Preprints of the
9th International Symposium on Advanced Control of Chemical Processes
The International Federation of Automatic Control
June 7-10, 2015, Whistler, British Columbia, Canada

Design and Implementation of a Multiple-Model based Control scheme for Boiler-Turbine Unit

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Abstract: In this work, the authors have proposed a multiple-linear model based control scheme for the boiler-turbine unit. The proposed control scheme makes use of local linear state space models determined at different load conditions, by linearizing the nonlinear boiler-turbine model reported by Bell and Astrom, 1987. Each local linear state space model is stabilized via state feedback approach and is used to design a multiple-linear model based controller for the boiler-turbine unit. Genetic Algorithm is employed to optimally tune the parameters of each local linear controller. The global controller output is determined as a linear combination of all local controller outputs. The extensive simulation studies show that the proposed control scheme effectively handles the input constraints of the boiler-turbine unit and meets the required electrical demand.

Keywords: Model-based controller, Boiler-turbine system, Genetic Algorithm, Adaptive control.

1. INTRODUCTION

A boiler-turbine system is an energy conversion device where a single boiler is used to generate steam that is directly fed to a single turbine. It transforms the chemical energy of fuel into mechanical energy and then to electrical energy. The principal objective in the control of the boiler-turbine system is to regulate the electric power output to meet the load demand arising from the power grid, while maintaining the output variables (drum pressure and drum level) within desired bounds. Moreover, the controller outputs should satisfy the magnitude and rate constraints imposed on the control valves manipulating the fuel flow, steam flow and feed water flow respectively. In addition, to meet the load demand for electric power, the power plant should be able to operate in multiple operating regimes (Arasu *et al*., 2013).

The boiler-turbine model developed by Bell and Astrom (1987) has been widely analysed in the literature using various control schemes: genetic algorithm based control (Dimeo and Lee, 1995), dynamic matrix control (Moon and Lee, 2009), moving horizon control (Lu *et al*., 2010), explicit model predictive control (Keshavarz *et al*., 2010), adaptive dynamic matrix control (Moon and Lee, 2011), genetic algorithm based nonlinear predictive switching control (Wu *et al*., 2012), fuzzy based model predictive control (Li *et al*., 2012, Liu and Kong, 2013), stable model predictive tracking controller based on a piecewise linear model (Wu *et al*., 2012).

In this work a multiple-linear model based controller has been designed and implemented for the highly nonlinear and tightly coupled Boiler-turbine unit exhibiting non-minimum phase behaviour and instability (because of the integrating type behaviour of drum-level dynamics). The efficacy of the proposed control scheme is demonstrated by conducting simulation studies on the simulated model of boiler-turbine unit.

The organization of the paper is as follows: Section 2 discusses the design of a model based controller in reset configuration for a nonlinear system exhibiting integrating type behaviour. The multiple model based control scheme for the boiler-turbine unit is reported in section 3. Simulation results for the nonlinear control of the boiler-turbine unit are presented in section 4, followed by concluding remarks in section 5.

2. DESIGN OF MULTIPLE-LINEAR MODEL BASED CONTROLLER

Pathiran and Prakash, (2014) had proposed a model based controller realized in reset configuration for a stable SISO system. The steps involved in designing the model-based control scheme are as follows:

- Separate the process model into gain and dynamic parts.
- Use the dynamic part of the process model in the positive feedback loop of the proposed control scheme, realized in the reset configuration that is shown in figure 1. This ensures offset-free closed loop response without additional tuning parameter.
- Determine the controller gain K_C to satisfy either a desired performance or robustness specification.

The main advantage of this control scheme is that, it does not require model order reduction, factorization of model into invertible and non-invertible parts, explicit inversion of the process model. Also it has a single tuning parameter K_C, which can be tuned by conventional design procedures namely root locus method and Nyquist plot method, to satisfy either desired performance or robustness specification.

