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Model-based Robust Adaptive Control for Power-generating Systems in the Presence of Long Time Delay

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Abstract: This paper proposes a model-based robust adaptive control (MB-RAC) which is derived from the L_1 robust adaptive control (L_1-RAC). By inheriting excellent control performance from the L_1-RAC for systems with nonlinearity and uncertain conditions, the MB-RAC offers its own feature for dealing with a long time delay by using dual-feedback adaptive law from the built-in model and the plant. A nonlinear boiler-turbine-generator unit augmented with time delays is adopted as the plant for verifying the MB-RAC. Simulation results present good control performances of the MB-RAC in a wide-range load-following process with long time delays and show its strong robustness to inner model mismatches from the plant on both dynamics and time delays. The MB-RAC is shown to be reliable and easy to implement for industrial processes.

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Keywords: robust adaptive control, time delay, uncertainty, boiler-turbine system, nonlinearity, disturbance, load following.

1. INTRODUCTION

Nowadays, boiler-turbine power-generating systems are facing more and more challenges in operations, such as fast load-following demands, wide-range nonlinear operations, unmeasured disturbances (e.g., heat rate influenced by flue emission control), unknown time-varying uncertainties related to frequent fuel quality variation, and the last but not the least, frequency and voltage disturbances when it is connected to grid involving much uncertain power supply from renewable energy resources (Pan et al., 2015). In dealing with these issues, the controllers for boiler-turbine power systems should achieve fast, adaptive, robust and stable control performance.

Improving load-following capability of boiler-turbine-generator systems in the presence of wide and rapid load changes has been a hotspot and drawn much attention in recent years. Many different kinds of advanced control methods have been studied for the issue, such as robust and optimal control (Park and Lee, 1996), gain-scheduling control (Zhang et al., 2005), multivariable model predictive control (Keshavarz et al., 2010), genuine nonlinear control (Yang et al., 2012), intelligent control (Li et al., 2012), and L_1 robust adaptive control (Pan et al., 2015), and have achieved much more improved control performance than conventional approaches in wide-range load-following processes.

Among above control methods, L_1 robust adaptive control (L_1 -RAC) is a class of new adaptive control approach. It provides some distinctive and attractive features, including fast and robust adaptation, ensuring closed-loop stability and permitting transient analysis for both control signals and system responses (Hovakimyan and Cao, 2010; Luo and Cao, 2014). In our previous study (Pan et al., 2015), the L_1 robust adaptive controller is designed as the coordinated controller of a boiler-turbine unit for rapid load demand tracking in the presence of nonlinearities, internal un-modelled dynamics, time-varying unknown disturbances and parameters, and small time delay. The closed-loop stability of the boiler-turbine control system has been verified under unknown uncertainties, along with fast-varying load demand in a wider range, showing strong robustness, fast response and large stability margins.

Although the L_1-RAC has been verified superior to many other control methods in handling nonlinearities and uncertainties, it is greatly inferior to model predictive control in dealing with time delays. As presented in the paper (Pan et al., 2015), the L_1-RAC can tolerate some extent of uncertain dead time within its time-delay margin, usually several seconds, but even a larger time-delay margin cannot satisfy long time delays like 30~100 seconds, which often exist in many boiler-turbine power-generating systems, or like much longer ones in other industrial chemical loops. The limited time-delay margin is a crucial obstacle to hinder L_1-RAC from being applied in many industrial processes. Unlike model predictive control, the L_1-RAC doesn't require model of controlled plant to design its parameters, namely it is not model-based control approach. This principle leads to its poor ability to predict future behaviour of the plant as well as time

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delay. What if we incorporate a model into the L_1-RAC? To answer this question, we study a model-based robust adaptive controller (MB-RAC) which is derived from the L_1-RAC but with more focus on long time delay in this paper. Comparing to the L_1-RAC, the main change of the MB-RAC architecture is in the adaptive law which uses a dual-feedback error-generating mechanism based on a built-in plant model for adaptive compensation.

