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Fault-tolerant model predictive control (FTMPC) for the BioGrate boiler

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***Abstract*—The fuel bed height sensor is a critical element in the control of the BioGrate boiler. A fault appearing in this sensor greatly affects the control performance in the sense that air distribution in the BioGrate boiler deviates from its nominal distribution. To address this problem, a fault tolerant model predictive control (FTMPC) has been developed to accommodate the fault in this fuel bed height sensor by the active controller reconfiguration. In this fault tolerant strategy, water evaporation in the furnace is estimated by fuel moisture soft-sensor, and thermal decomposition of dry fuel is estimated by utilizing oxygen consumption. This renders the power output of the boiler to be accurately predicted and controlled. The proposed FTMPC is successfully tested with the BioPower 5 CHP plant data and the results are presented, analyzed, and discussed.**

I. INTRODUCTION

The utilization of biomass fuel for heat and power production is growing due to an increasing demand for the replacement of fossil energy sources with renewable energy. As a result, the fast and the efficient control of power producing units becomes increasingly important in combustion of biomass [1]. However, the main challenges in biomass combustion control are caused by the unpredictable variability of the fuel quality, which results in disturbances, faults, and failures in the plant behavior and operations. In particular, this is true for the grate firing that is one of the main technologies currently used in biomass combustion [2].

Several different control strategies have been developed to control the combustion. The combustion power method developed by Kortela and Lautala [3] was employed by many control strategies to compensate variations in the fuel quality. Based on the combustion power method, in the same publication Kortela and Lautala [3] suggested a feed-forward control: adjusting the fuel feed flow according to the thermal decomposition rate to stabilize the amount of the fuel in the furnace. As a result, the effect of the feed disturbance on the generated steam pressure decreased to about one third of the original value, and the settling time decreased from 45 min to only 13 min. The same method has later been applied to a grate boiler [4].

Recently, the model predictive control has proven to be a successful method for controlling renewable fuel power plants. In particular, the benefits of MPC-based control over conventional multivariable control have been demonstrated by Leskens et al. [5] at a grate boiler combusting municipal solid waste. Gölles et al. [6], [7] implemented and experimentally verified a model based control in a commercially available small-scale biomass boiler using the simplified first-principle model. In more details, the mass of water in the water evaporation zone and the mass of dry fuel in the thermal decomposition zone on the grate are considered as the states of the simplified model and are estimated by an extended Kalman filter. Test results showed that the control was always able to provide the required power whereas the conventional control (PID control based on standard control strategies) could not tolerate a feed water temperature drop of more than 7 °C. In addition, the control was able to operate the plant with a lower excess oxygen content during the load drop and especially under partial load conditions. The better control of the residual oxygen and the control of the air ratio led to lower emissions and higher efficiencies. In addition, the model-based control was able to handle without difficulties a step-wise change in the fuel moisture content from 26% to 38% and vice versa. However, in addition to controlling the power production, the plant control has to maintain the optimal operating conditions in the furnace. According to the boiler design, for the complete combustion of biomass, the fuel bed height should be kept at the level to achieve the specified ratio between the primary and secondary air, and the amount of fuel in the furnace [8].

In this paper a FTMPC strategy is proposed to accommodate the fault in fuel bed height sensor by active controller reconfiguration. The paper is organized as follows: Section 2 presents the BioPower 5 CHP process. The FTMPC strategy is presented in Section 3. The test results are given in Section 4, followed by the conclusions in Section 5.

II. DESCRIPTION OF THE BIOPOWER 5 CHP PROCESS

The BioPower 5 CHP process consists of two main parts: the furnace and the steam-water circuit. The heat used for steam generation is obtained by burning solid biomass fuel – consisting of bark, sawdust, and pellets – which is fed into the furnace together with combustion air. The heat of the flue gas is transfered by the heat exchangers to the steam-water circulation, where superheated steam is generated [9].

In the BioGrate system, the fuel is fed onto the center of a grate from below through a stoker screw, as shown in Fig. 1. The grate consists of alternate rotating and stationary concentric rings with the rotating rings alternately rotated clockwise and counter-clockwise by hydraulics. This design distributes the fuel evenly over the entire grate, with the burning fuel forming an even layer of the required thickness.