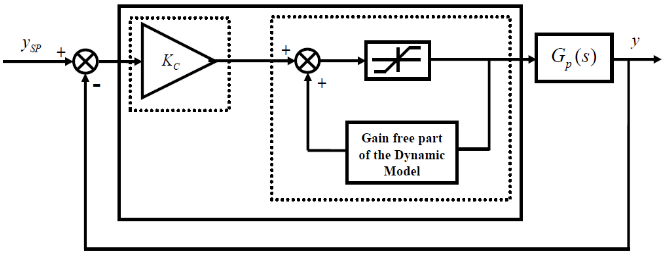

Fig. 1. Model-based PI-like control scheme.

The proposed work extends the design of model based PI like control scheme for a non-linear MIMO system exhibiting integrating type behaviour at all operating points. A control scheme with n-local linear model based controllers is designed. The global controller output is a fusion of all local controller outputs. The schematic of the proposed control scheme is shown in figure 3.

Consider a non-linear square system represented as follows:

$$\left.\begin{aligned} \dot{x} &= F[x,u] \\ y &= H[x,u] \end{aligned}\right\} \tag{1}$$

where, x, u and y represent the states, inputs and outputs respectively. Let us assume that the entire operating region can be divided into "n" linear regions around the steady state points ($x_{s,i}, u_{s,i}$). Then the above system can be represented as:

$$\left.\begin{aligned} \dot{\tilde{x}}_i &= A_i\tilde{x}_i + B_i\tilde{u}_i \\ \tilde{y}_i &= C_i\tilde{x}_i + D_i\tilde{u}_i \end{aligned}\right\}, \quad i \in \{1,2,...,n\} \tag{2}$$

where, A_i, B_i, C_i and D_i represent the Jacobian corresponding to the region ($x_{s,i}, u_{s,i}$) and $\tilde{x}$, $\tilde{u}$, $\tilde{y}$ represent the deviation variables (Bhagwat *et al*., 2003).

The steps involved in the design of a multiple-linear model based controller for the non-linear integrating systems represented in the form of (2) are as follows:

- For each operating point, the system is stabilized using a state feedback approach.
- Determine the gain of the stabilized model (K_m) for the multi-variable system at each operating point.
- The proposed controller for integrating type MIMO system can be realized as shown in figure 3, which is an extension of the model based controller proposed by Pathiran and Prakash (2014) for stable SISO system.
- Determine controller gain (K_C) to satisfy either desired performance or robustness specification using appropriate optimization technique.
- The global controller output is the weighted sum of all local controller outputs.

2.1 Stabilization of a non-linear system with integrating behaviour.

Consider a state space model of the system at i^{th} operating point:

$$\dot{\tilde{x}}_i = A_i\tilde{x}_i + B_i\tilde{u}_i \tag{3}$$

where,

$$\left.\begin{aligned} \tilde{x}_i &= x_i - \overline{x}_i \\ \tilde{u}_i &= u_i - \overline{u}_i \end{aligned}\right\} \tag{4}$$

If any of the Eigenvalues of the state matrix (A_i) is zero, it denotes that the system has a pole at the origin, leading to integrating type behaviour. The pole could be shifted to a desired location using a state feedback matrix, $\mathrm{K_i}$ as shown in figure 2.

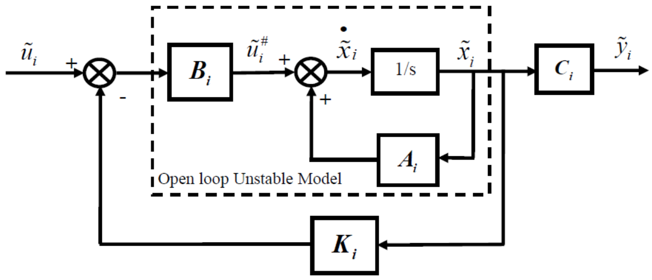

Fig. 2. Stabilization of i^{th} model using state feedback method.

