Centralized PID Control by Decoupling of a Boiler-Turbine Unit

Juan Garrido, Fernando Morilla, and Francisco Vázquez

Abstract—**This paper deals with the control of a nonlinear boiler-turbine unit, which is a 3x3 multivariable process with great interactions, hard constraints and rate limits imposed on the actuators. A control by decoupling methodology is applied to design a multivariable PID controller for this unit. The PID controller is obtained as a result of approximating an ideal decoupler including integral action. Three additional proportional gains are tuned to improve the performance. Because of the input constraints, a conditioning anti wind-up strategy has been incorporated in the controller implementation in order to get a better response. A good decoupled response with zero tracking error is achieved in all simulations. The results have been compared with other controllers in literature, showing a similar or better response.**

Keywords: boiler-turbine unit, multivariable PID control, centralized control by decoupling, anti wind-up techniques.

I. INTRODUCTION

A boiler-turbine unit is a 3x3 process showing nonlinear dynamics under a wide range of operating conditions [1]. In order to achieve a good performance, the control of the unit must be carried out by multivariable control strategies. In fact, the requirements to control simultaneously several measures with strong couplings, justify the use of any multivariable control.

In recent years many researchers have paid attention to the control of boiler-turbine units using different control methodologies, such as robust control, genetic algorithm (GA) based control, fuzzy control, gain-scheduled approach, nonlinear control and so on.

Robust multivariable controllers using H_∞ loop-shaping techniques [2], [3] achieve good robustness and zero tracking error; however, H_∞ controllers encounter difficulties in dealing with the control input constraints. Genetic algorithm based method such as GA/PI or GA/LQR control [4], [5] may cause large overshoot or steady-state tracking error. Nonlinear controllers [6] show good decoupling, tracking and robustness properties in different operating points, because they consider the nonlinear dynamic of the system in their design stage.

This paper illustrates the application of a multivariable PID controller to the boiler-turbine unit considered in [1]. This PID controller is a full matrix controller (centralized control) designed by the methodology of "decoupling control" [7-9]. The centralized control depicted in Fig. 1 has been chosen instead of decentralized control (diagonal control) because the boiler-turbine unit shows significant interactions [10-12]. PID decoupling control design methodology within the framework of a unity feedback control structure has been tested by the authors for TITO (two-input two-output) processes in [9], obtaining good results.

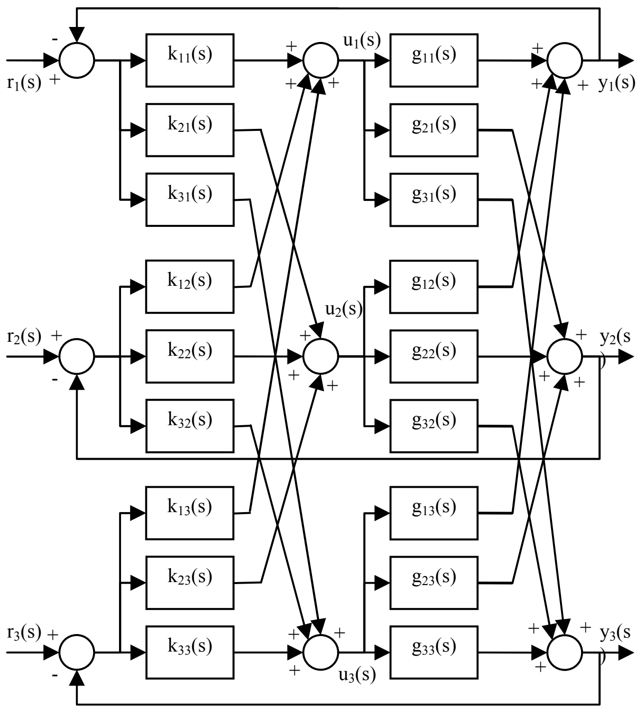

Fig. 1. 3x3 centralized control using a unity feedback control structure

Moreover, because of hard constraints imposed on the actuators of the boiler-turbine unit, an anti wind-up strategy is used to improve the response of the system. In section II the nonlinear multi-input/multi-output (MIMO) boiler-turbine model is presented. Section III deals with the PID centralized control by decoupling of this system. In section

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IV the results are evaluated in comparison with other authors. Finally, section V presents the main conclusions of this paper.