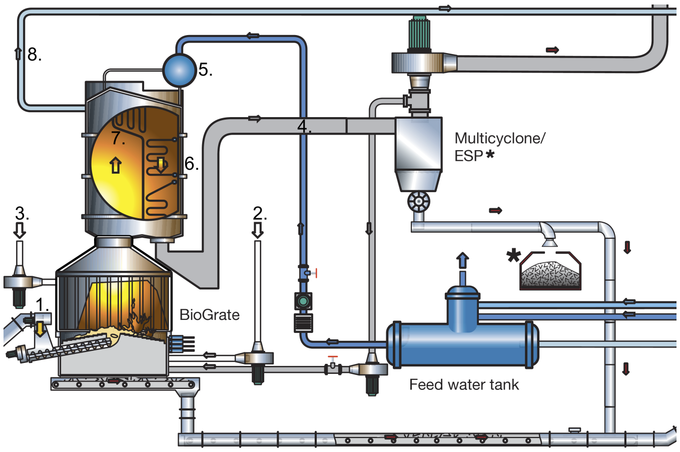

Fig. 1. 1. Fuel, 2. Primary air, 3. Secondary air, 4. Economizer, 5. Drum, 6. Evaporator, 7. Superheaters, 8. Superheated steam

The moisture content of the wet fuel in the centre of the grate evaporates rapidly due to the heat of the surrounding burning fuel and the thermal radiation coming from the brick walls. The gasification and visible combustion of the gases and solid carbon takes place as the fuel moves to the periphery of the circular grate. At the edge of the grate, ash finally falls into a water-filled ash basin underneath the grate.

The primary air for combustion and the recirculation flue gas are fed from underneath the grate and they penetrate the fuel through the slots in the concentric rings. The secondary air is fed directly into the flame above the grate and the air distribution is controlled by dampers and speed-controlled fans. The gases released from biomass conversion on the grate and a small number of entrained fuel particles continue to combust in the freeboard, in which the secondary air supply plays a significant role in the mixing, burnout, and the formation of emissions. The design of the air supply system, the ratio between primary and secondary air, plays a key role in the efficient and complete combustion of biomass [8]. In modern grate-fired boilers burning biomass, the split ratio of primary to secondary air is 40/60, which should be followed by a control design for the most efficient energy production. The overall excess air for most biomass fuels is normally set at 25% or above.

The essential components of the water-steam circuit are an economizer, a drum, an evaporator, and superheaters. Feed water is pumped from a feed water tank into the boiler. First the water is led into the economizer (4), which is the last heat exchanger extracting the energy from the flue gas, and thus, improving the efficiency of the boiler. From the economizer, the heated feed water is transferred into the drum (5) and along downcomers into the bottom of the evaporator (6) through tubes that surround the boiler. From the evaporator tubes, the heated water and steam return back into the steam drum, where they are separated. The steam rises to the top of the steam drum and flows into the superheaters (7) where it heats up further and superheats. The superheated high-pressure steam (8) is then passed into the steam turbine, where electricity is generated.

III. FTMPC FOR THE BIOGRATE BOILER

The overall structure of the FTMPC follows the active FTC scheme, adjusting the plant control according to the fault diagnosis results. In more detail, two different MPC configurations have been developed for the cases of normal and faulty operations of the fuel bed height sensor. In the faultless mode, the MPC configuration is as follows: the primary air flow rate and the stoker speed are the manipulated variables (u); the moisture content in the fuel feed and the steam demand are the measured disturbances (d); and the fuel bed height and the steam pressure are the controlled variables (y). The fault is accommodated by employing an alternative estimation of the fuel bed height, which is based on the thermal decomposition rate. However, as the alternative estimation is less accurate, the control reconfiguration is also needed, shifting its focus to the combustion power control while the fuel height is given a low priority. Additionally, the fuel bed height is kept within the security limits in both configurations in order to avoid plant shutdowns.