Then the input to the system is:

$$\tilde{u}_i^{\#} = -K_i * \tilde{x}_i + B_i\tilde{u}_i \tag{5}$$

The state equation for the closed loop stable system becomes

$$\dot{\tilde{x}}_i = A_i^*\tilde{x}_i + B_i\tilde{u}_i \tag{6}$$

where,

$$A_i^* = A_i - B_iK_i \tag{7}$$

2.2 Model based controller for a stabilized nonlinear MIMO system.

Consider a stabilized state space model at i^{th} operating point:

$$\dot{\tilde{x}}_{m,i} = A_i^*\tilde{x}_{m,i} + B_i\tilde{u}_i \tag{8}$$

The gain of the model represented in (8) is given by

$$K_{m,i} = -B_i(A_i^*)^{-1} \tag{9}$$

The state variables, $\tilde{x}_{m,i}(t)$ of the system can be computed by solving the model described in (8). The controller output u_i is obtained from u_i^* satisfying the constraints given in (10) and (11).

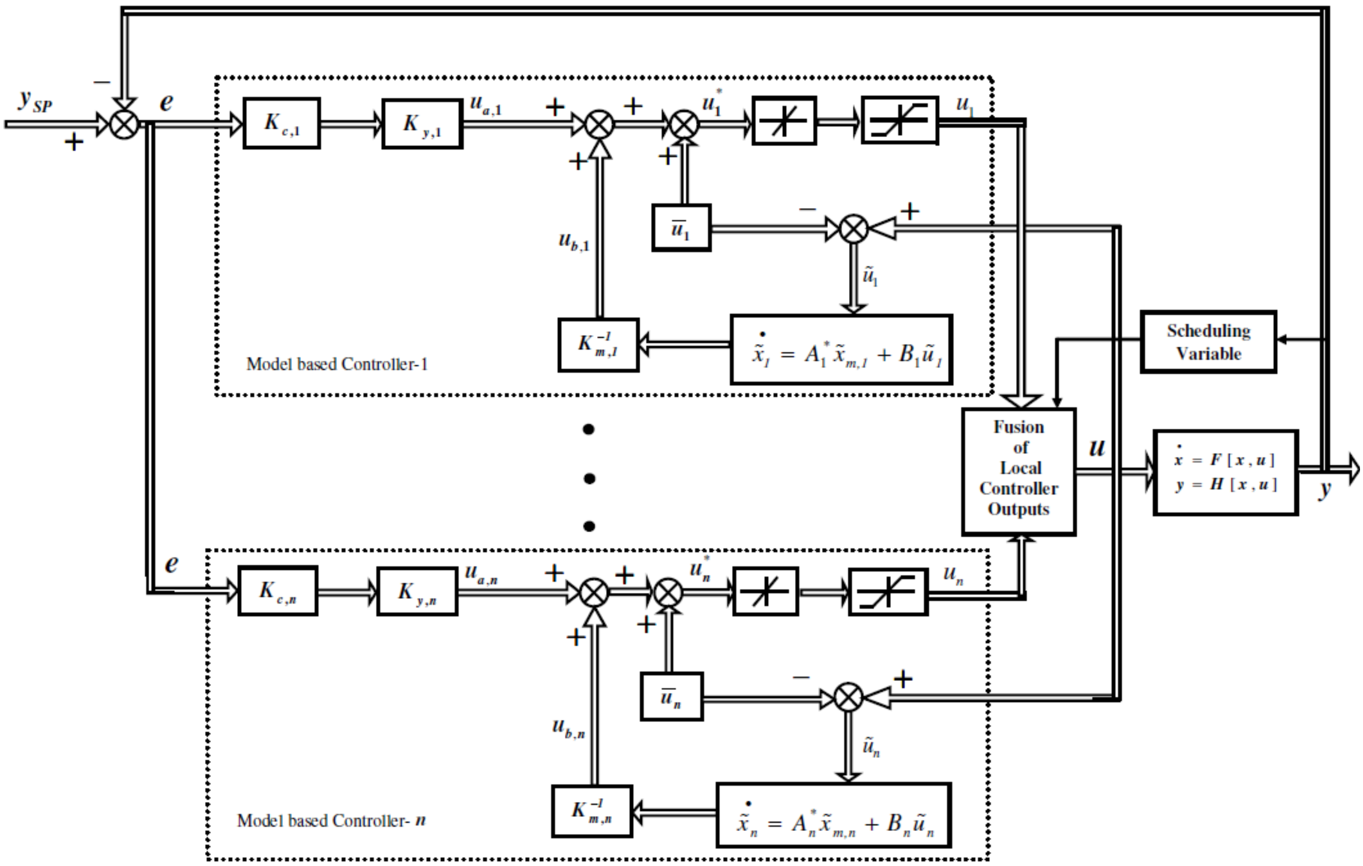

Fig. 3. Proposed Multiple Model based Control scheme for integrating type MIMO system

