Multivariable robust regulation of an industrial boiler-turbine with model uncertainties

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***Abstract*— Efficient robust control methods are required to keep the boiler-turbine unit performance appropriately. In this paper, a hybrid multivariable robust control strategy including the regulator and observer is designed to improve the performance of an industrial boiler-turbine unit. In the nonlinear model of the process, output variables including the drum pressure, electric power and water level of the drum are controlled at the desired set-points by manipulation of the fuel, steam, and feed-water flow rates. Due to economic and technical reasons and for the estimation of process states, the full-order observer is designed. For disturbance rejection and process stability, a regulator system is used. The performance of the hybrid control system is investigated in the presence of model uncertainties for two cases. For the regulation purpose, the dynamic system of Case I shows a more smooth variation of drum water level. Finally, it is observed that in the presence of model uncertainties, the hybrid control system guarantees the robust stability and performance of the process in estimation and regulation objectives. Implementation of the above-proposed control law in its related electronic circuit of the boiler-turbine will be considered as the future stage of the current research.**

Keywords— Boiler-turbine; Nonlinear uncertain model; Multivariable control; Observer; Robust performance.

I. INTRODUCTION

Power plant construction needs a vast investment and its operation has economic and environmental expenses. Boiler-turbine unit is the most important component of power planet and its performance affects the whole power plant performance, as well as its safety, is critical. The primary boiler-turbine unit responsibility is converting the fuel chemical energy into mechanical energy and then electrical energy. An automatic control system is needed to achieve the desired performance and efficiency in boiler-turbine units. It must be able to keep the mechanical energy generation in balance with the electrical energy. For this purpose, regulation of the variables such as the steam pressure, electric power and drum water level in desired operating points with acceptable tolerances as well as satisfactory tracking of the desired command references are demanded. However, the physical constraints exerted on the actuators must be satisfied by the control signals. These constraints can be the magnitude and saturation rate for the control valves of the fuel, steam and feed-water flows [1, 2].

Among the early works on dynamic modeling of the boiler-turbine units, simplification of nonlinear models [3], dynamic modeling based on parameter estimation [4], system identification using neural networks [5] and modeling based on data logs [6] have been done. In the recent studies, simple dynamic modeling and stability analysis of a steam boiler drum [7], development of various simulation packages for steam plants with natural and controlled recirculation (e.g.,[8]), optimization of thermal systems in heat recovery steam generator during cold start-up operation [9] and proposing a computational model to minimize the fuel and environmental costs of a 310 MW fuel oil fired boiler have been investigated [10].

Various control methods have been used to improve the boiler or boiler-turbine units' performance. Among them, optimal control [11], improved sliding mode control [12], hierarchical optimization using fuzzy-model predictive control [13], PID-based control using iterative feedback tuning methodology [14] and multi-objective control with inclusion of actuators' limitations [15] have been studied. In addition, predictive control has been extensively implemented in this area via fuzzy clustering and subspace methods [16], nonlinear genetic algorithm (GA) [17], data-driven modeling [18], nonlinear adaptive controllers [19,20] and local model networks [21].

However, due to variations of the dynamic parameters, the boiler-turbine model associates with uncertainties in practice. In many applications of boiler-turbine units, the development of state observers is essential, especially in the case of faults in sensors. When the sensor fusion systems fail, full-order observers can be used as a supportive tool to provide an acceptable estimation of all state variables. to make the control system hardware less expensive, the development of robust controllers for the disturbance rejection is also necessary. For realistic uncertain dynamic systems, traditional control approaches may result in aggressive or sluggish response at other operating conditions. This is because the tuned control parameters cannot cover all the operating ranges of the boiler-turbine unit.

In this article, a robust hybrid control system including the regulator, full-order observers are designed for a nonlinear multivariable model of boiler-turbine unit. The drum pressure, electric power, and drum water level (as output variables) are controlled via manipulation of valve positions for fuel, steam, and feed-water flow rates (as control inputs). For the first time, the results of this study are presented for two cases of boiler-turbine unit dynamics in which the fluid density and water level of the drum are considered as the third state, respectively (while in both cases, drum pressure and electric power are considered as the first two states).

II. NONLINEAR MULTIVARIABLE MODEL OF AN INDUSTRIAL BOILER-TURBINE UNIT

The schematic view of a water-tube boiler is shown in Fig. 1 in which the preheated water is fed into the steam drum and flows through the down-comers into the mud drum.