In more details, the FTC scheme is presented in Fig. 2. The combustion power and fuel moisture soft-sensors are used to compensate the effect of the fuel quality variations. The results show that these soft-sensors predict the thermal decomposition rate of dry fuel and the water evaporation with good precision. Furthermore, the results of the tests show that these methods are able to detect variations in these properties within seconds [10]. In particular, the fuel moisture estimation is considered by the MPC as a measured disturbance and is also used to estimate the amount of water in the furnace. Considering the combustion power as a model state enables rapid energy production level changes and improves the control performance during the transitions. In addition, the thermal decomposition rate is used in the calculations of the fuel bed height (estimator 2 in Fig. 2), which makes the fault detection and accommodation possible. According to the fault detection results, the decision on the control reconfiguration is made, which is then communicated to the fault accommodation and the FTMPC. Depending on the r_p value, the fault accommodation employs either the fuel bed height measurement or the thermal decomposition rate and the primary air flow for the MPC state estimation. Also, FTMPC is switched between the normal and the faulty configurations according to the r_p signal.

A. Controller reconfiguration

1) Detection of faults in the fuel bed height sensor: Two state estimators in Fig. 2 utilize fuel moisture soft-sensor and combustion power estimations, steam, temperature, drum pressure measurements, and alternatively fuel bed height measurement and calculated fuel bed height to filter the states of the system, Fig. 3. In order to detect faults in the fuel bed height sensor, its filtered calculated value is compared with the filtered measurement (pressure drop over the grate). The calculated fuel bed height can be expressed from the primary air flow rate and the thermal decomposition rate as follows:

$$m_{ds} = \frac{c_{thd} \cdot \dot{m}_{pa} \cdot \beta_{thd} - \dot{m}_{gf}}{c_{ds}} \quad (1)$$

where c_{thd} is the thermal decomposition rate coefficient, $\dot{m}_{pa}$ is the primary air flow rate (m^3/s), β_{thd} is the coefficient for a dependence on the position of the moving grate, $\dot{m}_{gf}$ is the

