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Fault Tolerant Model Predictive Control for the BioPower 5 CHP Plant

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The main aim of control of the BioGrate boiler is stable energy production, where a fuel bed height sensor is a critical element in the control of the BioGrate boiler and its faulty operation should thus be avoided. A fault tolerant model predictive control (FTMPC) has been developed to accommodate the fault in this fuel bed height sensor by active controller reconfiguration. The proposed FTMPC is tested with the BioPower 5 CHP plant data by simulation and finally the results are presented, analysed, and discussed.

1. Introduction

In energy production, the substitution of fossil fuels by solid biomass has increased in an attempt to reduce CO_2 emissions. Great efforts have been made to develop biomass boilers and significant technological steps have been achieved in recent years (Grölles et al., 2014). One of the newest successful processes which can burn biomass with a moisture content as high as 65 % is a BioGrate boiler technology developed by MW Power (Boriouchkine et al., 2012).

Due to the long time delay and the moisture in fuel feed, development of FTMPC for the BioGrate boiler requires special considerations especially in the modelling of the BioGrate combustion. Bauer et al. (2010) derived a simple model for the grate combustion of biomass based on two mass balances for dry fuel and water. The model was subsequently verified by experiments in a pilot scale furnace with a horizontally moving grate. Based on the literature (Johansson et al., 2007), they suggested that the overall effect of the primary air flow rate on the thermal decomposition of dry fuel is multiplicative. In addition, the test results of Bauer et al. (2010) showed that the water evaporation rate is mainly independent of the primary air flow. Based on the models, Grölles et al. (2014) implemented a model based control strategy in a commercially available small-scale biomass boiler. Test results showed that the model based control strategy could always provide the required load whereas the conventional control could not avoid a feed temperature drop of more than 7 °C. In addition, better control of the residual oxygen and the control of the air ratio led to lower emissions and higher efficiencies. Moreover, the control was able to handle the step-wise change of the fuel water content from 26 % to 38 % and vice versa without difficulties. As the developed control requires the knowledge of variables like the mass of water in the water evaporation zone and the mass of dry fuel in the thermal decomposition zone but as only the feed temperature could be measured, the extended Kalman filter was incorporated into the model to estimate the current state of the furnace. Kortela and Jämsä-Jounela have presented a solution for this issue in (Kortela and Jämsä-Jounela, 2012) where these variables are estimated by using fuel and moisture soft-sensors.

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. The effect of occuring faults, especially for sustainable energy development, can be prevented by using fault-tolerant control (FTC) strategy. These strategies are generally categorized into passive and active approaches as described in (Zhang and Jiang, 2008). An active FTC strategy for the Naantali refinery dearomatisation process was developed by Sourander et al. (2009). While a novel model-free fault tolerant wind turbine control strategy was proposed by Jain and Yamé (2013). The analysis of the results showed that the FTC strategies were capable of handling faults in the online quality monitoring in the former whilst maintaining a desired power generation

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in the latter in the event of faults. In addition, Kettunen et al. (2011) presented an active integrated fault-tolerant MPC for an industrial dearomatisation process. On the basis of the economic evaluation of just one feed grade, the annual estimated savings of the integrated FTMPC were predicted to be up to as much as USD 143,000.

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 plant process. FTMPC strategy is presented in Section 3. The test results are given in Section 4 and Section 5, followed by the conclusions in Section 6.

2. Description of the BioPower 5 CHP plant and its control strategy

In the BioPower 5 CHP plant, heat for electricity generation and a hot water network is obtained by direct combustion of solid biomass – bark and woodchips – which is fed into the BioGrate together with combustion air.

The essential components of the boiler are an economizer, an evaporator, a drum, and primary and secondary superheaters. Figure 1 illustrates the boiler of the BioPower 5 CHP plant. Feed water is pumped into the boiler from a feed water tank. The water is first run into the economizer (4), which is heated by means of flue gases.

From the economizer, the heated feed water is fed into the drum (5) and along downcomers into the bottom of the evaporator (6) 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 temperature of the steam is increased first in the primary and the secondary superheaters (7) before the superheated high-pressure steam (8) is led into a steam turbine, where electricity is generated.

2.1 Current control strategy of the BioPower 5 CHP plant

The main objective of the BioPower 5 CHP plant is to produce a desired amount of energy by keeping the drum pressure constant. This is achieved by controlling boiler power by managing the stoker speed, as well as the primary and secondary air intakes.

The fuel feed is controlled by manipulating the motor speed of the stoker screw to track the primary air flow measurement with required amount of primary air and secondary air for diverse power levels, specified by air curves. The set point of the secondary air controller is adjusted by the flue gas oxygen controller to provide excess air for combustion and enable the complete combustion of fuel.

