Robust Control for a Nonlinear Boiler-Turbine System *

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Abstract: A loop-shaping H_∞ controller is designed for a nonlinear multivariable boiler-turbine system. In order to implement the complex H_∞ controller, we propose a method to reduce it to a multivariable PID controller. The final simplified controller is composed of three main-channel PI controllers plus one off-channel PI controller. Simulation shows that the designed controllers have good tracking, disturbance rejection properties, and robustness against the variations of the operation points due to the plant nonlinearity.

Key words: loop shaping H_∞ control; nonlinear bolier-turbine system; multivariable PI controller; robust stability and performance

非线性锅炉-汽轮机系统的鲁棒控制

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摘要: 本文采用环路成形 H_∞ 控制方法对一非线性锅炉-汽轮机系统进行设计. 为了能方便地在实际工程中实现复杂的控制器, 本文提出用多变量 PID 控制器逼近所得控制器的方法. 最终简化的控制器由位于主对角通道的三个 PI 控制器及位于次对角通道的一个 PI 控制器实现, 仿真表明所得控制器具有较好的信号跟踪、抗干扰性能, 并能在较大范围操作点工作, 从而具有较佳鲁棒性.

关键词: 环路成形 H_∞ 控制; 非线性锅炉-汽轮机系统; 多变量 PID 控制器; 鲁棒稳定及性能

1 Introduction

The boiler-turbine system is a typical nonlinear multivariable control system. Currently, the design of the power plant controllers are mainly based on classical SISO control strategies. So the following problems exist:

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

· Even if each PID controller's parameters can be tuned at the nominal operation point, the whole controller cannot be guaranteed to work well at other operation points.

So in order to make full use of the potential of the boiler-turbine unit, multivariable control strategies should be taken. In fact, the need for simultaneous control of the strongly interacting variables of the boiler-turbine system makes the boiler-turbine control an ideal application for multivariable control[1].

Direct application of the multivariable control theories in the boiler-turbine system had been reported in some literature, e.g., [2,3]. However, these methods usually need an accurate plant model and the designed controllers are usually very complex. For a boiler-turbine system, 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 is needed here.

In this paper, loop shaping H_∞ control is applied to the same power plant considered in [1]. In our opinion, the approach is more appropriate for industrial process control[4,5]. We show that our controller has good tracking and disturbance rejection properties despite the variation of the operation points. Further, we propose a method to reduce a controller in the state-space form to a PID form, in this way we reveal the underlying structure of a multivariable controller and implement it by using the usual PID structure. Simulation results show that the final simplified controller maintains the properties of the original H_∞ controller.

* Supported by the National Electric Power Corporation (1998032).
Manuscript received Aug.5, 1998, revised Aug.4, 1999.

2 Boiler-turbine model

The boiler-turbine control system can be modeled as a 3×3 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). Since disturbance exists in the practical environment, the controller also needs to be able to reject the disturbance.

The system we consider is a 160MW fossil fueled power generation unit. The model for the unit was studied extensively in the past[6]. It was generally regarded to model the real plant well enough. The nonlinear model is given by the following equations:

$$\begin{cases} \dot{x}_1 = -0.0018 u_2 x_1^{9/8} + 0.9 u_1 - 0.15 u_3, \\ \dot{x}_2 = (0.073 u_2 - 0.016) x_1^{9/8} - 0.1 x_2, \\ \dot{x}_3 = (141 u_3 - (1.1 u_2 - 0.19) x_1)/85, \\ y_1 = x_1, \\ y_2 = x_2, \\ y_3 = 0.05(0.13073 x_3 + 100 a_{cs} + q_e/9 - 67.975), \end{cases} \tag{1}$$

where the variables x_1, x_2, and x_3 denote the drum steam pressure (kg/cm^2), the electrical output (MW), and the density of fluid in the system (kg/m^3), respectively. The control inputs, u_1, u_2, and 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 a_{cs} and q_e are the quality factor of steam and the evaporation mass flow rate (kg/s), respectively and expressed by

$$\begin{aligned} a_{cs} &= \frac{(1 - 0.001538 x_3)(0.8 x_1 - 25.6)}{x_3(1.0394 - 0.0012304 x_1)}, \\ q_e &= (0.854 u_2 - 0.147) x_1 + 45.59 u_1 - \\ &\quad 2.54 u_3 - 2.096. \end{aligned} \tag{2}$$

Note that the control inputs are saturated, i.e., $0 \leqslant u_i \leqslant 1 (i = 1, \cdots, 3)$. This fact puts additional nonlinearity in the system.