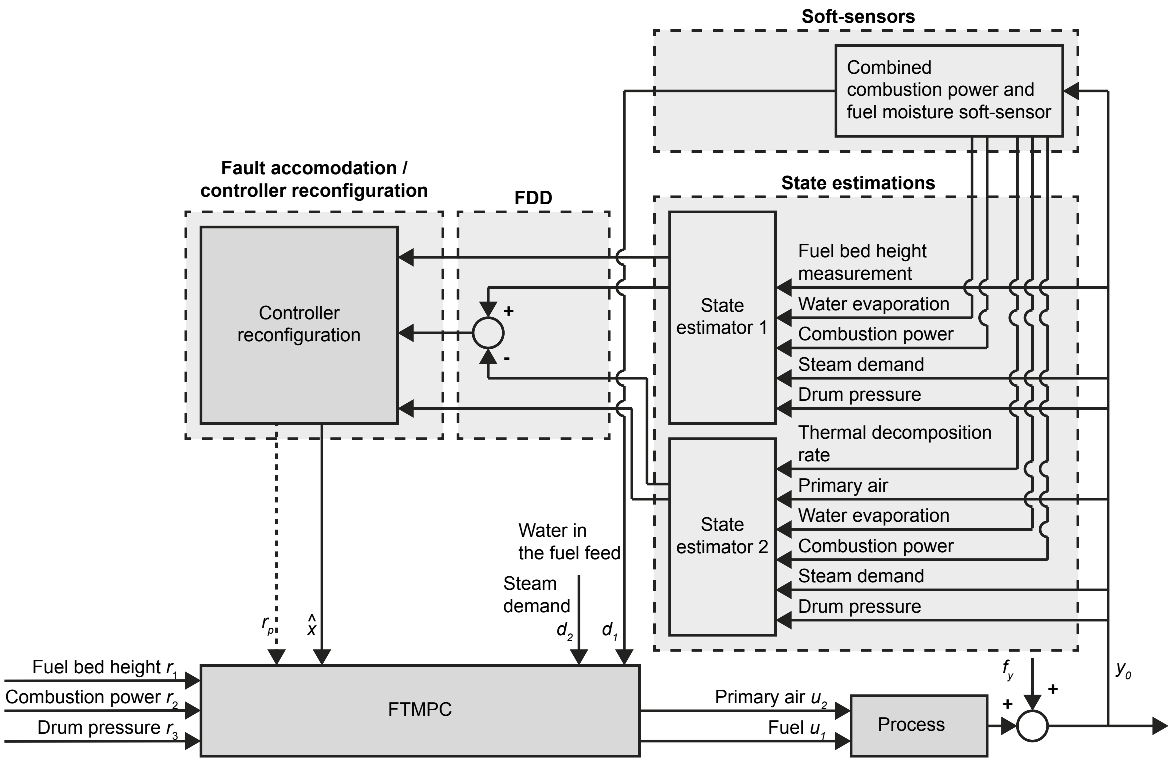

Fig. 2. FTMPC of the BioGrate boiler

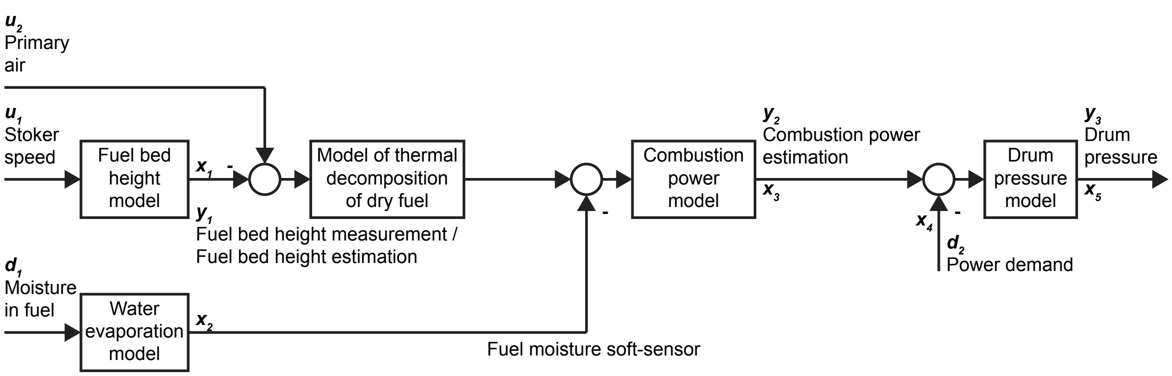

Fig. 3. The models of the BioGrate boiler

thermal decomposition rate of the fuel, c_{ds} is the fuel bed height cofficient, describing the mass of the fuel proportional to the density of the fuel. If a bias of magnitude $b_{y,i}$ occurs at time instant t in the ith sensor, then the measurement output for this sensor is given by [11]

$$y(k) = Cx(k) + v(k) + b_{y,i}e_{y,i}\sigma(k-t) \tag{2}$$

Furthermore, when a fuel bed height sensor fault occurs, the residual $\nu(k)$ and the two state fuel bed height estimates $\hat{x}(k|k)$ start to diverge from each other.

$$\nu(k) = y(k) - C\hat{x}(k|k-1) \tag{3}$$

$$\hat{x}(k|k) = \hat{x}(k|k-1) + K(k)\nu(k); \hat{x}(0|0) = \hat{x}(0) \tag{4}$$

The failure of the fuel bed height measurement is detected if the $RMSEP$ exceeds the detection threshold:

$$RMSEP = \sqrt{\frac{\sum_{i=1}^{n} |\hat{x}(i)_{1,1} - \hat{x}(i)_{1,2}|^2}{n}} \tag{5}$$

where n is the number of the samples in the test data set, $\hat{x}(i)_{1,1}$ is the estimated fuel bed height of the first MPC configuration, and $\hat{x}(i)_{1,2}$ the estimated fuel bed height of the second MPC configuration. The limit of detecting the faults is set above the normal disturbances of the states. Note that the fault isolation is implicitly done in the above fault detection procedure.

2) MPC of the BioGrate boiler: The MPC utilizes the linear state space system [12]:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + Ed(k) \\ y(k) &= Cx(k) \end{aligned} \tag{6}$$

where A is the state matrix, B is the input matrix, E is the matrix for the measured disturbances, and C is the output matrix. According to (6), the k-step ahead prediction is formulated as:

$$y(k) = CA^k x(0) + \sum_{j=0}^{k-1} H(k-j)u(j) \tag{7}$$

where $\mathbf{H}(k-j)$ contains the impulse response coefficients. Therefore, using the Equation (7), the MPC optimization problem is:

$$\begin{aligned} &\min \phi = \frac{1}{2}\sum_{k=1}^{N_p} \|y(k) - r(k)\|^2_{Q_z} + \frac{1}{2}\|\Delta u(k)\|^2_{Q_u} \\ &s.t. x(k+1) = Ax(k) + Bu(k) + Ed(k), \\ &\quad k = 0, 1, \ldots, N_p - 1 \\ &\quad y(k) = Cx(k), k = 0, 1, \ldots, N_p \\ &\quad u_{\min} \leq u(k) \leq u_{\max}, k = 0, 1, \ldots, N_p - 1 \\ &\quad \Delta u_{\min} \leq \Delta u(k) \leq \Delta u_{\max}, k = 0, 1, \ldots, N_p - 1 \\ &\quad y_{\min} \leq y(k) \leq y_{\max}, k = 1, 2, \ldots, N_p \end{aligned} \tag{8}$$

where r is the target value and $\Delta u(k) = u(k) - u(k-1)$.

The process models of the BioGrate boiler have been developed in [13] and [14]. Defining the inputs u, states x, outputs y and the measured disturbances d according to Fig. 3, the process models of the BioGrate are as follows:

$$\frac{\mathrm{d}x_1}{\mathrm{d}t} = c_{ds}x_1 - c_{thd}\beta_{thd}u_2 + c_{ds,in}u_1 + w_2 \tag{9}$$

$$\frac{\mathrm{d}x_2}{\mathrm{d}t} = -c_{wev}\beta_{wev}x_2 + c_{w,in}d_1 + w_1 \tag{10}$$

$$\frac{\mathrm{d}x_3}{\mathrm{d}t} = -x_3 + q_{wf}(c_{thd}\beta_{thd}u_2 - c_{ds}x_1) \tag{11}$$

$$-0.0244c_{wev}\beta_{wev}x_2 + w_3 \tag{12}$$

$$\frac{\mathrm{d}x_4}{\mathrm{d}t} = -x_4 + d_2 \tag{13}$$

$$\frac{\mathrm{d}x_5}{\mathrm{d}t} = \frac{1}{e}(x_3 - x_4) + w_4 \tag{14}$$

$$y_1 = x_1 + v_1 \tag{15}$$

$$y_2 = x_3 + v_2 \tag{16}$$

$$y_3 = x_5 + v_3 \tag{17}$$

where $c_{ds,in}$ is the correction coefficient identified from the data, β_{wev} is the coefficient for a dependence on the position from the center to the periphery of the moving grate, c_{wev} and $c_{w,in}$ are the model parameters estimated from the process data, q_{wf} is the effective heat value of the fuel (higher heat value) and 0.0244 the heat of vaporization of water.

The set points r_2 and r_3 for the combustion power and the drum pressure directly result from procedural considerations. The set point for the combustion power is calculated according to the steam demand and the drum pressure is kept constant. An important process parameter is λ_{fb} describing the ratio of primary air fed to the fuel bed and minimum amount of the air necessary for a complete combustion of fuel. From the amount of dry fuel in the thermal decomposition zone, the input variable $\dot{m}_{pa}$ and the constant parameters (c_{thd}, β_{thd}, c_{ds}), the set point r_1 for the mass of dry fuel in the thermal decomposition zone is calculated.

$$m_{ds} = \frac{c_{thd} \cdot \dot{m}_{pa} \cdot \beta_{thd} - \dot{m}_{gf}}{c_{ds}} \tag{18}$$

Two different MPC configurations are developed for the process operating in two different modes, i.e. faultless or healthy mode and faulty mode. In the faultless mode, the primary air flow rate and the stoker speed are the manipulated variables (u); the moisture content in the fuel feed and the steam demand are the measured disturbances (d); and the fuel bed height and the steam pressure are the controlled variables (y). While for the faulty mode, the controlled variables are modified: i.e. the output y is composed of the fuel bed height, the combustion power and the steam pressure. Once the fault is detected and isolated using the scheme described in Section III-A1, the controller is reconfigured from the healthy mode to the faulty mode.

IV. Test results of the FTMPC strategy

A. Description of the simulation and testing environment

A simulation model of the BioPower 5 CHP plant was built in the MATLAB environment and additionally, the code for the FTMPC was developed. Parameters of the models of the water evaporation, the thermal decomposition of the dry fuel, and the drum were identified by using the data from the BioPower 5 CHP plant. Moreover, to identify the fuel bed height model, the plant was further modified by installing 8 pressure sensors for the BioGrate to measure the fuel bed height pressure.

