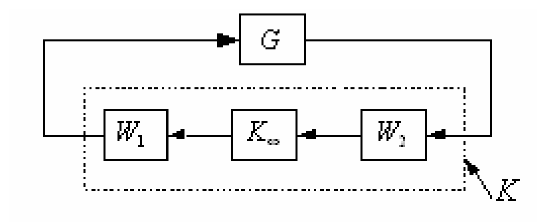
The final feedback controller is obtained as $K = W_1 \tilde{K} W_2$ (See Fig.2c).



a. The Shaped Plant



b. H_∞ Compensation



c. Final Controller

Fig. 2. The Loop Shaping Design Procedure

We now apply this method to the utility boiler model. For the scaled model, we will choose $W_2=I$ and set $W_1 = W_a W_i$, where W_a is a static decoupler and W_i is a diagonal PI compensator that determines the desired open-loop shapes. The pre-compensator was selected as:

$$W_1 = \begin{bmatrix} 0.0011 & 0.0037 & 0.0271 \\ -0.0043 & 0.0071 & 0 \\ -0.0005 & 0.006 & 0.1625 \end{bmatrix} \times \begin{bmatrix} 3(1+\frac{1}{s}) & 0 & 0 \\ 0 & 3(1+\frac{1}{s}) & 0 \\ 0 & 0 & 3(1+\frac{1}{s}) \end{bmatrix}$$

open-loop singular values nominal plant and shaped plant show in fig 3.

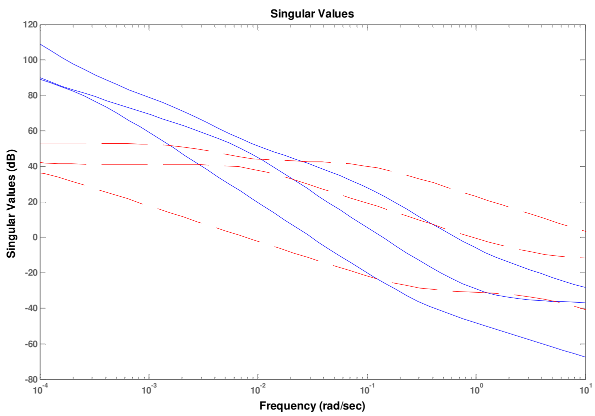


Fig. 3. Open-loop singular values-nominal plant and shaped plant (solid: shaped plant; dashed: nominal plant)

by using pre- and/or post-compensators W_2 and W_1, the condition number of the system frequency response matrix is reduced significantly as shown in Fig.4.

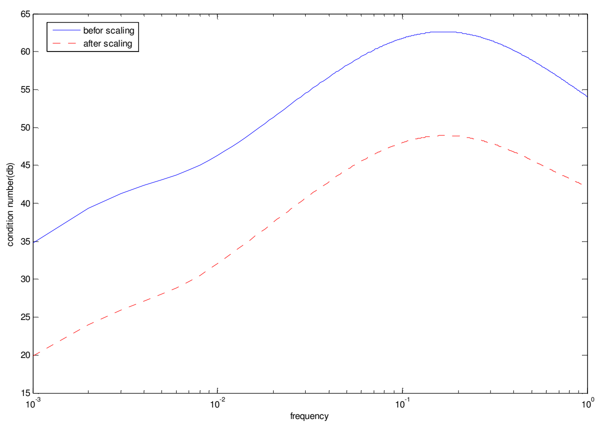


Fig. 4. Condition number of the frequency response matrices (solid: before scaling; dashed: after scaling)

Secondly, Robust stabilization, it synthesize a feedback controller K_∞ ,which robustly stabilizes the normalized left coprime factorization of $\tilde{G}$, with stability margin $\varepsilon_{\max} = 0.3963$.