$$u^L \le u_i^* \le u^U \tag{10}$$

$$\Delta u^L \le \Delta u_i^* \le \Delta u^U \tag{11}$$

where,

$$u_i^*(t) = u_{a,i}(t) + u_{b,i}(t) + \bar{u}_i \tag{12}$$

$$u_{a,i}(t) = K_{C,i} * \left\{ K_{y,i} * [y_{SP}(t) - y(t)] \right\} \tag{13}$$

$$K_{y,i} = [C_i * (-A_i^*)^{-1} * B_i + D_i]^{-1} \tag{14}$$

$$K_{C,i} = \begin{pmatrix} K_{C1,i} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & K_{Cq,i} \end{pmatrix} \tag{15}$$

$$u_{b,i}(t) = K_{m,i}^{-1} * \tilde{x}_{m,i}(t) \tag{16}$$

Determination of the controller gain ($K_{C,i}$), can be formulated as an optimization problem by minimizing the objective function given in (17).

$$J = \min_{K_{C,i}} \sum_{q=1}^{p} w_q * E_q \tag{17}$$

where, p is the total number of output variables, w_q weight corresponding to the q^{th} variable and E_q can be any suitable performance criteria such as ISE, IAE, ITAE.

The global controller output is calculated as

$$u = \sum_{i=1}^{n} v_i * u_i \tag{18}$$

where, u_i is the output of the i^{th} local controller; v_i is the weight corresponding to the i^{th} local controller. The weights are determined as a function of the scheduling variable.

3. MULTIPLE-MODEL BASED CONTROL OF BOILER-TURBINE UNIT

The model for the boiler-turbine unit used in this work was developed by Bell and Astrom (1987). The governing equations of the system are as follows:

$$\dot{x}_1 = -0.0018 u_2 x_1^{9/8} + 0.9 u_1 - 0.15 u_3 \tag{19}$$

$$\dot{x}_2 = (0.073 u_2 - 0.016) x_1^{9/8} - 0.1 x_2 \tag{20}$$

$$\dot{x}_3 = [141 u_3 - (1.1 u_2 - 0.19) x_1] / 85 \tag{21}$$

$$y_1 = x_1 \tag{22}$$

$$y_2 = x_2 \tag{23}$$

$$y_3 = 0.05(0.13073x_3 + 100\alpha_{cs} + \frac{q_e}{9} - 67.975) \tag{24}$$

where state variables x_1, x_2 and x_3 denote drum pressure (kg/cm^2), electric output (MW) and fluid density (kg/m^3), respectively. The manipulated inputs u_1, u_2 and u_3 are normalized control valve positions that control the mass flow rates of fuel, steam to the turbine and feed water to drum respectively. The output y_3 denotes the drum water level deviation (m). α_{cs} and q_e are the steam quality (mass ratio) and the evaporation rate (kg/s), respectively, and are given by

$$\alpha_{cs} = \frac{(1-0.001538x_3)(0.8x_1 - 25.6)}{x_3(1.0394 - 0.0012304x_1)} \tag{25}$$

$$q_e = (0.854u_2 - 0.147)x_1 + 45.59u_1 - 2.514u_3 - 2.096 \tag{26}$$

The manipulated inputs are subject to the following magnitude and rate constraints:

$$0 \le u_q \le 1 \qquad (q = 1,2,3) \tag{27}$$

$$-0.007 \le \dot{u}_1 \le 0.007 \tag{28}$$

$$-2 \le \dot{u}_2 \le 0.02 \tag{29}$$

$$-0.05 \le \dot{u}_3 \le 0.05 \tag{30}$$

The nominal operating points for the boiler-turbine system are reported in Table 1. For any given electrical load demand x_2^0, the nominal values of the corresponding states x_1, x_3 and the manipulated inputs u_1, u_2, u_3 and drum level y_3 are determined accordingly.