B. Test results of the FTMPC strategy

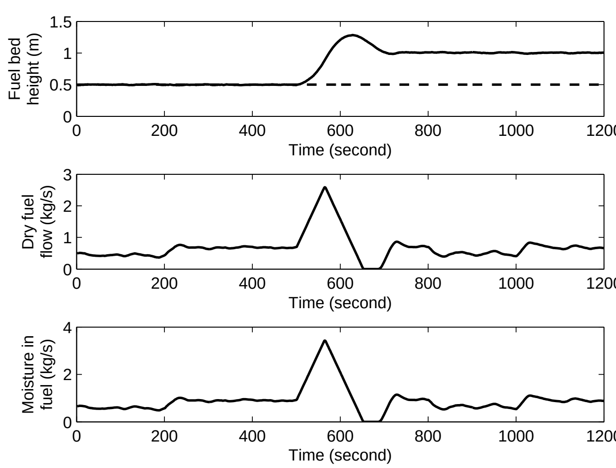

Fig. 4. Responses of the moisture in fuel, dry fuel flow, and fuel bed height to 100% bias fault in the fuel bed height sensor without the FTMPC active.

To demonstrate the effectiveness of the proposed FTMPC strategy, the performance of the FTMPC was evaluated using the BioGrate boiler simulator in a MATLAB environment.

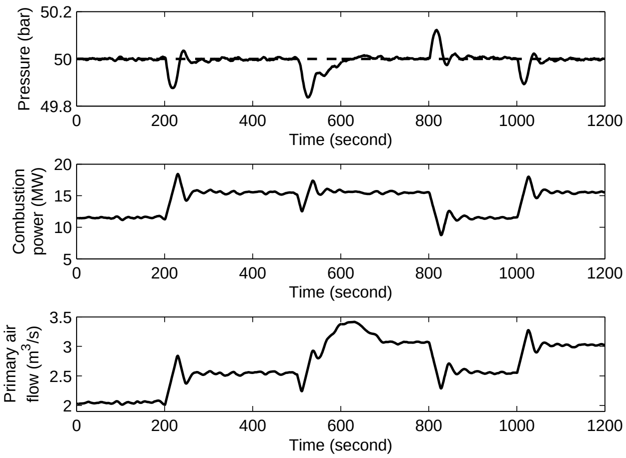

Fig. 5. Responses of the pressure, combustion power, and primary air flow to 100% bias fault in the fuel bed height sensor without the FTMPC active.

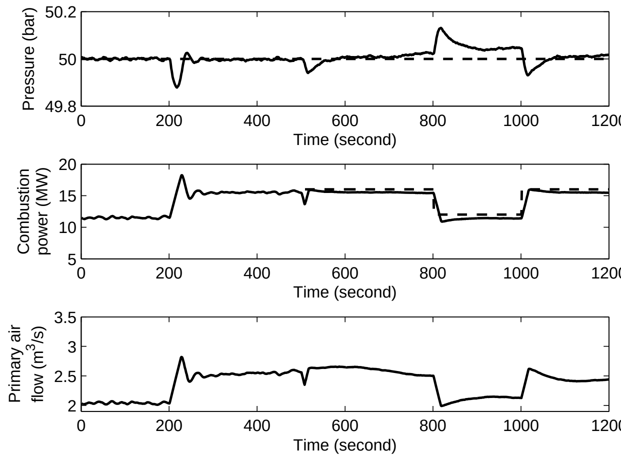

Fig. 7. Responses of the pressure, combustion power, and primary air flow to 100% bias fault in the fuel bed height sensor with the FTMPC active.

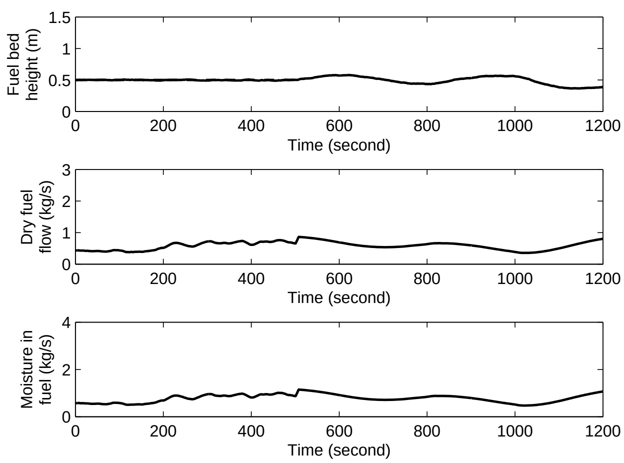

Fig. 6. Responses of the moisture in fuel, dry fuel flow, and fuel bed height to 100% bias fault in the fuel bed height sensor with the FTMPC active.