II. The Boiler-Turbine Model

The boiler-turbine model used in this paper was developed by Bell and Aström [1]. The model is a third order nonlinear multivariable system with great interactions, hard constraints and rate limits imposed on the actuators. The dynamics of the unit is given by

$$\begin{cases} \dot{x}_1 = -0.0018u_2x_1^{9/8} + 0.9u_1 - 0.15u_3 \\ \dot{x}_2 = \left(0.073u_2 - 0.016\right)x_1^{9/8} - 0.1x_2 \\ \dot{x}_3 = \left(141u_3 - \left(1.1u_2 - 0.19\right)x_1\right)/85 \\ y_1 = x_1 \\ y_2 = x_2 \\ y_3 = 0.05\left(0.13073x_3 + 100a_{cs} + q_e/9 - 67.975\right) \end{cases} \tag{1}$$

where state variables x_1, x_2 and x_3 denote drum pressure (kg/cm^2), power output (MW) and fluid density (kg/m^3), respectively. The inputs u_1, u_2 and u_3 are the valve positions for fuel flow, steam control, and feed-water flow, respectively. The output y_3 is the drum water level (m) regarding the operating reference level, so it can take positive and negative values. Variables a_{cs} and q_e are steam quality and evaporation rate (kg/s), respectively, and they are given by

$$\begin{aligned} a_{cs} &= \frac{\left(1 - 0.001538x_3\right)\left(0.8x_1 - 25.6\right)}{x_3\left(1.0394 - 0.0012304x_1\right)} \\ q_e &= \left(0.854u_2 - 0.147\right)x_1 + 45.59u_1 - 2.514u_3 - 2.096 \end{aligned} \tag{2}$$

Due to actuator limitations, the control inputs are subject to the following constraints:

$$\begin{gathered} 0 \le u_i \le 1\left(i = 1,2,3\right) \\ \left|\dot{u}_1\right| \le 0.007 \\ -2 \le \dot{u}_2 \le 0.02 \\ \left|\dot{u}_3\right| \le 0.05 \end{gathered} \tag{3}$$

There are several typical operating points of the Bell and Astrom model (1), but the linear control design for the unit found in literature usually takes the linearized model at the operating point x^0=[108 66.65 428]^T, u^0=[0.34 0.69 0.433]^T and y^0=[108 66.65 0]^T. The linearized model is given by the following transfer function matrix G(s).

$$G(s) = \frac{1}{398.6s+1} \cdot \begin{pmatrix} 358.7 & \dfrac{249.1}{(10s+1)} & \dfrac{0.0113(34.5781s+1)(258.3312s-1)}{s} \\ -139.1 & \dfrac{44.9621(1255.3s+1)}{(10s+1)} & \dfrac{0.0022(1428.6s+1)(65.1466s-1)}{s} \\ -59.79 & \dfrac{-41.49}{(10s+1)} & \dfrac{-0.0097(282.5657s+1)(2.0333s-1)}{s} \end{pmatrix}^T \tag{4}$$

There is a common pole $s=-0.002509$ in all its elements, as well as a common pole $s=-0.1$ in the second row (y_2), and a common integrator in the third row (y_3). This 3x3 matrix is used to design the centralized control by decoupling.

For interaction analysis we obtain the Relative Gain Array (RGA) of the model. Since G(s) contains integrator elements in the third row, the RGA is calculated in the alternative way described in [13]. The expression of the RGA is

$$RGA = \begin{pmatrix} 0.3119 & 0.6824 & 0.0058 \\ 0.9294 & 0.3176 & -0.2471 \\ -0.2413 & 0 & 1.2413 \end{pmatrix} \tag{5}$$

The high number of RGA values which are far of the unit shows a process with great interactions, as it was expected. Furthermore, its high condition number of 58722 is indicative of an ill-conditioned plant. So, scaling the process should be advisable in order to reduce this number. Nevertheless, scaling is not used because it is integrated in the proposed design methodology.