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

$$x^0 = [108 \quad 66.65 \quad 428]^{\mathrm{T}},$$
$$u^0 = [0.34 \quad 0.69 \quad 0.436]^{\mathrm{T}},$$
$$y^0 = [108 \quad 66.65 \quad 0]^{\mathrm{T}}.$$

At these values, a linearized model can be obtained, and the system matrices are given by

$$\begin{aligned} A &= \begin{bmatrix} -2.509e-3 & 0 & 0 \\ 6.940e-2 & -0.1 & 0 \\ -6.690e-3 & 0 & 0 \end{bmatrix}, \\ B &= \begin{bmatrix} -0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{bmatrix}, \\ C &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 6.34e-3 & 0 & 4.71e-3 \end{bmatrix}, \\ D &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.253 & 0.512 & -0.014 \end{bmatrix}. \end{aligned} \tag{3}$$

3 Loop shaping H$_\infty$ design

Given a plant G, the loop-shaping H$_\infty$ design procedure goes as follows[7]:

· Loop Shaping.

Pre-compensator W_1 and/or post-compensator W_2 are used to shape the singular values of G such that the shaped plant $\tilde{G} = W_2 G W_1$ has the desired open loop shape.

· Robust Stabilization.

For the shaped plant $\tilde{G}$, solve the following H$_\infty$ optimization problem:

$$\varepsilon_{\max}^{-1} = \inf_{\tilde{K}} \left\| \begin{bmatrix} S & S\tilde{G} \\ \tilde{K}S & \tilde{K}S\tilde{G} \end{bmatrix} \right\|_\infty. \tag{4}$$

Here $S := (I + \tilde{G}\tilde{K})^{-1}$ and $\varepsilon_{\max}$ is a "design indicator". A reasonable value (e.g. > 0.2) indicates that the loop shapes can be well approximated together with good robust stability.

· Final Controller.

The final feedback controller is constructed as $K = W_1 \tilde{K} W_2$.

Some advantages of the approach are as follows:

1) Easy to use. The approach combines the classical loop shaping idea with the robust control idea. An engineer who has some backgrounds on classical loop shap-

ing can use the approach.

2) Easy to solve. The H_∞ problem (4) is always regular and the infimum can be computed explicitly without iteration[7].

4 Design results

The pre-compensator we select is $W_1 = K_c K_s$ and $W_2 = I_3$, where K_c is selected as an alignment to DC part of the linearized model in order to achieve static decoupling, while K_s is a PI controller used to shape the open loop. After trial, W_1 is selected as:

$$W_1 = \begin{bmatrix} 0.0011 & 0.0037 & 0.0213 \\ -0.0043 & 0.0071 & 0 \\ -0.0004 & 0.0059 & 0.1280 \end{bmatrix} \times \begin{bmatrix} 3+3/s & 0 & 0 \\ 0 & 3+3/s & 0 \\ 0 & 0 & 3+3/s \end{bmatrix}. \quad (5)$$

With this pre-compensator, the design indicator ε_{max} equals 0.4059, and we get an H_∞ controller of order 8 (see Appendix).

It is difficult to implement a controller of order 8. Below we will present a method to approximate a high-order controller with a PID controller. Given a controller with a state-space realization $\begin{cases} \dot{x} = A_k x + B_k y, \\ u = C_k x + D_k y, \end{cases}$ the reduction procedure goes as follows:

1) Take a transformation T such that the zero eigenvalues of the matrix A_k are decomposed from others, i.e., $TA_kT^{-1} = \begin{bmatrix} 0 & 0 \\ 0 & \alpha_2 \end{bmatrix}$, where a_2 does not have zero eigenvalue.

2) Decompose TC_k and B_kT^{-1} accordingly, i.e.,

$$TC_k = [c_1 \quad c_2], \quad B_kT^{-1} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}.$$

3) Then a PID approximation to the controller is $K_p + K_i/s + K_d s$, where

$$\begin{cases} K_p = D_k - c_2 a_2^{-1} b_2, \\ K_i = c_1 b_1, \\ K_d = -c_2 a_2^{-2} b_2. \end{cases} \quad (6)$$

The procedure is, in fact, to find the first three terms of the Maclaurin series of the controller with respect to the frequency domain variable s. Thus the resulting PID controller approximates the low frequency part of the controller.