Table 1: Nominal operating points

n	#1	#2	#3	#4	#5	#6	#7
$\mathbf{x_2^0}$	**15.27**	**36.65**	**50.52**	**66.65**	**85.06**	**105.8**	**128.9**
x_1^0	75.60	86.40	97.20	108.0	118.8	129.6	140.4
x_3^0	299.6	342.4	385.2	428.0	470.8	513.6	556.4
u_1^0	0.156	0.209	0.271	0.34	0.418	0.505	0.6
u_2^0	0.483	0.552	0.621	0.69	0.759	0.828	0.897
u_3^0	0.183	0.256	0.340	0.433	0.543	0.663	0.793
y_3^0	-0.97	-0.65	-0.32	0.0	0.32	0.64	0.98

Consider the nominal operating point #4. The linearized model is:

$$\left.\begin{aligned} \dot{\tilde{x}} &= A_4\tilde{x} + B_4\tilde{u} \\ \tilde{y} &= C_4\tilde{x} + D_4\tilde{u} \end{aligned}\right\} \tag{31}$$

with

$$\begin{aligned} A_4 &= \begin{pmatrix} -0.0025 & 0 & 0 \\ 0.0694 & -0.1 & 0 \\ -0.0067 & 0 & 0 \end{pmatrix}, \\ B_4 &= \begin{pmatrix} 0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.3976 & 1.6588 \end{pmatrix}, \\ C_4 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0.0063 & 0 & 0.0047 \end{pmatrix}, \\ D_4 &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.2533 & 0.5119 & -0.0140 \end{pmatrix}. \end{aligned} \tag{32}$$

The Eigenvalues of the system matrix, A_4 are [0 -0.1 -0.0025]. Clearly it indicates the presence of a pole at the origin denoting the integrating type behaviour of the system, and it is observed at all operating points. Hence a new set of poles are defined for the closed loop system with state matrix, A_4^* with Eigenvalues [-0.0025 -0.3 -0.0075]. The state feedback matrix, K_4 is calculated based on pole assignment method proposed by Kautsky *et al.*, (1985), ensuring the robustness of the closed loop system.

$$K_4 = \begin{pmatrix} 0.0019 & 0.0075 & 0.0008 \\ 0.0049 & 0.0141 & 0 \\ 0.0001 & 0.0119 & 0.0045 \end{pmatrix}. \tag{33}$$

Thus a nonlinear system exhibiting integrating behaviour have been linearized and then stabilized. Utilizing this stable linear model a linear controller for the 4^{th} operating point is designed. Similarly seven controllers are designed, each based upon the linear model stabilized around each operating point. A multiple-model based control scheme with the developed linear model based controllers is implemented as shown in figure 3. As the drum pressure (y_1), is the slowly varying variable, it has been chosen as the scheduling variable. A linear interpolating function based on the scheduling variable is used to determine the weights of each controller. The manipulated variables are determined by weighted sum of the local controller outputs.

Due to the multi-dimensional nature of the problem, genetic algorithm (GA) has been chosen to optimally determine the controller gains. In this work, an algorithm reported by Goldberg, (1989) is used. The population size is fixed to 20 and the maximum generation is set to 30. Appropriate lower and upper bound values are defined for each parameter. The performance measure chosen to be minimized is ITAE, which is calculated using (34).

$$E_q = \int_{t=0}^{t_s} t * \left| sp_q(t) - y_q(t) \right| dt \qquad q = 1,2,3 \tag{34}$$

4. SIMULATION STUDIES

The proposed model based control scheme has been implemented on the simulated non-linear model of boiler-turbine unit assuming all the state variables are available for measurement. However a suitable observer (Prakash *et al.*, 2014, Bavdekar *et al.*, 2014), can be used to predict the immeasurable state.