Most of the studies on boiler-turbine power systems are based on a boiler-turbine-generator nonlinear dynamic model developed by Bell and Aström (1987). Although this model is in a simplified form and thus easy for control study, it involves the key characteristics of real boiler-turbine-generator systems, including nonlinearity, coupled variables, large inertia, unmeasured internal state, non-minimum phase and unstable plant, etc., and therefore, it has often been chosen as the benchmark for coordinated control studies in literature. We have developed and verified the L_1-RAC (Pan et al., 2015a, b) approach on this Bell and Aström (B-A) model. For a subsequence study, we also use the B-A model for developing and verifying the MB-RAC approach. To handle the time-delay characteristics, a delay-augmented boiler-turbine-generator nonlinear model will be proposed based on the B-A model in this paper. The time delay will be augmented as an output delay which would not influence any inner state, but only make the outputs to be delayed.

In the rest of the paper, we propose the model-based robust adaptive control for long time delays in Section 2, and two kinds of models for the design of MB-RAC in Section 3. One model is a delay-augmented classic nonlinear boiler-turbine-generator model as the simulation model. Another one is the linearized model with time delay for controller design. For verify the robustness of the MB-RAC in the presence of long time delay, several simulation experiments are made in Section 4 and then the conclusions for the study is drawn in Section 5.

2. MODEL-BASED ROBUST ADAPTIVE CONTROL FOR A LONG TIME DELAY

2.1 Problem Formulation

The dynamics of the controlled plant can be described as following:

$$\begin{aligned} &\dot{x}_D(t) = A_D x_D(t) + B_D u(t) + f(x_D, z, t), x_D(0) = x_0, \\ &\dot{z}(t) = g(z, x_D, t), z(0) = z_0, \\ &x(t) = x_D(t - T_d) \\ &y(t) = C_D^T x(t) + D u(t) \end{aligned} \tag{1}$$

where $x_D(t) \in R^n$ is the system state vector (immeasurable), $x(t) \in R^n$ is the system measurable state vector with time delay $T_d \geq 0$, $u(t) \in R^m$ denotes the input ($m \leq n$), $y(t) \in R^m$ denotes the output, $A_D \in R^{n \times n}$ is a known Hurwitz matrix, $B_D \in R^{n \times m}$ is a known full-rank constant matrix, (A_D, B_D) is controllable, $C_D \in R^{m \times n}$ is a known full-rank constant matrix, (A_D, C_D) is observable, $C_D^T(sI-A_D)^{-1}B_D$ defines the desired dynamics for the closed-loop system and its zeros lie in the open left-half S- plane, $z(t) \in R^p$ denotes the immeasurable state i.e., internal un-modeled dynamics, and function $f : R^n \times R^p \times R \to R^n$ and function $g : R^n \times R^p \times R \to R^p$ denote unknown nonlinearities.

Let $X = [x_D^T z^T]^T$, and $f(X,t) = f(x_D, z, t)$. The following assumptions are essential for maintaining stability of the L_1-RAC as well as its derivative algorithms like MB-RAC:

Assumption 1: For any $\delta > 0$, there exist, $L(\delta) > 0$ and $B_f > 0$ such that

$$\left\| f(X,t) - f(\bar{X},t) \right\|_\infty \leq L(\delta) \left\| X - \bar{X} \right\|_\infty, \left\| f(0,t) \right\|_\infty \leq B_f, \tag{2}$$

for all $\|X\|_\infty \leq \delta$ and $\|\bar{X}\|_\infty \leq \delta$ uniformly in u and t.