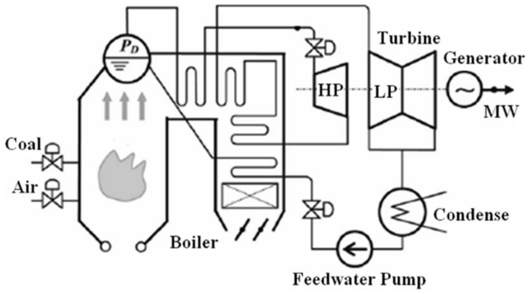


Fig. 1. A schematic view of the boiler-turbine components

The boiler-turbine model used in this paper was presented by Bell and Astrom, which is a third-order MIMO nonlinear system and its parameters are obtained through physical modeling, system identification and model simplification. This model of the boiler-turbine unit has been guided by plant experiments in Sweden and Australia [3], which is described as:

$$\begin{cases} \dot{x}_1 = -\alpha_1 u_2 x_1^{9/8} + \alpha_2 u_1 - \alpha_3 u_3 \\ \dot{x}_2 = (\beta_1 u_2 - \beta_2) x_1^{9/8} - \beta_3 x_2 \\ \dot{x}_3 = [\gamma_1 u_3 - (\gamma_2 u_2 - \gamma_3) x_1] / \gamma_4 \end{cases} ; \quad \begin{cases} y_1 = x_1 \\ y_2 = x_2 \end{cases} \tag{1}$$

where, y_1, y_2, and x_3 are the drum pressure(kgf/cm^2), electric power (MW) and fluid density (Kg/m^3), respectively, are system outputs. Coefficients $\alpha_i . \beta_i . \gamma_i$ $i = 1.2.3$ $j = 1 \dots 4$are given in Table 1. Drum water level (y_3) can be obtained through the following complex equation:

$$\begin{aligned} y_3 &= 0.05(0.13073 x_3 + 100 a_{cs} + q_e/9 - 67.975) \\ a_{cs} &= \frac{(1-0.001538 x_3)(0.8 x_1 - 25.6)}{x_3(1.0394 - 0.0012304 x_1)}; \\ q_e &= (0.854 u_2 - 0.147) x_1 + 45.59 u_1 - 2.514 u_3 - 2.096 \end{aligned} \tag{2}$$

where a_{cs} is the steam quality and $q_e(\frac{kg}{s})$ is the evaporation rate. Control inputs and their constraint are presented as follows:

$$\begin{aligned} &0 \le u_i \le 1, \quad -0.007 \le \dot{u}_1 \le 0.007, \quad -2 \le \dot{u}_2 \le 0.02, \\ &-0.05 \le \dot{u}_3 \le 0.05 \quad (i = 1,2,3) \end{aligned} \tag{3}$$

Where the u_1, u_2 and $u_3$are the position of the valve for the fuel, steam, and feed-water flows respectively.

TABLE I. TABLE 1: DYNAMIC COEFFICIENTS OF THE BOILER-TURBINE MODEL BY BELL AND ASTROM [3, 12]

$\alpha_1 = 0.0018$	$\beta_1 = 0.073$	$\gamma_1 = 141$
$\alpha_2 = 0.9$	$\beta_2 = 0.016$	$\gamma_2 = 1.1$
$\alpha_3 = 0.15$	$\beta_3 = 0.1$	$\gamma_3 = 0.19$
		$\gamma_4 = 85$

III. ESTIMATION & REGULATION OBJECTIVES VIA A HYBRID CONTROL SYSTEM

In this section, a regulator system is designed for the disturbance rejection of two cases. In Case I,$x_1 . x_2 . x_3$ are considered as system states, as a traditional approach in the control of Bell & Astrom model. As an alternative and novel configuration, $x_1 . x_2 . y_3$ are supposed to be system states in Case II. It means that in both cases, drum pressure and electric power are considered as the first two states (denoted by $x_1 . x_2$); while the fluid density (x_3) and water level of the drum (y_3) are considered as the third state in Case I & II, respectively.