III. PID Decoupling Control

In [9], centralized PID control by decoupling for TITO processes is presented. In this section this design methodology is extended to 3x3 processes given by

$$\mathbf{G}(s) = \begin{pmatrix} g_{11}(s) & g_{12}(s) & g_{13}(s) \\ g_{21}(s) & g_{22}(s) & g_{23}(s) \\ g_{31}(s) & g_{32}(s) & g_{33}(s) \end{pmatrix} \tag{6}$$

where the process is controlled by a control law depending on the error signal, such as it is shown in Fig 1. This is,

$$\begin{pmatrix} u_1(s) \\ u_2(s) \\ u_3(s) \end{pmatrix} = \begin{pmatrix} k_{11}(s) & k_{12}(s) & k_{13}(s) \\ k_{21}(s) & k_{22}(s) & k_{23}(s) \\ k_{31}(s) & k_{32}(s) & k_{33}(s) \end{pmatrix} \cdot \begin{pmatrix} r_1(s) - y_1(s) \\ r_2(s) - y_2(s) \\ r_3(s) - y_3(s) \end{pmatrix} \tag{7}$$

where K(s) is the 3x3 full-cross coupled multivariable transfer matrix of the controller.

The paradigm of "decoupling control" [7-9] propose to find a K(s) such that the closed loop transfer matrix G(s)·K(s)·[I + G(s)·K(s)]$^{-1}$ is decoupled over some desired bandwidth. This goal is ensured if the open loop transfer matrix L(s)=G(s)·K(s) is diagonal. For this reason, the techniques used in decoupling control are very similar to the techniques used to design decouplers.

Then, assuming that the open loop transfer matrix should be diagonal

$$\mathbf{L}(s)=\begin{pmatrix} l_1(s) & 0 & 0 \\ 0 & l_2(s) & 0 \\ 0 & 0 & l_3(s) \end{pmatrix} \tag{8}$$

the following expression for the ideal controller by decoupling is obtained

$$\mathbf{K}(s)=\mathbf{G}(s)^{-1}\cdot\mathbf{L}(s)=$$
$$\frac{1}{|\mathbf{G}|}\begin{pmatrix} G^{11}l_1 & G^{21}l_2 & G^{31}l_3 \\ G^{12}l_1 & G^{22}l_2 & G^{32}l_3 \\ G^{13}l_1 & G^{23}l_2 & G^{33}l_3 \end{pmatrix}=\begin{pmatrix} \tilde{g}_{11}^{-1}l_1 & \tilde{g}_{21}^{-1}l_2 & \tilde{g}_{31}^{-1}l_3 \\ \tilde{g}_{12}^{-1}l_1 & \tilde{g}_{22}^{-1}l_2 & \tilde{g}_{32}^{-1}l_3 \\ \tilde{g}_{13}^{-1}l_1 & \tilde{g}_{23}^{-1}l_2 & \tilde{g}_{33}^{-1}l_3 \end{pmatrix} \tag{9}$$

where the complex variable s has been omitted, where G^{ij} is the cofactor corresponding to $g_{ij}(s)$ in G(s), and where the nine transfer functions $\tilde{g}_{ij}(s)=\frac{|\mathbf{G}(s)|}{G^{ij}(s)}$ are the equivalent processes for the nine decoupled SISO loops [7] controlled by $k_{ji}(s)$ respectively.

It can be seen in (9) that each column of K(s) are related to the same diagonal element of L(s). Therefore, specifying the three $l_i(s)$ transfer functions is enough to determine the nine elements $k_{ij}(s)$ of the controller from expression (9).

A. How to specify the $l_i(s)$

The design problem in (9) will have solution if the specifications of $l_i(s)$ are well proposed, in other words, if they take into account the dynamic of the three corresponding equivalent processes, the achievable performance specifications of the corresponding SISO closed loop system, and, not less important, that the controllers must be realizable. Since the closed loop must be stable and without steady-state errors due to set point or load changes, the open loop transfer function $l_i(s)$ must contain an integrator. Then, the following general expression for $l_i(s)$ is proposed [9]:

$$l_i(s)=k_i\cdot\bar{l}_i(s)\frac{1}{s} \tag{10}$$

Parameter k_i becomes a tuning parameter in order to met design specifications and $\bar{l}_i(s)$ must be a rational transfer function taking into account the common not cancelable dynamic of the corresponding equivalent processes. Typical not cancelable dynamics are the non-minimum phase zeros and unstable poles.