Assumption 2: The internal un-modeled dynamics are Bounded-Input Bounded-Output (BIBO) stable with respect to both initial conditions z_0 and input $x_D(t)$, i.e., there exist positive L_z and B_z such that for all $t \geqslant 0$

$$\left\| z_t \right\|_{L\infty} \leq L_z \left\| x_{D,t} \right\|_{L\infty} + B_z. \tag{3}$$

The control objective is to generate an adaptive state feedback control signal $u(t)$ to drive the system output $y(t)$ tracking the desired system output $y_{des}(t)$ rapidly, while all other signals remain bounded. The desired closed-loop system is described by

$$\begin{aligned} &\dot{\bar{x}}_{des}(t) = A_D \bar{x}_{des}(t) + B_D K_g r(t), \\ &x_{des}(t) = \bar{x}_{des}(t - T_d), \\ &y_{des}(t) = C_D^T x_{des}(t), \end{aligned} \tag{4}$$

where $r(t)$ is a given bounded reference input signal, and $K_g = -(C_D^T A_D^{-1} B_D)^{-1}$.

2.2 Control Algorithm

The main components of the model-based robust adaptive controller for long output delay are shown in Fig. 1 and given specifically below:

1) **Plant Model:**
Assume that the plant with long time delay (1) can be approximately expressed by the following linear model:

$$\begin{aligned} &\dot{\bar{x}}(t) = A_m \bar{x}(t) + B_m u(t), \bar{x}(0) = x_0, \\ &\bar{x}_e(t) = \bar{x}(t - T_m), \\ &\bar{y}(t) = C_m^T \bar{x}_e(t) + D_m u(t), \end{aligned} \tag{5}$$

where the state vector $\bar{x}(t)$ and $\bar{x}(t - T_m)$, input vector $u(t)$ and output vector $\bar{y}(t)$ has the same dimensions with their corresponding vectors in (1), and $T_m \geq 0$ is the time delay of the model. The immeasurable state vector $z(t)$ in (1) is not necessary here. The model (5) can be obtained by using many modeling methods like linearization from a known nonlinear math model or identification from field data of a plant. Model (5) provides an explicit expression of output delay separate from its dynamic part, which is required by the MB-RAC algorithm.

2) **State Predictor:**

We consider the following state predictor

$$\begin{aligned}\dot{\hat{x}}(t) &= A_D\hat{x}(t) + B_D u(t) + \hat{\sigma}(t), x(0) = x_0,\\ \hat{y}(t) &= C_D^T\hat{x}(t),\end{aligned} \tag{6}$$

where $\hat{\sigma}(t) \in R^n$ is a vector of adaptive parameters. We can find a constant matrix, $B_{uD} \in R^{n\times(n-m)}$ such that $B_D^T B_{uD} = 0$ and rank($[B_D \quad B_{uD}]$) = n. Then, (6) is transformed into

$$\begin{aligned}\dot{\hat{x}}(t) &= A_D\hat{x}(t) + B_D(u(t) + \hat{\sigma}_1) + B_{uD}\hat{\sigma}_2,\\ \hat{y}(t) &= C_D^T\hat{x}(t), \hat{y}(0) = y_0,\end{aligned} \tag{7}$$

where $\hat{\sigma}_1(t)$ represents the input-matched component of $\hat{\sigma}(t)$, and $\hat{\sigma}_2(t)$ represents the input-unmatched component.

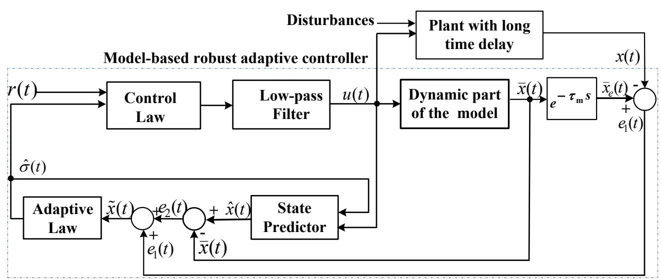

Fig. 1. The MB-RAC for plants with long time delays.

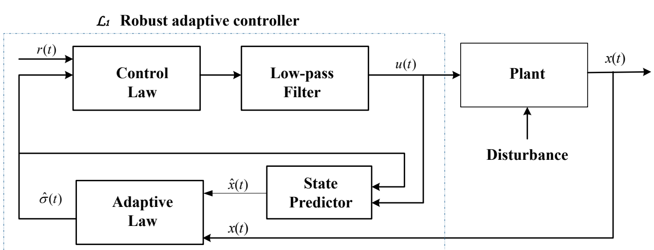

Fig. 2. The architecture of L_1-RAC.