IV. BILINEAR TRANSFORM

H_∞ optimal control try to cancel undesired dynamic by inversing stable part of open loop plant and inversing the projection of unstable part of plant, so the effect of zero open loop will be omitted; in other words the deficiency of robust control is that to tries to improve steady state (includes tracking, disturbance repel,…) but the problem of pole zero cancelation appears in transition response and also If the plant has jω-axis poles or zeros (Fig. 5a), the controller can not be computed because of ill conditioning problems (computational assumptions are not met). Several methods can be used to overcome this situation [5,10]. We have found that the bilinear transform is the appropriate technique to treat this problem.

Let the new complex plane be $\bar{S}$ - plane, the transformation equation is as (6):

$$S = \frac{(\bar{S} + P_1)}{(1 + \frac{\bar{S}}{P_2})} \qquad (6)$$

where $p_1 < 0$ and $p_2 < 0$ are the end-points of the diameter of a circle in the left s-plane. The final closed-loop poles will be placed inside this circle (see Fig. 5).

By using the bilinear transform, we can shift these poles and zeros away from the jω-axis. After the controller is computed, the inverse bilinear transform is used to map the controller back to the original s-plane. It should be pointed out that the resulting controller is suboptimal for the actual system, but it can prevent the pole-zero cancellation and improve the damping of the poorly damped poles. This method has been applied to the plant in our design.

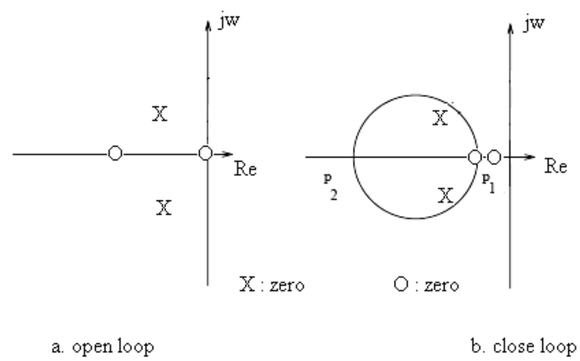


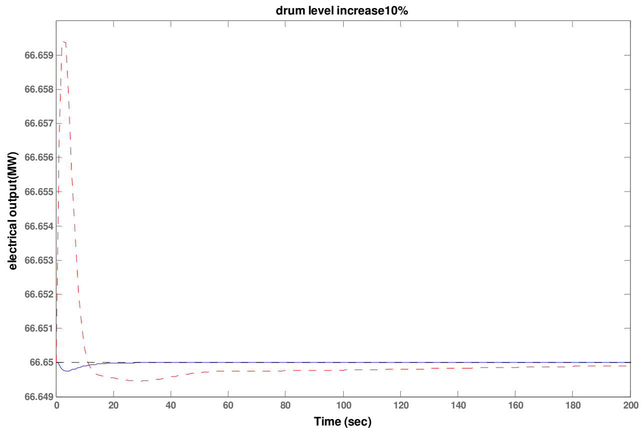
Fig. 5. Bilinear Transform

V. SIMULATION

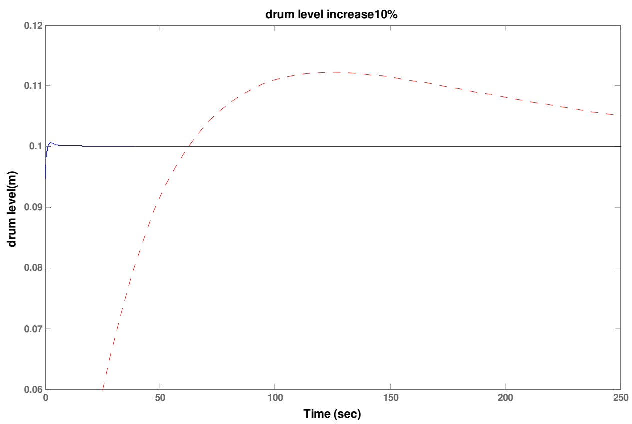
In this section on the base of explained model and designed controller in the previous section, simulation will be done and the effect of significant parameters of drum level and output load change on pressure drum, drum level and output load will be studied by two controllers (common multivariable robust controller and multivariable robust controller with bilinear transform). Finally we will consider the advantage of bilinear transform.