For the controller designed above, a PID approximation can be obtained by using the procedure. After removing the small terms and some unrealized terms (e.g., terms with the proportional gain positive while the integral action negative), we simplify the H_∞ controller to the following multivariable PI controller:

$$K(s) = \begin{bmatrix} 0.0736+\frac{0.0034}{s} & 0 & 0.9338+\frac{0.0282}{s} \\ 0 & 0.0331+\frac{0.0121}{s} & 0 \\ 0 & 0 & 5.6035+\frac{0.1694}{s} \end{bmatrix}. \quad (7)$$

So we can implement it with only four PI controllers.

To test the performance of the controllers, simulation under various conditions is performed using the nonlinear dynamic model (1). We consider the following situations:

Case 1 A step input disturbance of magnitude 0.1 at the 1st input channel is inserted at $t = 10$ and a step output disturbance of magnitude 10 at the 1st output channel is inserted at $t = 200$, and a step change in y_1 of magnitude -10 is inserted at $t = 500$.

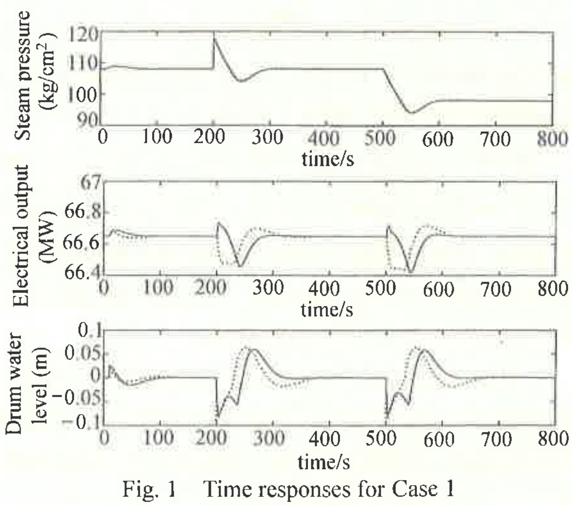

Fig. 1 Time responses for Case 1

Case 2 A step input disturbance of magnitude 0.1 at the 2nd input channel is inserted at $t = 10$ and a step output disturbance of magnitude 10 at the 2nd output channel is inserted at $t = 200$, and a step change in y_2 of magnitude 20 is inserted at $t = 500$.

Case 3 A step input disturbance of magnitude 0.1 at the 3rd input channel is inserted at $t = 10$ and a step output disturbance of magnitude 0.1 at the 3rd output

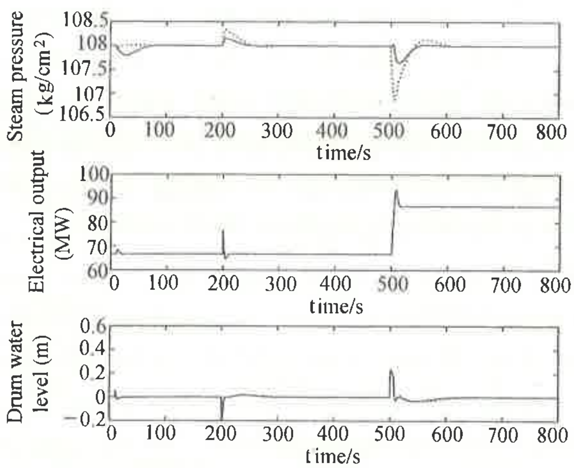

Fig. 2 Time responses for Case 2

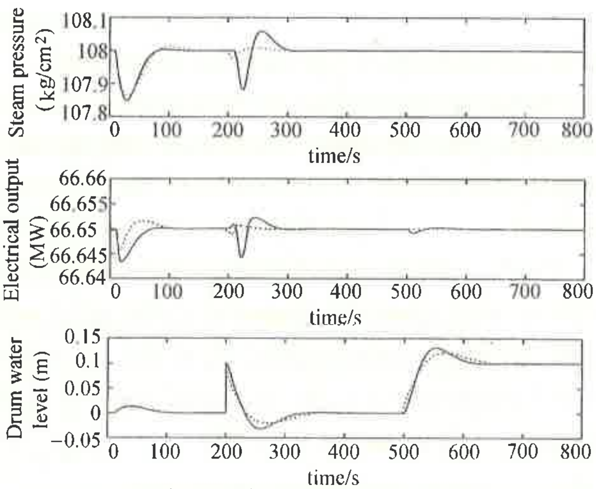

Fig. 3 Time responses for Case 3

channel is inserted at $t = 200$, and a step change in y_3 of magnitued 0.1 is inserted at $t = 500$.