3) **Adaptive Law:**
We introduce a dual-feedback strategy to the MB-RAC for the adaptive law and thus make two errors. One error is made between the measured state of the plant and the put-off state output of the model, i.e., the outer feedback error $e_1(t) = \bar{x}_e(t) - x(t)$; another error is made between the state from the state predictor and the state before the delay item of the model, i.e., the inner feedback error $e_2(t) = \hat{x}(t) - \bar{x}(t)$.

Letting $\tilde{x}(t) = e_1(t) + e_2(t)$, the updated law for $\hat{\sigma}(t)$ is given by

$$\begin{aligned}\hat{\sigma}(t) &= \hat{\sigma}(iT), t \in [iT, (i+1)T),\\ \hat{\sigma}(iT) &= -\Phi^{-1}(T)\mu(iT), i = 0,1,2,\ldots,\end{aligned} \tag{8}$$

where $\Phi(T) = \int_0^T e^{A_D(T-\tau)}d\tau, \quad \mu(iT) = e^{A_D T}\tilde{x}(iT).$

$\Phi(T) = \int_0^T e^{A_D(T-\tau)}d\tau, \quad \mu(iT) = e^{A_D T}\tilde{x}(iT)$, and $T>0$ represents the adaptation sampling time.

4) **Control Law:** The control signal is defined as follows:

$$\begin{bmatrix}\hat{\sigma}_1(t)\\ \hat{\sigma}_2(t)\end{bmatrix} = [B_D \quad B_{uD}]^{-1}\hat{\sigma}(t), \tag{9}$$

$$u(s) = K_g r(s) - F(s)(\hat{\sigma}_1(s) + M(s)\hat{\sigma}_2(s)), \tag{10}$$

where $r(s)$, $\hat{\sigma}_1(s)$ and $\hat{\sigma}_2(s)$ are the Laplace transformations of $r(t)$, $\hat{\sigma}_1(t)$ and $\hat{\sigma}_2(t)$, respectively; $F(s) = KD(s)(I_m+KD(s))^{-1}$ is a strictly-proper stable low-pass filter matrix with DC gain $F(0) = I_m$, $K\in R^{m\times m}$ is a gain matrix, $D(s)$ is an $m\times m$ strictly-proper transfer function matrix, the choice of K and $D(s)$ needs to ensure that $F(s)M(s)$ is proper and stable, and $M(s)$ is defined by

$$M(s) = (C_D^T(s)H_{xD}(s))^{-1}(C_D^T(s)H_{xuD}(s)), \tag{11}$$

$$H_{xD}(s) = (sI_n - A_D)^{-1}B_D, H_{xuD}(s) = (sI_n - A_D)^{-1}B_{uD}. \tag{12}$$

The MB-RAC controller consists of (5)-(12).

2.3 Analysis of the MB-RAC Algorithm

The MB-RAC derives from the L_1-RAC consisting of control law, adaptive law and state predictor as shown in Fig. 2. MB-RAC enlarges time-delay margin of the L_1-RAC by taking advantage of the models built from controlled systems. Comparing Fig. 1 with Fig. 2, we can find three major differences between them.

First, the L_1-RAC makes an error for the adaptive law between the state feedback of plant and the state of the state predictor. The MB-RAC uses the state feedback before the time-delay item of the model and then makes the error $e_2(t)$ with the state of the state predictor. Therefore, the inner feedback of MB-RAC constructs a closed-loop only with the dynamic part of the model but does not include the plant and the whole model.

Second, the MB-RAC makes another error $e_1(t)$ which denotes the modelling error and sends it to adaptive law for compensation by adaptive control action. The error $e_1(t)$ comes from the state feedback of plant and the state of model after delay element, therefore it is in the outer closed-loop including the plant and the whole model.