In the 3x3 system under review (4), $\bar{l}_i(s)=1$ is chosen for $l_1(s)$ and $l_2(s)$, since their corresponding equivalent processes do not have common non-minimum phase zeros and unstable poles. In this case, the closed loop transfer function has the typical shape of a first order system

$$h_i(s)=\frac{\frac{k_i}{s}}{1+\frac{k_i}{s}}=\frac{1}{T_i s+1} \tag{11}$$

with time constant $T_i=1/k_i$. Then, in order to determine k_i it is enough to specify the time constant of the closed loop system. $T_1=25$ and $T_2=12.5$ are selected, so $k_1=0.04$ and $k_2=0.08$.

On the other hand, $\bar{l}_3(s)=\frac{s+z_i}{s}$ is chosen for $l_3(s)$ because the corresponding equivalent processes have a pole in s=0. Now, the closed loop transfer function is given by the following expression, a second order system with a zero in $s=-z_i$.

$$h_i(s)=\frac{k_i\frac{s+z_i}{s^2}}{1+\frac{s+z_i}{s^2}}=\frac{k_i\left(s+z_i\right)}{s^2+k_i s+k_i z_i} \tag{12}$$

Its poles are characterized by the undamped natural frequency and the damping factor

$$\omega_n=\sqrt{k_i z_i} \quad ; \quad \delta=\sqrt{\frac{k_i}{4z_i}} \tag{13}$$

Particularly, it is sufficient to select $k_i=4z_i$ in order to achieve poles with critical damping ($\delta=1$) and $\omega_n=2z_i$. In the controller design $z_3=0.01$ and $k_3=0.04$ are tuned, so it is obtained a system with critical damping and $\omega_n=0.02$ in the third loop.

These adjustable parameters k_i have been chosen in order to have the similar settling time of the system output responses with other authors' methods, and to have into account the actuator constraints of the system. Increasing tuning parameter k_i in the controller matrix, the corresponding *i*th system output response becomes faster, but the output energy of the *i*th column controllers of K(s) and their corresponding actuators grows larger, tending to exceed their output capacities in practice. So, tuning parameters k_i is a trade-off between the achievable system response performance and the actuator constraints.

Consequently, after selecting the three transfer functions $l_i(s)$, the diagonal equivalent open loop process L(s) is the following

$$\mathbf{L}(s)=\begin{pmatrix} \dfrac{0.04}{s} & 0 & 0 \\ 0 & \dfrac{0.08}{s} & 0 \\ 0 & 0 & \dfrac{0.0004(100s+1)}{s^2} \end{pmatrix} \tag{14}$$

Then, the nine elements $k_{ij}(s)$ of the multivariable centralized controller by decoupling K(s) are obtained by replacing (4) and (14) in (9). Nevertheless, the resulting elements do not have PID structure. In order to get a centralized PID control by decoupling, model reduction techniques based on the frequency response are used, just as it is described in the next subsection.

B. Using PID structure

If it is intended that controllers become PID controller with filtered derivative, it is necessary to force the following structure in all controller elements

$$k_{ji}(s)=k_i K_{Pji}\left(1+\frac{1}{T_{Iji}s}+\frac{T_{Dji}s}{\alpha_{ji}T_{Dji}s+1}\right) \tag{15}$$

where it appears the controller with its four parameters: proportional gain (K_{Pji}), integral time constant (T_{Iji}), derivative time constant (T_{Dji}) and derivative time noise filter constant (α_{ji}). Also note that the same tuning parameter k_i appears in k_{1i}, k_{2i} and k_{3i}. For PI structure derivative time constant is forced to zero.

After applying this reduction to K(s), a matrix $K_{PI}(s)$ with eight PI controllers (16) was selected for the control of the boiler-turbine unit. PID structure has also been tested in some elements but it shows a worse performance with the nonlinear model. The reduction is carried out in the frequencies from 10^{-4} to 0.5 rad/s.

$$K_{PI}(s)=\begin{pmatrix} 0.041+\dfrac{0.041}{1176.2s} & -0.0061+\dfrac{0.0061}{19.9s} & 0.822+\dfrac{0.822}{95.7s} \\ -5.817{\cdot}10^{-7}-\dfrac{5.817{\cdot}10^{-7}}{0.003s} & 0.0056+\dfrac{0.0056}{10s} & 0 \\ -0.021-\dfrac{0.021}{5525.8s} & -0.0424+\dfrac{0.0424}{88.2s} & 4.9331+\dfrac{4.9331}{95.8s} \end{pmatrix} \tag{16}$$

The singular value plots of the ideal controller by decoupling and the reduced $K_{PI}(s)$ controller are shown in Fig. 2. It can be shown that they are close at the low frequencies but different at the high frequencies. So the reduced controller will have similar performance as the ideal controller at low frequencies.