A. Simulation by 10% drum level increasing

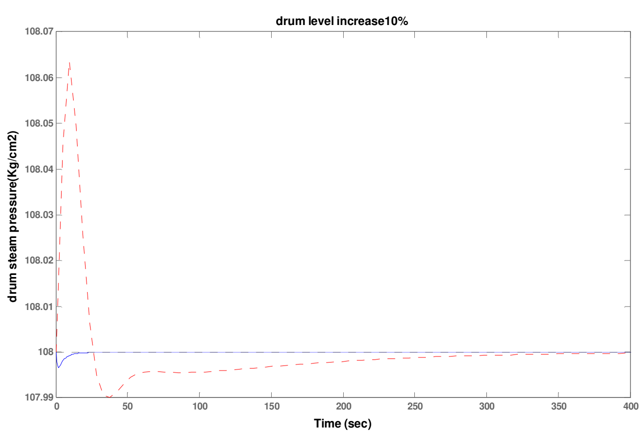
In fig 6 the simulation of changes caused by 10% drum level increasing, with two designed controller is shown. So that it is definite the system response with controller that reached by bilinear transform, with regard to damping and settling time is much better. In fig 6 the changes of the output load (fig 6.a), pressure drum (fig 6.b) and drum level (fig6.c) parameters, by 10% drum level increasing is shown. In fig 6.bfor better comparison between two responses; a part of graph is magnified (because the response of improved control system has very less over shoot and settling time relative to common robust control).



a.Output load changes



b. Drum level changes

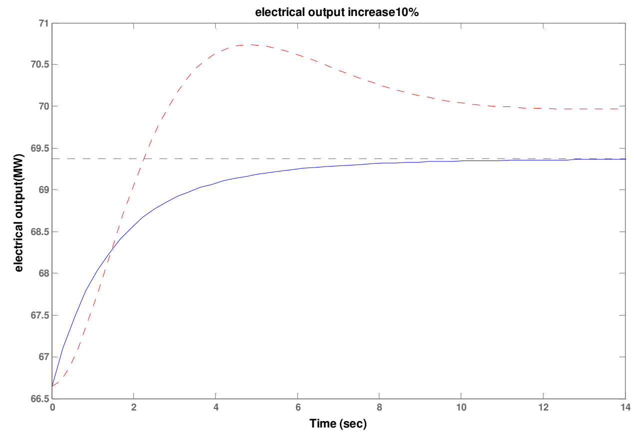


c.Drum pressure changes

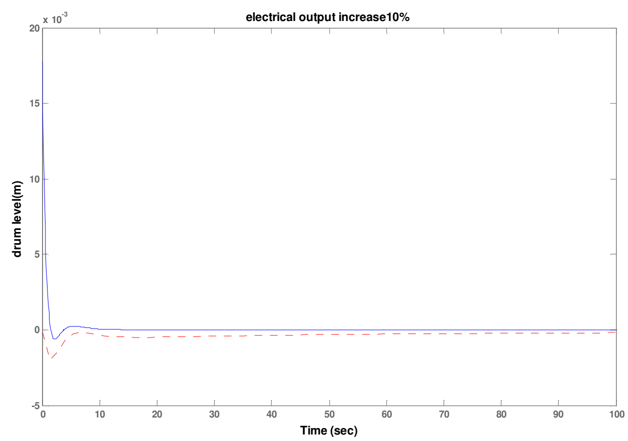
Fig. 6. Boiler time response by 10% drum level increasing. (Solid: improved cotroller with bilinear transorm; dashed: common robust controller).