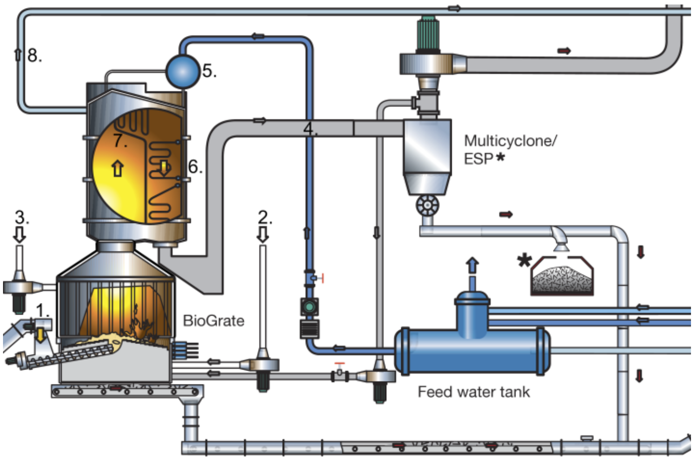

Figure 1: 1. Fuel, 2. Primary air, 3. Secondary air, 4. Economizer, 5. Drum, 6. Evaporator, 7. Superheaters, 8. Superheated steam

3. Fault Tolerant Model Predictive Control of the BioGrate boiler

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. The strong coupling between the primary and secondary air flows necessitates that the plant operates in a very narrow range of the air distribution. As a result, the amount of fuel on the grate needs to be strictly controlled around a set point, which can be done by using the fuel bed height sensor or by controlling the fuel bed height indirectly through the combustion power variable.

The overall structure of the FTMPC follows an active reconfiguration-based FTC scheme, relying on directly adjusting the controller itself by changing the controller structure though the parameter vector r_p . The controller reconfiguration-based FTC scheme is presented in Figure 2.

The proposed strategy of the BioGrate boiler uses controller reconfiguration-based FTC for the fuel bed height sensor fault where active FDD is utilized. The failure of the measurement is detected by calculating a root mean square error of prediction (RMSEP) index of the fuel bed height state values from two different control observers and comparing this value to a detection threshold:

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

where n is the number of the samples in the test data set, $\hat{x}_{i,1}$ is the estimated fuel bed height state of the first MPC configuration, and $\hat{x}_{i,2}$ the estimated fuel bed height state of the second MPC configuration. The two control observers are run in parallel with an input disturbance model for fault detection purposes and for smooth interconnection of the two controllers.

The proposed FTMPC consists of two different MPC configurations. The models of the first MPC configuration are structured as follows: The primary air flow rate and the stoker speed (u) are the manipulated variables; 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 (z).The models of the second MPC are configured as follows: The primary air flow rate and the stoker speed (u) are the manipulated variables; the moisture content in the fuel feed and the steam demand are the measured disturbances (d); and the combustion power and the steam pressure are the controlled variables (z).

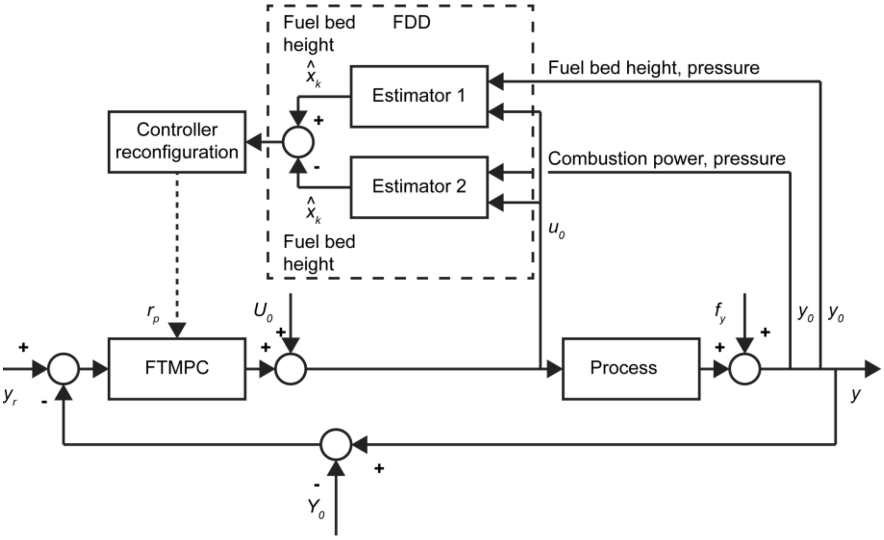

Figure 2: FTMPC of the BioPower 5 CHP plant

There is a direct relation between the combustion power and the fuel bed height controlled variables. Therefore, the fuel bed height can be controlled and the fault in the fuel bed height sensor can be detected through the combustion power variable. However, a variation in a fuel moisture content needs to be considered:

$$Q = q_{wf}\left(c_{thd}\dot{m}_{pa}\alpha_{thd} - c_h h\right) - 0.0244\dot{m}_{wev} \text{ [MJ/s]} \tag{2}$$

where q_{wf} is the effective heat value of the dry fuel (MJ/kg), c_{thd} is the thermal decomposition rate coefficient, m_{pa} is the primary air flow rate (m^3/s), α_{thd} is the coefficient for a dependence on the position of the moving grate, c_h is the fuel bed height coefficient, h is the fuel bed height (m), and $\dot{m}_{wev}$ water evaporation rate (kg/s).