Case 1: The system is maintained at a nominal operating point (#4) and a ramp change is introduced in the setpoints for drum pressure from 108 to 120 and electric power from 66.65 to 120 at t=100s, while the drum level is maintained constant at 0. The proposed control scheme is able to maintain the drum pressure and electric output at their desired reference values, while regulating the drum level (See Figure 4).The dashed red line denotes the reference signal and the blue line indicates the process variable. Figure 5 shows the outputs of the proposed model based control scheme in brown colour (i.e., the manipulated variables) and it can be seen that the input constraints (green colour) are never violated.

Case 2: To demonstrate the efficacy of the proposed controller on severe tracking problem, the system is made to transit from operating point #1 to #7. In order to do this, setpoint variations in the drum pressure (from 75.6 to 140.4), electrical power (from 15.27 to 128) and drum level (from -0.97 to 0.98) have been introduced, and the system responses are shown in figure 6. Figure 7 shows the evolution of controller outputs.

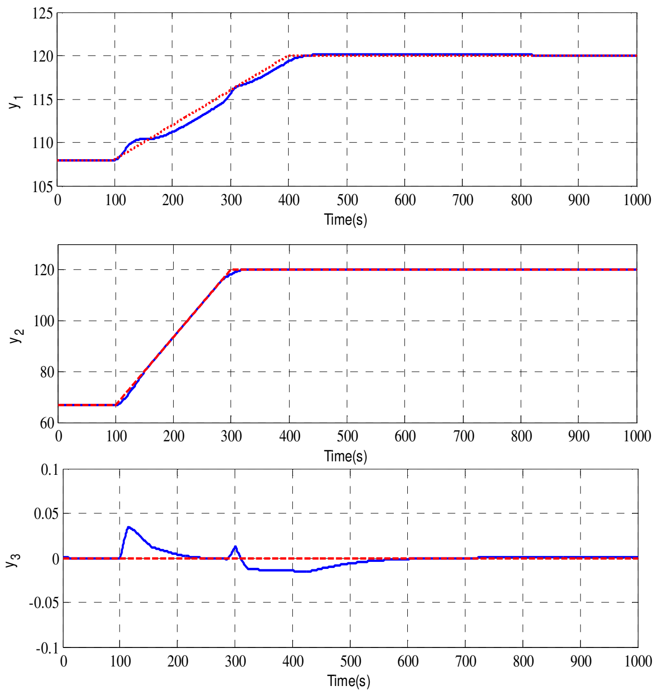

Fig. 4. Closed loop responses of the boiler-turbine unit with proposed control scheme for Case 1

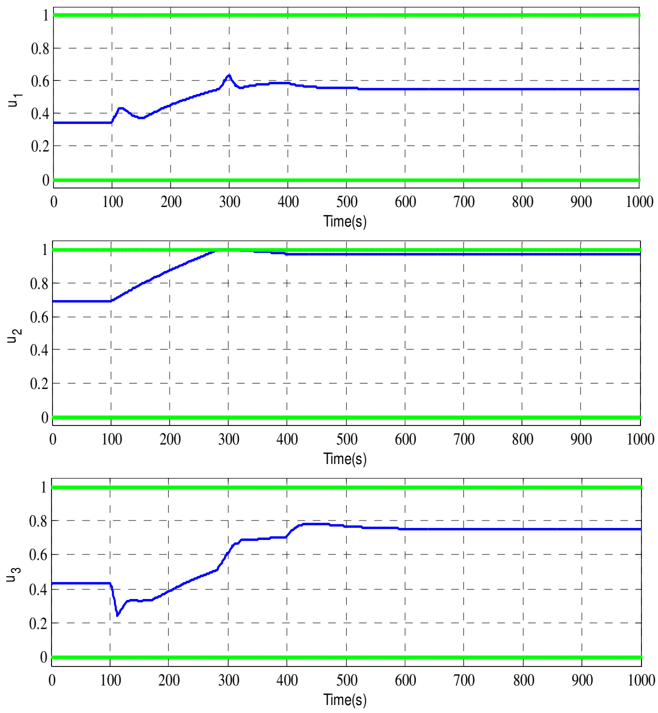

Fig. 5. Evolution of controller outputs (Case 1)