B. Simulation by 4% output load increasing

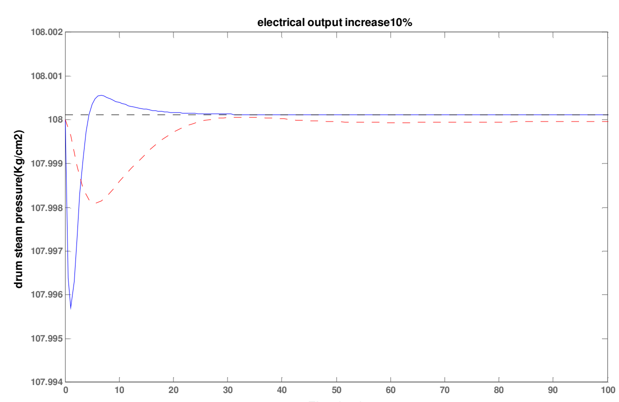
In this section result of system simulation by 4% output load increasing (from 66.56 to 69.5) is shown in fig 7. as it is definite from result of simulation, by using bilinear transform method, the controller has more proper response and in most of the cases, causes to reduce oscillations of response and improves the system damp.



a. Output load changes



b. Drum level changes



c. Drum pressure changes

Fig. 7. Boiler time response by 4% output load increasing. (Solid: improved cotroller with bilinear transorm; dashed: common robust controller).

In fig 7.b and 7.c the response by controller that reached from bilinear transform, has upper amplitude in first peak but the amplitude are very insignificant, but instead; system has less settling time.

VI. CONCLUSION

In this paper for reaching to proper performance and robustness in boiler control system and overcome pole zero cancelation phenomena between plant and controller in designing multivariable robust controller; compound of bilinear transform and H_∞ Synthesis method is used. this method in comparison with using common multivariable robust control, improves system performance for control of significant parameters, considerably.

REFERENCES

[1] L. Johanssson and H. N. Koivo, "Inverse Nyquist array technique in the design of a multivariable controller for a solid-fuel boiler," *Int. J. Contr.*, vol. 40, pp. 1077–1088, 1984.

[2] Z. Hu,H. Fan and Y. He, "Robust Controller Design for boiler system," *int. IEEE Conf . Intelligent Computation Techno*, pp.445-449, 2008.

[3] W. Tan, H. Marquez, T. chen , "Multivariable Robust Controller Design for a Boiler System," *IEEE Trans Control Syst Techno* , Vol.10,No.5, Sep. 2002.

[4] W. Tan, Y. Niu and J. Liu, "H_∞ Control for a Boiler-turbine Unit," *Proc. IEEE Conf. Contr.* Aug.,USA,pp.910-914 .1999.

[5] L. Johanssson and H. N. Koivo, "Design Of H_∞-PSS Using Numarator-Denamarotor Uncertainty Representation," *IEEE Trans Energy Conversion.*, Vol. 12, No. 1, March 1997.

[6] M.R. Gharib, I. Dabzadeh, S.A. S.Mousavi, S.Kamelian, "Robust Controller Design with QFT and Sliding Mode for Boiler Pressure," *int. IEEE Conf . Modelling, Identifcation and Control*, pp.412-417, 2010.

[7] G.Pellegrinetti , J.Bentsman,"H_∞ controller design for boilers,", *Int.J.Robust Nonlinear Contr.* ,vol.4,pp.645–671,1994.

[8] B. M. Hogg and N. M. E. Rabaie,"Multivariable generalized predictive control of a boiler system," *IEEE Trans. Energy Conversion*, vol. 6, pp.282–288, Jan. 1991.

[9] D. C. McFarlane and K. Glover, *Robust Controller Design Using Normalized Coprime Factorization Description*. New York: Springer-Verlag, 1990.

[10] M.C. Tsai, E.J.M. Geddes and I. Postlethwaite, ," Pole-Zero cancelation and close loop properties of an H_∞ mixed sensitivity design problem," *Proc. IEEE Conf. Declslon and Contr. 1990*.