As mentioned before, sometimes actual states are not physically realizable or their measurement is expensive. Under such conditions, using full order observers for estimation of states is unavoidable. The observers are designed based on Luenberger's model for estimation of the state variables on-line. Regulators and full order observers constitute the whole hybrid controller used for the boiler-turbine unit. In the state-space formulation of the linearized problem, Eq. (1) can be written in terms of the state and input matrices ($A . B$) as:

$$\dot{\bar{\mathbf{x}}} = \mathbf{A}\,\bar{\mathbf{x}} + \mathbf{B}\,\bar{\mathbf{u}} \tag{4}$$

A. Controller and observer gains

According to the reference [20] the feedback control law, is:

$$u = -K\bar{x} \tag{5}$$

where the feedback gain matrix is determined for Cases I and II as:

$$\mathbf{K_I} = \begin{bmatrix} 0.0058 & -0.0034 & 0.0014 \\ 0.0049 & -0.0064 & 0 \\ 0.0001 & -0.0054 & 0.0084 \end{bmatrix}$$
$$\mathbf{K_{II}} = \begin{bmatrix} 0.0197 & 0.0204 & 0.0826 \\ 0.0049 & -0.0064 & 0 \\ 0.0838 & 0.1374 & 0.4956 \end{bmatrix} \tag{6}$$

Similarly for the full order observer, according to the reference [22] , we have:

$$\begin{aligned} \dot{\tilde{\bar{x}}} &= A\tilde{\bar{x}} + B\bar{u} + K_e(\bar{y} - C\tilde{\bar{x}}) \\ &= (A - K_e C)\tilde{\bar{x}} + Bu + K_e\,\bar{y} \end{aligned} \tag{7}$$

Where the observer gain for considered two case is calculated as follows:

$$K_{\mathbf{eI}} = \begin{bmatrix} 0.0215 & 0.0694 & -0.0067 \\ 0 & -0.0600 & 0 \\ 0 & 0 & 0.0560 \end{bmatrix}'$$
$$K_{\mathbf{eII}} = \begin{bmatrix} 0.0215 & 0.0694 & 0.0063 \\ 0 & -0.0600 & 0 \\ 0 & 0 & 0.0560 \end{bmatrix}' \tag{8}$$

IV. RESULTS AND DISCUSSION ON BOILER-TURBINE PERFORMANCE IN CONTROL OBJECTIVES

In this section, the effects of designed components of the hybrid control system including the regulator for disturbance rejection, full order observers for estimation are investigated. A schematic view of the designed hybrid controller is shown in Fig.2.

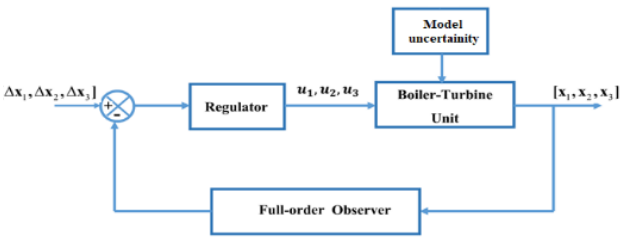
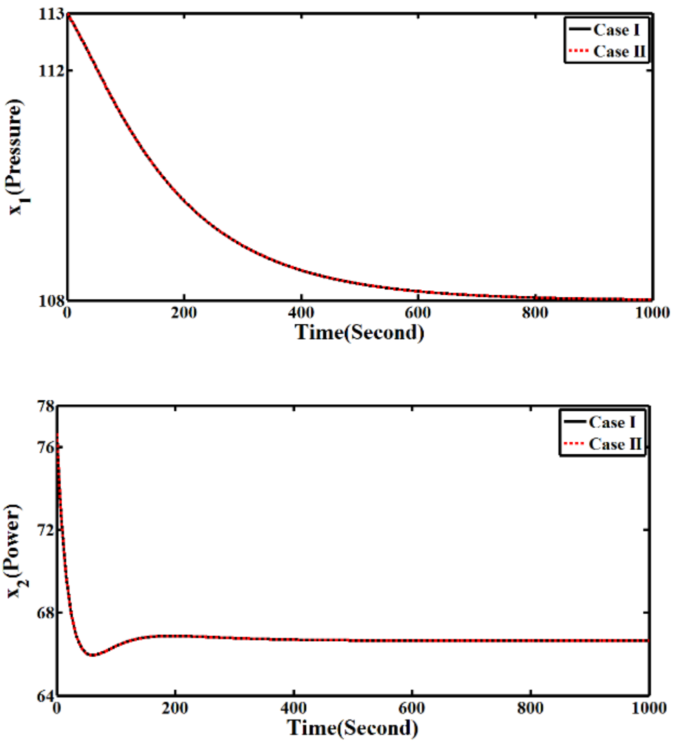