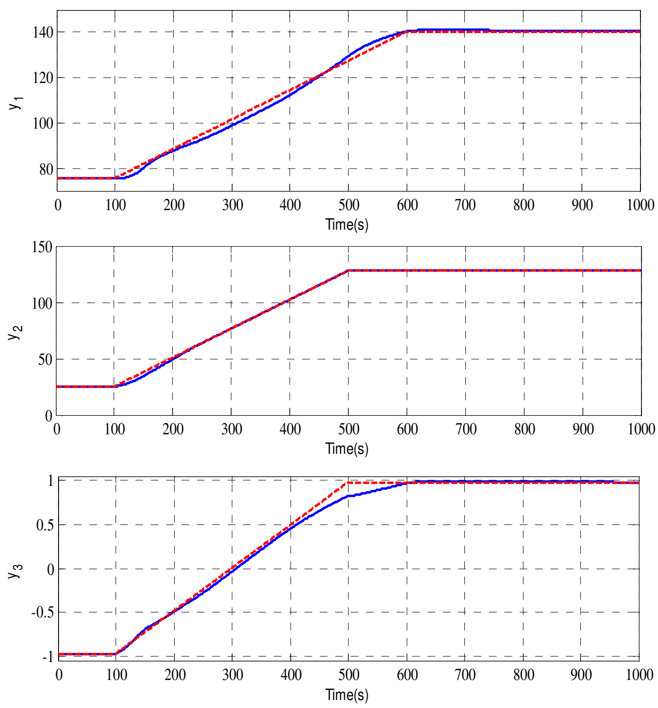

Fig. 6. Servo response of the boiler-turbine unit with proposed control scheme (Case 2)

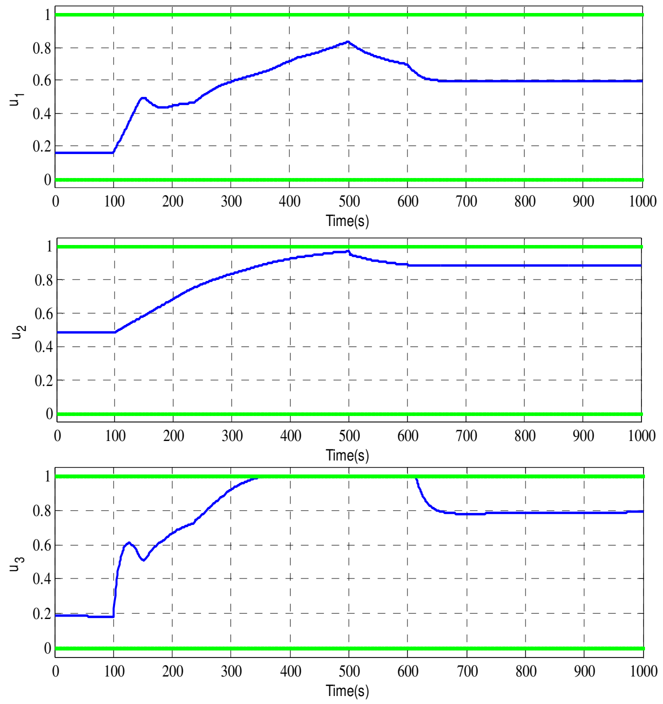

Fig. 7. Evolution of controller outputs (Case 2)

5. CONCLUSIONS

A multiple model based control scheme have been designed and implemented on the simulated model of the nonlinear boiler-turbine unit exhibiting non-minimum phase behaviour due to shrink/swell and instability because of integrating type behaviour of drum-level dynamics. From the extensive simulation studies it can be inferred that the highly nonlinear and tightly coupled boiler-turbine unit can be maintained satisfactorily at all operating points without violating input constraints using the proposed control scheme.

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