Fault tolerant model predictive control for the BioPower 5 CHP plant

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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.

1 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 /2/. 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 /8/.

Several different control strategies have been developed to control the combustion. The combustion power method developed by Kortela and Lautala /6/ 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 /6/ 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 /7/.

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. /9/ at a grate boiler combusting municipal solid waste. Gölles et al. /3//4/ 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 /10/.

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.

2 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 /1/.

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.

3 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. 1. The combustion power and fuel moisture soft-sensors are used to compensate the effect of the fuel quality variations /5/. 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. 1), 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.

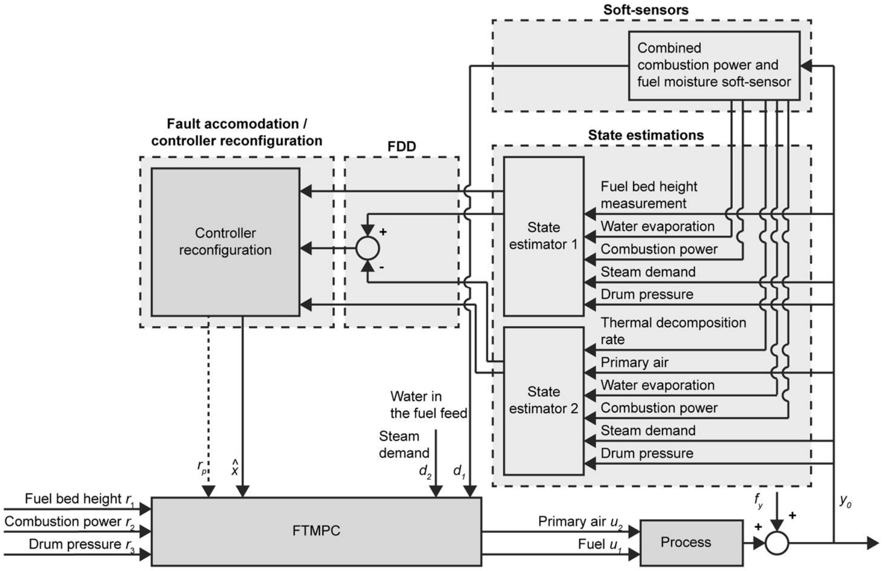

Figure 1. FTMPC of the BioGrate boiler.

4 TEST RESULTS OF THE FTMPC STRATEGY

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.

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

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. 2-5, the fault resulted in the high values of the primary air and the fuel bed height.

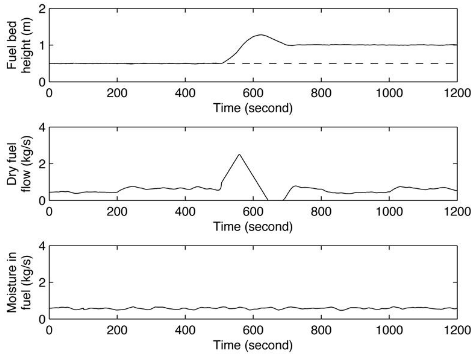

Figure 2. Responses of the moisture in fuel, dry fuel flow, and fuel bed height to 100% bias fault in the fuel bed height sensor without the FTMPC active.

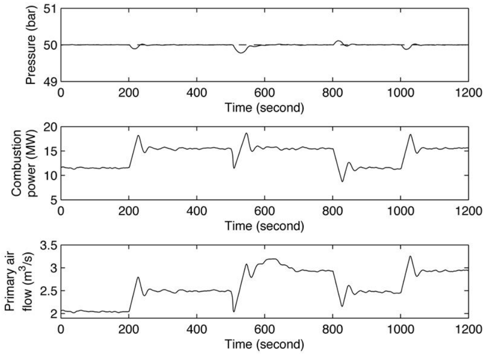

Figure 3. Responses of the pressure, combustion power, and primary air flow to 100% bias fault in the fuel bed height sensor without the FTMPC active.

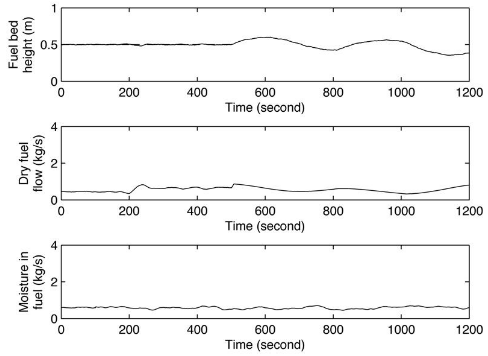

Figure 4. Responses of the moisture in fuel, dry fuel flow, and fuel bed height to 100% bias fault in the fuel bed height sensor with the FTMPC active.

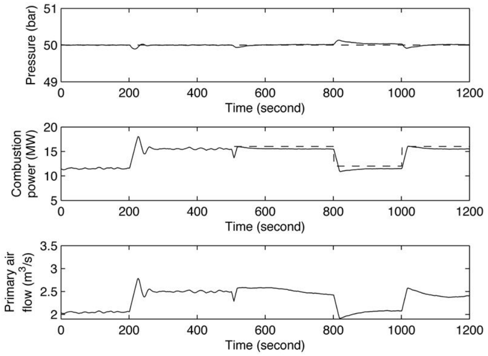

Figure 5. Responses of the pressure, combustion power, and primary air flow to 100% bias fault in the fuel bed height sensor with the FTMPC active.

5 CONCLUSIONS

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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