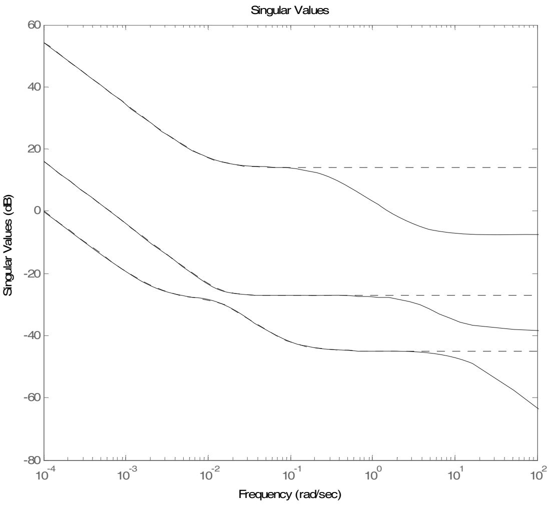

Fig. 2. Singular value plots of the ideal controller (solid line) and the reduced K_{PI} controller (dotted line)

C. Conditioning anti wind-up strategy

The boiler-turbine unit is subject to hard constraints in control input signals (3), therefore the controller needs to be equipped with some protection mechanism against the wind-up effect. Otherwise its performance could deteriorate when the input signal constraints are exceeded.

In this paper it is used a multivariable anti wind-up technique that is described in [14] and called "conditioning". To use this strategy the controller elements have to be biproper, that is, the number of poles equals the number of zeros. In the case of PID structure given by (15) this condition is fulfilled.

The conditioning anti wind-up scheme is shown in Fig. 3, where K_∞ is the high frequency gain matrix and $\bar{K}(s)$ is the transfer matrix that fulfils the following equation

$$K(s)=K_\infty+\bar{K}(s) \tag{17}$$

In addition, the "Constraints" block must incorporate a model of the control signal constraints.

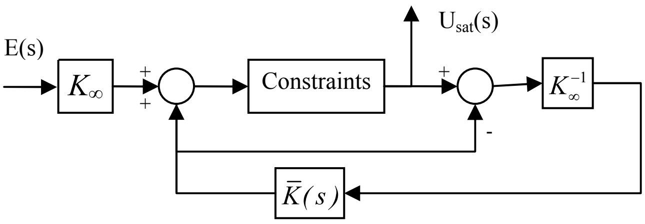

Fig. 3. Conditioning anti wind-up scheme

For the designed controller $K_{PI}(s)$, K_∞ and $\bar{K}(s)$ matrices can be easily identified from (16) where each element is expressed as the sum of a gain ($K_{\infty ij}$) and a rational transfer function $\bar{K}_{ij}(s)$. K_∞ is nonsingular, which it is necessary to the control implementation. So, in order to implement the control depicted in Fig. 3, we need the 3x3 gain matrix K_∞ and its inverse, the 3x3 integrator matrix $\bar{K}(s)$ and the actuator constraint model (3).

IV. Simulation Results

In this section, we analyze the performance of the developed controller for the nonlinear boiler-turbine unit described in section II through simulation and comparison with other authors. Specifically, we compare the proposed controller with a robust controller of Tan in [3], and with a decentralized multivariable nonlinear controller (MNC) in [6]. Although the controller of Tan was designed via loop-shaping H_∞ approach, then it was reduced to four PI elements. The proposed NMC in [6] is based on state space representation of the nonlinear system (1). After defining the desired closed loop equation for each output, controller parameters are obtained in order to compensate interactions as disturbances.

To test the performance of the proposed controller, designed in section III, three simulations are given. In the first one we show the superiority of the proposed controller over the Tan's controller with regard to decoupling when the boiler-turbine model (1) is used without input constraints. In the other simulations we compare the proposed controller with MNC and Tan's control using the nonlinear dynamic model (1) with the input constraints (3) and conditioning anti wind-up strategy for the proposed and Tan's controller. In the second simulation we change from the nominal point to another operating point that is close. In the third one, a large operating point change is simulated.