Third, the L_1-RAC has a single closed-loop but MB-RAC has dual closed-loops. If the modelling is accurate in terms of both dynamics and time delays, MB-RAC becomes a single loop and only has one feedback for the states from the dynamic part of the model, so the time delay is not in the closed-loop anymore and thus the stability of the control system would be greatly improved. If the model is not accurate, i.e., the error $e_1(t)$ is not a zero vector, the outer feedback will take effect and make the robust adaptive controller to compensate for it.

Remark 1: The L_1-RAC makes an error between the state feedback from the plant and the state predictor. Because of the presence of output delay in the closed-loop, the error may be very large and then the compensation of the controller may become very intensive. In the MB-RAC control system, if we use a good modelling tool to obtain a very accurate model, i.e., the error $e_1(t)$ is very small, the system will be controlled like without time delay and in a low compensation intensity, which contributes significantly to the stability of the whole control system.

3. MODELS USED BY DESIGN AND SIMULATION OF THE MB-RAC

3.1 A Nonlinear Boiler-turbine-generator Unit Augmented with Time Delay

For verifying the performance of the MB-RAC, the nonlinear B-A model (1987) is chosen as the controlled boiler-turbine-generator plant in this study. Because the model represents many key characteristics of real boiler-turbine-generator systems, including nonlinearity, strong coupling variables, large inertia, unmeasured internal state, non-minimum phase and unstable plant etc., many different kinds of advanced control algorithms for boiler-turbine-generator systems have been tested on this model, but it does not have any time delay. In order to verify the MB-RAC algorithm, we augment it with multiple output delays without changing its inner dynamics. Based on the original third-order nonlinear dynamic equations which are described in (Bell and Åström, 1987), the delay-augmented boiler-turbine-generator nonlinear model is described in the following:

$$\begin{cases} \dot{x}_{D1}(t) = -0.0018u_2(t)x_{D1}(t)^{9/8} + 0.9u_1(t) - 0.15u_3(t) \\ \dot{x}_{D2}(t) = (0.073u_2(t) - 0.016)x_{D1}(t)^{9/8} - 0.1x_{D2}(t) \\ \dot{x}_{D3}(t) = [141u_3(t) - (1.1u_2(t) - 0.19)x_{D1}(t)]/85 \\ x_1(t) = x_{D1}(t - T_d) \\ x_2(t) = x_{D2}(t - T_d) \\ y_1(t) = x_1(t) \\ y_2(t) = x_2(t) \\ \overline{y}_3(t) = 0.05(0.1307x_{D3}(t) + 100a_{cs}(t) + q_e(t)/9 - 67.975) \\ x_3(t) = \overline{y}_3(t - T_d) \\ y_3(t) = x_3(t) \end{cases} \tag{13}$$

where the state x_{D1} (*kg/cm*^{2}) is drum steam pressure, x_{D2} (*MW*) is electric power and x_{D3} (*kg/cm*^{3}) is drum/riser fluid density. The output variables y_1 and y_2 denote the same quantities as x_{D1} and x_{D2} but delayed by T_d seconds; the output y_3 (*meter*) is the T_d - delayed drum water level deviation $\overline{y}_3$, where evaporation rate α_{cs} (*kg*) and steam quality q_e (*kg/s*) are given by

$$q_e(t) = [0.854u_2(t) - 0.147]x_{D1}(t) + 45.59u_1(t) - 2.514u_3(t) - 2.096,$$

$$a_{cs}(t) = \frac{[1 - 0.001538x_{D3}(t)][0.8x_{D1}(t) - 25.6]}{x_{D3}(t)[1.0394 - 0.0012304x_{D1}(t)]}. \tag{14}$$

The normalized manipulated variables are fuel flow rate u_1, control valve position of steam to the turbine u_2 and feedwater flow rate u_3. All the manipulated variables have constraints in magnitude and rate as follows:

$$\begin{aligned} &0 \le u_i \le 1, i = 1,2,3. \\ &-0.007 \le \dot{u}_1 \le 0.007 \\ &-2 \le \dot{u}_2 \le 0.002 \\ &-0.005 \le \dot{u}_3 \le 0.05 \end{aligned} \tag{15}$$

Table 1 lists some equilibrium working points of the B-A model and point #2 is for the nominal operating condition.