Figures 1 ~ 3 show the time response of y_1, y_2 and y_3 under the three cases for the H_∞ (solid line) and the PI controllers (dotted line). Note that control input saturation is considered in all the cases. We find that our controllers have the following properties:

1) The variables y_1 (the steam pressure) and y_2 (the electrical output) are almost decoupled since a step change in one variable has little effect on the other variable.

2) The variable y_3 (the water level) is decoupled from y_1 and y_2 in a uni-direction, i.e., a step change in y_3 has little influence on y_1 and y_2, but the converse is not true.

3) The closed loop system can follow the load command rapidly (in about 20 seconds), and the safe operation is guaranteed.

4) The effect of input and output disturbance is small and vanishes rapidly.

In all cases, the operation point varies, but the designed control systems function well. The controllers have good command tracking ability, disturbance rejection at the input and output channels, and robustness to modeling errors. The controller designed in [1] does not have the same good decoupling property as ours. Furthermore, it needs more control energy to track the electrical output of the same magnitude, thus it is more liable to saturation. So our controllers are superior. From the simulation, we also find that the multivariable PI controller has almost the same proporties as the original H_∞ controller.

5 Conclusion

In this paper, the robust control based on the loop shaping H_∞ method is designed for a 160MW fossil fueled nonlinear boiler-turbine unit. Simulation shows that the designed controller has good command tracking and disturbance rejection properties at the input and output channels, and robustness to modeling errors. We also propose a method to reduce a complex state-space controller to a multivariable PID controller. The final simplified controller reveals the underlying structure of the boiler-turbine control system and maintains the good performance of the original controller.

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Appendix

The state-space data of the designed 8-th H_∞ controller are:

$$A_k = \begin{bmatrix} -0.1340 & 0.0181 & -0.2703 & -0.1750 & -0.1191 & 0 & 0 & 0 \\ 0.0595 & -0.1492 & -0.4062 & -0.3261 & -0.1480 & 0 & 0 & 0 \\ -0.0104 & -0.0079 & 0.1669 & 1.7727 & -0.2008 & 0 & 0 & 0 \\ 0.0074 & 0.0247 & -1.2110 & -2.8783 & 0.2842 & 0 & 0 & 0 \\ 0.0163 & -0.0176 & 0.1995 & 0.2863 & -0.4544 & 0 & 0 & 0 \\ 0.0303 & -0.0196 & -0.0268 & -0.2020 & 0.0275 & 0 & 0 & 0 \\ 0.0153 & -0.0133 & 0.0350 & 0.3206 & -0.0314 & 0 & 0 & 0 \\ -0.0040 & 0.0066 & 0.0008 & 0.0022 & 0.0715 & 0 & 0 & 0 \end{bmatrix},$$

$$C_k = \begin{bmatrix} 0.0000 & 0.0002 & 0.0004 & 0.0031 & 0.0043 & 0.0033 & 0.0112 & 0.0640 \\ -0.0001 & 0.0000 & 0.0011 & 0.0094 & -0.0010 & -0.0128 & 0.0212 & 0.0000 \\ -0.0013 & 0.0023 & 0.0009 & 0.0067 & 0.0268 & -0.0011 & 0.0177 & 0.3839 \end{bmatrix},$$

$$B_k = \begin{bmatrix} -5.5071 & 1.7501 & -49.4133 \\ 5.3604 & 2.6984 & -69.7761 \\ 0.2735 & -2.1246 & -0.2591 \\ -0.1692 & 7.4489 & 1.2021 \\ 0.3213 & -1.2468 & 16.1019 \\ 1.9096 & 0.0450 & -0.1207 \\ 1.1673 & 0.0275 & -0.0738 \\ -0.1946 & -0.0046 & 0.0123 \end{bmatrix},$$

$$D_k = \begin{bmatrix} 0.0069 & 0.0002 & -0.0004 \\ 0.0003 & 0.0000 & 0.0000 \\ -0.0560 & -0.0013 & 0.0035 \end{bmatrix}.$$

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谭　文　见本刊 1999 年第 5 期第 686 页.

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