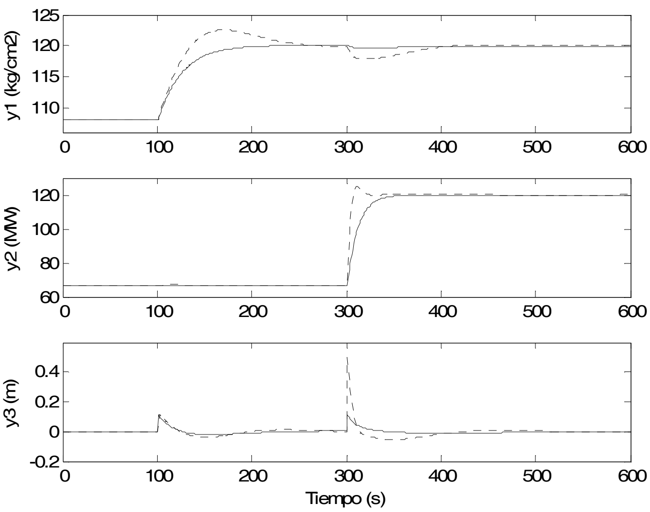

Fig. 4. System output responses for two set point changes from nominal operating point (Proposed control: solid line; Tan: dotted line)

In the first simulation, at t=100 s, drum pressure y_1 is increased from 108 to 120 kg/cm^2, at t=300 s, power output y_2 is increased from 66.65 to 120 MW, and drum level y_3 is kept at 0 m. In Fig. 4 the system output responses for the proposed and Tan's controllers are shown. The proposed control achieves a better decoupling than the Tan's controller. In addition, it has a smoother response and without overshoot in y_1 and y_2, and a lower deviation in y_3.

In the second simulation we use the nonlinear model of the boiler-turbine with actuator constraints and we carry out the same two set point changes of the first simulation, but both changes occur at the same time t=100 s. In Fig. 5 and Fig. 6 the system responses for the proposed and the two previous controllers are shown.

Figure 5 shows the time response of outputs. The responses of the three different controllers are similar; however, the proposed control achieves a smoother response and without overshoot in y_1, and a lower deviation in y_3. Also, control signals of this controller (Fig. 6) are less aggressive than control signals of the other controllers.

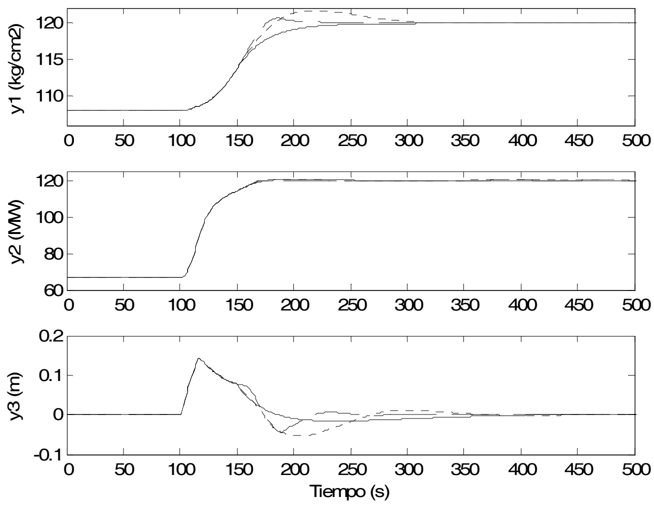

Fig. 5. Output signals of the system for a change from nominal operating point to a "near" operating point (Proposed control: solid line; Tan: dotted line; MNC: dashed line)

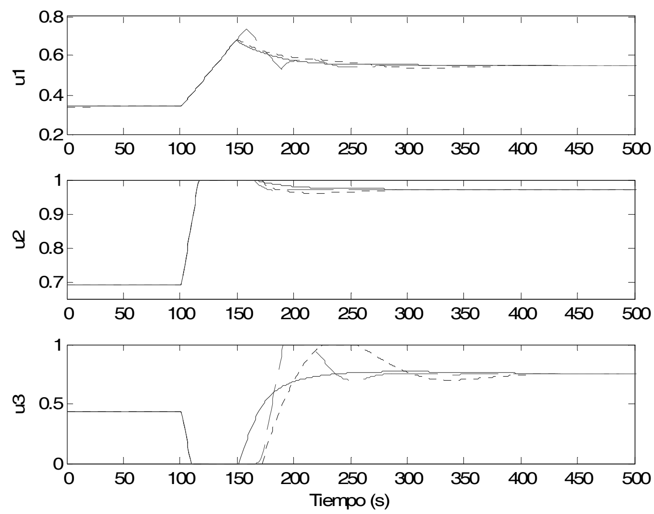

Fig. 6. Input signals of the system for a change from nominal operating point to a "near" operating point (Proposed control: solid line; Tan: dotted line; MNC: dashed line)