Remark 2: For designing the MB-RAC in the case of the delay-augmented nonlinear boiler-turbine system (13)-(15), let measureable state $x = [x_1 \quad x_2 \quad x_3]^T$, and let the internal unmeasured un-modeled dynamics state $z = x_{D3}$, i.e., the fluid density which satisfies **Assumption 2**. The measureable state vector x is corresponding to the output $y = [y_1 \quad y_2 \quad y_3]^T$ and will be made error with the output vector of the linear model of the plant as shown in Fig. 1.

Table 1. Equilibrium points of boiler-turbine-generator unit

	#1	#2	#3
x_1	75.6	108	129.6
x_2	15.2	66.65	105.86
x_3	-0. 97	0	0.64
u_1	0.156	0.34	0.505
u_2	0.483	0.69	0.828
u_3	0.183	0.433	0.663

3.2 Linearization model with time delay

Because MB-RAC requires a mathematical model with separate expression of time delay of the controlled system, we linearize the nonlinear equation group (13)-(15) by taking Taylor's series expansion around the operating point #2 in Table 1 and then obtain the state-space model coefficients in (5) as follows:

$$A_m = \begin{bmatrix} -0.0025 & 0 & 0 \\ 0.0694 & -0.1 & 0 \\ -0.0067 & 0 & 0 \end{bmatrix}, \quad B_m = \begin{bmatrix} 0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.66 \end{bmatrix},$$

$$C_m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0.0063 & 0 & 0.0047 \end{bmatrix}, \quad D_m = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.253 & 0.512 & -0.014 \end{bmatrix}. \tag{16}$$

The LTI system (A_m, B_m, C_m, D_m) approximately represents the dynamics of the plant. The output delay T_m can be taken as the same value of T_d in (13), representing the situation of accurately modelling about time delay, or as different values from T_d for the case of inaccurate modelling.

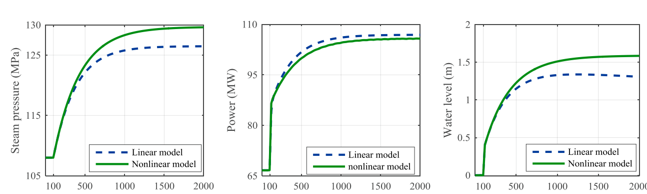

Fig. 3. Comparisons of the step responses from the delay-augmented B-A model and its linearized model .

Fig. 3 shows the comparisons of the step responses from the delay-augmented nonlinear boiler-turbine-generator model and its linearized model with time delay, where the time delay T_m= T_d=60*s*. Let the manipulated vector [u_1, u_2, u_3] of both models step up at 40*s* from the original value [0.34, 0.69, 0.433] to the final value [0.505, 0.828, 0.663], i.e., from nominal point #2 to an operating point #3 in Table 1. The result shows that the two models have similar dynamics but with obvious difference in values, because the linear model cannot describe precisely in a large operating range of the nonlinear process.

Considering that the robust adaptive control has good ability to deal with model mismatch and nonlinearity, we will incorporate the linear model with output delay into the MB-RAC to feedback the intermediate state $\bar{x}(t)$ which is unavailable by measurement on real plant. The error caused by model mismatch which is denoted as $e_1(t)$ in Fig. 1 will be compensated by the adaptive law.

4. SIMULATIONS AND DISCUSSION

Several simulation experiments on the delay-augmented nonlinear boiler-turbine-generator model of Eq. (13)-(15) will be made in this section to validate the MB-RAC algorithm.