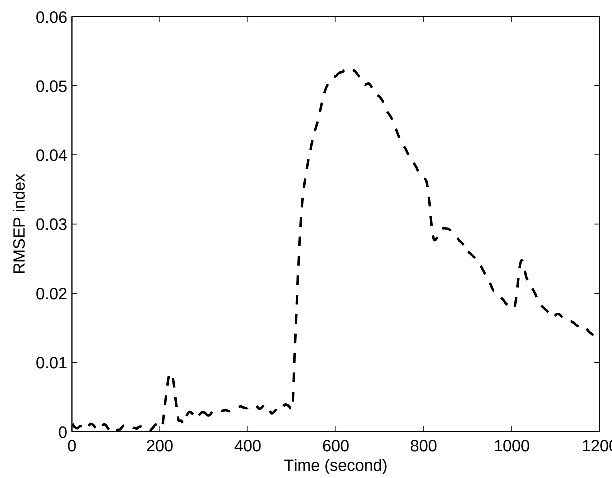

Fig. 8. Scenario 1: RMSEP index of fuel bed height state of MPC 1 and MPC 2.

The input limits were $u_{1,min} = 0$, $u_{1,max} = 4$, $\Delta u_{1,min} = -0.03$, and $\Delta u_{1,max} = 0.03$ [kg/s] for the stoker speed; $u_{2,min} = 0$, $u_{2,max} = 4$, $\Delta u_{2,min} = -0.03$, and $\Delta u_{2,max} = 0.03$ [kg/s] for the primary air.

In the nominal case, the output limits were $y_{1,min} = 0.2$, $y_{1,max} = 1$ [m] for the fuel bed height; and $y_{2,min} = 0$, $y_{2,max} = 55$ [bar] for the drum pressure.

$$\mathbf{Q}_{z,1} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix} \quad \text{and} \quad \mathbf{Q}_{u,1} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}$$

In the reconfiguration, the output limits were $y_{1,min} = 0.2$, $y_{1,max} = 1$ [m] for the fuel bed height; $y_{2,min} = 0$, $y_{2,max} = 30$ [MW] for the combustion power; and $y_{3,min} = 0$, $y_{3,max} = 55$ [bar] for the drum pressure.

$$\mathbf{Q}_{z,2} = \begin{bmatrix} 0.001 & 0 & 0 \\ 0 & 0.001 & 0 \\ 0 & 0 & 0.1 \end{bmatrix} \quad \text{and} \quad \mathbf{Q}_{u,2} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}$$

The test scenario had a downward step-shaped fault in the fuel bed height measurement of 100% of the nominal value and the power demand was changed from 12 MW to 16 MW after 200 seconds. The fault was introduced into the fuel bed height measurement after 500 seconds. Then, the power demand was changed from 16 MW to 12 MW during the time period of 800 - 1000 seconds. As it can be seen from the Figs. 4-7, the fault resulted in the extremely high values of the primary air and the fuel bed height. Fig. 8 shows the RMSEP index of the different fuel bed height state of MPC 1 and MPC 2.

V. Conclusion

A fuel bed height sensor is a critical element in the control of the BioGrate boiler and for optimal energy production its faulty operation should thus be avoided. In this paper a FTMPC strategy was proposed to accommodate the fault in the fuel bed height sensor by active controller reconfiguration where two different control configurations are run in parallel. In these configurations, two alternative control variables, fuel bed height and combustion power, were utilized.

The FTMPC was tested with the simulated BioPower 5 CHP plant. On the basis of the simulation results, the proposed FTMPC was able to counter the most typical fault in the BioPower 5 CHP plant caused by the unknown fuel quality and the status of the furnace (amount of fuel in the furnace). Therefore, the performance and the profitability of the BioPower 5 CHP plant would be significantly enhanced if such an FTMPC strategy is implemented.

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