To show that the proposed linear controller can operate well in a wide operating range, we consider a large operating point change at t=100 s in the last simulation. Drum pressure increases from 75.6 to 140 kg/cm^2, power output from 15.3 to 128 MW, and drum level from -0.97 to 0.98 m.

The system responses for the designed controller are shown in Fig. 7 and Fig. 8 in comparison with the other two controls. The three controllers have a very similar performance, but the proposed control achieves a bit lower settling time in outputs y_1. In addition, its control signals are the smoothest.

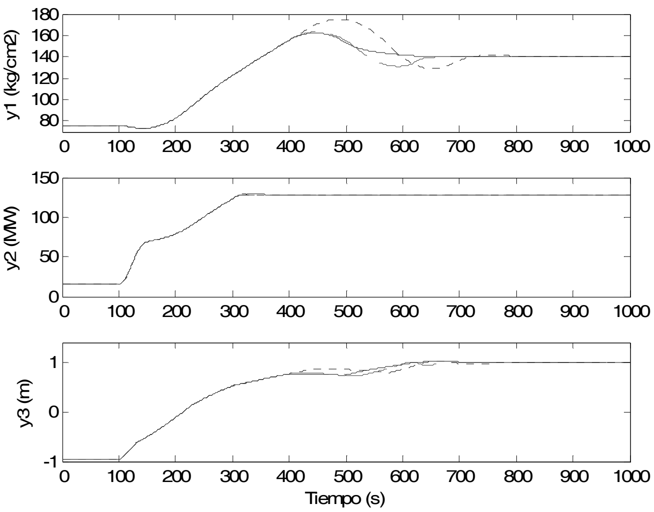

Fig. 7. Output signals of the system for a large operating point change (Proposed control: solid line; Tan: dotted line; MNC: dashed line)

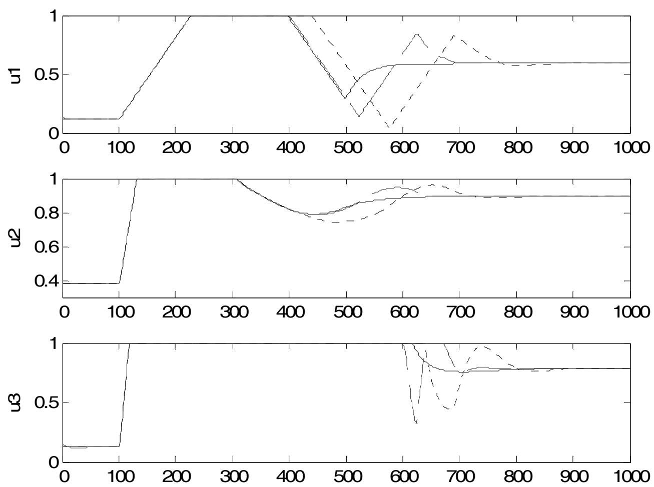

Fig. 8. Input signals of the system for a large operating point change (Proposed control: solid line; Tan: dotted line; MNC: dashed line)

Also LQR and GA/LQR controllers in [5] have been simulated and contrasted with the proposed controller; however they are not illustrated in this work because their responses were worse than the responses of other two controls that have been chosen for comparison here.

V. CONCLUSION

In this paper, we describe the application of a new design methodology of multivariable PID controls to a boiler-turbine unit. The design procedure consists of three steps: first, an ideal decoupler including integral action is determined. Second, the decoupler is approximated with PID controllers. Third, three proportional gains are tuned to achieve specifications. Due to the hard inputs constraints of the plant, the multivariable controller is implemented with an anti wind-up compensation.

Simulation results show that the controller introduced in this paper is well done for the nonlinear boiler-turbine system. Interactions are reduced, zero tracking error is achieved and it can operate well in a wide operating range. The results have been contrasted with other controllers in literature and the proposed control shows a similar or better performance.

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