The simulations focus on the robustness for load tracking of the boiler-turbine-generator system in the presence of long time delay. The simulations will compare three control performances of using: (1) the L_1-RAC, (2) the MB-RAC incorporating a linear model followed by matched time delay, and (3) the MB-RAC with linear model followed by unmatched time delay.

First we take the parameters of L_1-RAC from our previous work (Pan et al., 2015a) which has shown good control performance in a wide load tracking of the boiler-turbine-generator unit in the presences of time-varying parameter variations, input valve nonlinearity, output noise disturbances and small time delay. According to the principle of the MB-RAC, it inherits the same kind of state predictor of the L_1-RAC, so the state predictor coefficients of both controllers in (6) are given by

$$A_D=\begin{bmatrix} -0.06 & 0 & 0 \\ -0.0287 & -0.1 & 0 \\ 0.0022 & 0 & -0.005 \end{bmatrix},\quad B_D=\begin{bmatrix} 0.9 & -0.175 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{bmatrix},$$

$$C_D=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.00227 \end{bmatrix}. \qquad (17)$$

The filter $F(s) = 0.1/(s+0.1)$ and the sampling time T=0.01second are chosen the same for both controllers as well.

Then following (6)-(12), we incorporate the linearized model (5) with coefficients (16) and time delay T_m into the L_1-RAC architecture and thus build the MB-RAC as shown in Fig. 2. With the dual feedbacks from the linear model and the plant, the adaptive parameter $\hat{\sigma}(t)$ of the MB-RAC in (8) is updated at every sampling time, which is different from that generated by L_1-RAC. Figs. 4-6 show the control results of load tracking of the nonlinear boiler-turbine-generator system (13)-(15) with three different controllers and conditions.

Case 1: Load tracking with L_1-RAC in the presence of time delay.

As presented in our previous work (Pan et al., 2015a), the L_1-RAC can deal with about 6*s* time delay, so we gradually increase the value of the output delay T_d in model (13) till T_d=10*s* when it led to instability of the control system. Seen from Fig. 4, the system setpoints step up from the initial state at nominal point #2 to operating point #3 at t=40*s*. In the load tracking process, the controlled variable, steam pressure and power, have slow damping meanwhile the manipulated control variables vary severely. Eventually L_1-RAC cannot keep the stability of the nonlinear boiler-turbine-generator system. The control results denote that the L_1-RAC has very limited time-delay margin thus it is hard to handle long time delays which power plants always have.

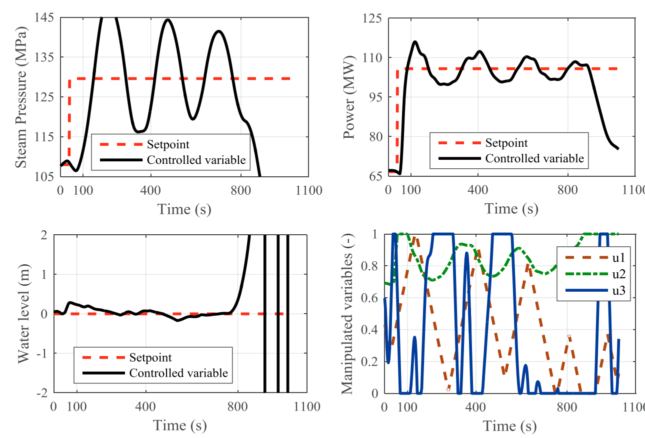

Fig. 4. Control result of the L_1-RAC (T_d=10*s*).

Case 2: Load tracking with MB-RAC using matched long time delay.

For testing the effect of MB-RAC, we extend the time delay to 60*s* in this case. It uses the linear model presented in (5) with coefficients (16) and matched time delay T_m=T_d=60*s*. In the same load-tracking process as in Case 1, the control result is pretty good as shown in Fig. 5. Except for water level and water flow rate which have a little fluctuation, the other controlled variables and manipulated variables converge to the steady state quickly and steadily. The results denote that MB-RAC has good robustness to mismatch between the linear model and the controlled plant.