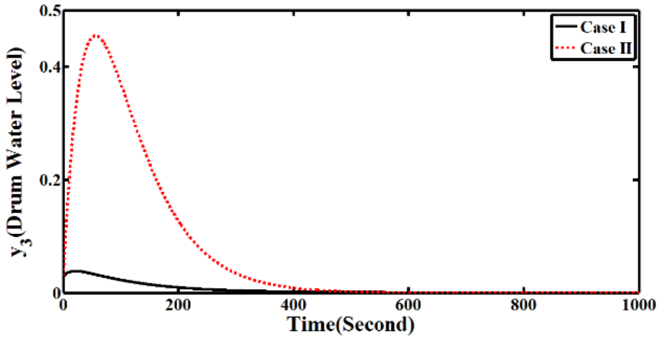
Fig. 2. Structure of the hybrid control system and its components used in the boiler-turbine unit.

A. *Comparison between the performance of dynamic systems of Case I & II*

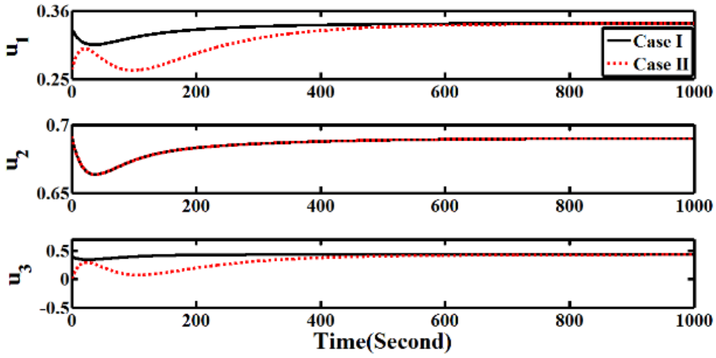
The performance of the control system in Case I and Case II is compared, in case of uncertainty about $\pm 20\%$ as well as the same initial condition, as shown in Fig. 3. Accordingly, the drum pressure and electric power demonstrate the coincident behavior in both cases. But, for Case II, there is an undesirable overshoot in drum water level (y_3), which is a critical issue for the performance and safety of the boiler-turbine unit. Valves' position of the steam control is almost the same for both cases while lower fuel and feed-water consumptions are predicted in Case II (in a slight manner). Therefore, in practice it is advised to design the control system for the model in which drum pressure, electric power, and fluid density are defined as the state variables; as done in Case I.



(a)



(b)



(c)

Fig. 3. Comparing the performance of Case I (black solid line) and Case II (red dashed line) with full order observer including: (a) Time response of the state variables (b) Variation of the drum water level and (c) Required variation of the fuel, steam and feed-water valves for the regulation around the nominal operating point # 4.

V. CONCLUSION

In this article, a multivariable nonlinear model of an industrial boiler-turbine unit is considered. A hybrid control strategy including the regulator, full-order observers is designed for the objectives of disturbance rejection. In this design, output variables including the drum pressure, electric power and water level of the drum (or alternatively, fluid density) are controlled at the desired set-points by manipulation of the fuel, steam, and feed-water flow rates (as control inputs).

For the first time, the results of this study are presented for two cases of boiler-turbine unit dynamics in which the fluid density and water level of the drum are considered as the third state, respectively (while in both cases, drum pressure and electric power are considered as the first two states). The robust performance of the hybrid control strategy in regulation and estimation objectives is examined under various operating conditions. According to the results obtained, the following conclusions are extracted:

• Comparing the performance of Cases I & II reveals that the drum pressure and electric power show the coincident behavior. But, there is an undesirable jump in the behavior of the drum water level for Case II (that is a critical issue for the performance and safety of the boiler-turbine unit). However, control efforts are almost the same for both cases.

• In the presence of model/parametric uncertainties, the proposed hybrid control strategy acts effectively and guarantees the robust stability and performance of the boiler-turbine unit. For the realistic perturbed models; robust regulation and estimation are achieved without saturation of control signals.

Finally, it should be mentioned that the Implementation of the above-proposed control law in its related electronic circuit of the boiler-turbine will be considered as the future stage of the current research

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