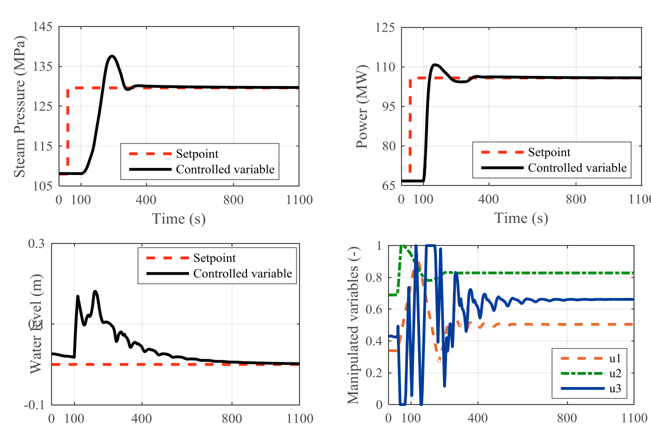

Fig. 5. Control result of the MB-RAC (using linear model with matched time delay, T_m=T_d=60s).

Case 3: Load tracking with MB-RAC using unmatched long time delay.

In this case, the robustness of MB-RAC is tested further, i.e., let T_m=65s, T_d=60s. This is because in field test the measurement delay always cannot be avoided and then a longer delay will be obtained in modeling. Seen from Fig. 6, the unmatched output delay in MB-RAC results in a little more fluctuation on all variables, but the variables still converges to steady state quickly and the system is far from instability. The results denote that MB-RAC has strong robustness to its inner model mismatch on both dynamics and time delays.

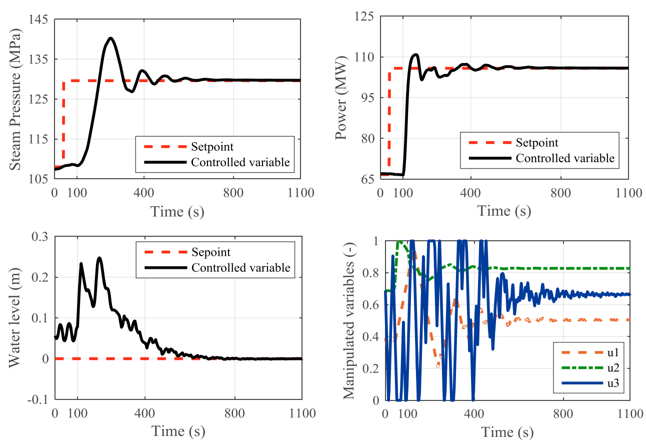

Fig. 6. Control result of the MB-RAC (using linear model with unmatched time delay, T_m=65s, T_d=60s).

Remark 3: Incorporating the internal model theory into robust adaptive controller, the resulting control performance of the MB-RAC is greatly improved. It fits in not only with nonlinear plants under uncertain conditions but also with plants in the presence of long time delays. Seen from the simulation results, the MB-RAC has strong robustness to the inner model mismatch, and it is easy to design and implement for industrial processes.

5. CONCLUSIONS

Most of the existing control methods for the boiler-turbine power-generating systems cannot ensure good performance as some uncertainties arise. The L_1 robust adaptive control has been proven to be effective for a wide-range load-tracking of the nonlinear B-A model in the presence of uncertain conditions. But its limited time-delay margin cannot deal with plants in the presence of long time delays which commonly exist in many industrial processes. In order to improve the L_1-RAC specifically in term of time-delay tolerance capability, this paper introduces the internal model theory into the robust adaptive algorithm, developing a novel model-based robust adaptive control. It not only inherits arbitrarily close tracking performance and fast, robust adaptation of the L_1-RAC, but also has good ability to deal with long time delay in control processes. Moreover, it shows strong robustness to inner model mismatches on both the dynamics and the time delays, so it is easy to design and maintain in operation. Because it has multi-abilities to solve the problems in the operations of boiler-turbine-generator systems, MB-RAC may become a promising control approach for power plants in the near future.

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