The MPCs utilize the linear state space system (Maciejowski, 2002):

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + Ed_k \\ z_k &= C_z x_k \end{aligned} \tag{3}$$

where A is the state matrix, B is the input matrix, E is the matrix for the measured disturbances, and C_z the output matrix.

3.1 Regulator

The system of Eq(3) is formulated as:

$$z_k = C_z A^k x_0 + \sum_{j=0}^{k-1} H_{k-j} u_j \tag{4}$$

where H_{k-j} are impulse response coefficients. Therefore – using the Eq(4) the MPC optimization problem with input – the input rate of movement, and output constraints are:

$$\begin{aligned} \min\phi &= \frac{1}{2}\sum_{k=1}^{N}\left\|z_k - r_k\right\|_{Q_z}^2 + \frac{1}{2}\left\|\Delta u_k\right\|_S^2 \\ s.t. \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \; k = 0,1,\ldots,N-1 \\ z_k &= C_z x_k, \; k = 0,1,\ldots,N \\ & u_{\min} \le u_k \le u_{\max}, \; k = 0,1,\ldots,N-1 \\ & \Delta u_{\min} \le \Delta u_k \le \Delta u_{\max}, \; k = 0,1,\ldots,N-1 \\ & z_{\min} \le z_k \le z_{\max}, \; k = 1,2,\ldots,N \end{aligned} \tag{5}$$

where ϕ is the objective function, N is the prediction horizon, r_k :s are the target variables, Q_z is the tracking error weight matrix, S is the move suppression factor weight matrix, and the $\Delta u_k = u_k - u_{k-1}$.

4. Description of the simulation and testing environment

A simulation model of the BioPower 5 CHP plant was built in the MATLAB environment. In addition, 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 determined by using the data of the BioPower 5 CHP plant. Moreover the plant was further modified by installing 8 pressure sensors the BioGrate to measure the fuel bed height pressure.

5. Test results of the FTMPC strategy

In order to demonstrate the effectiveness of the proposed FTMPC strategy, the performance of the FTMPC was evaluated using BioPower 5 CHP plant 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.

In the test scenario, the power demand was changed from 12 MW to 16 MW at time step 200 s. The effect of a drift-shaped fault in the fuel bed height was tested with and without the FTMPC strategy active. An upward drift-shaped gradually increasing fault was introduced into the fuel bed height measurement, starting from the time step 500 s. Then, the power demand was changed from 16 MW to 12 MW during a time period of 800 – 1,000 s. As can be seen from the Figures 3-6, without the FTMPC the drift fault had the effect that both the primary air and the fuel bed height started to increase rapidly. With the FTMPC, both the primary air and the fuel bed height remained within their normal operation limits, thus improving the reliability of the control system. The fuel moisture content was changed at a time 700 s but it didn't affect the fuel height as it was estimated by fuel moisture soft-sensor.

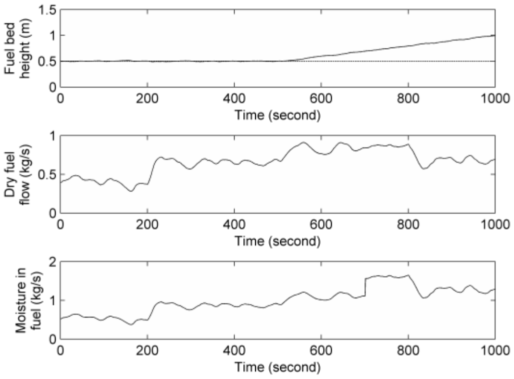

Figure 3: Reactions of moisture in fuel, dry fuel flow, and fuel bed height to drift fault in the fuel bed height sensor without the FTMPC active

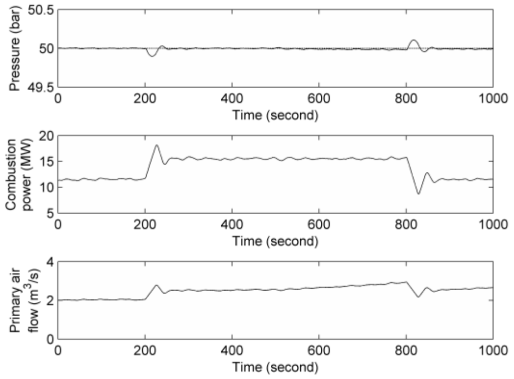

Figure 4: Reactions of pressure, combustion power, and primary air flow to drift fault in the fuel bed height sensor without the FTMPC active

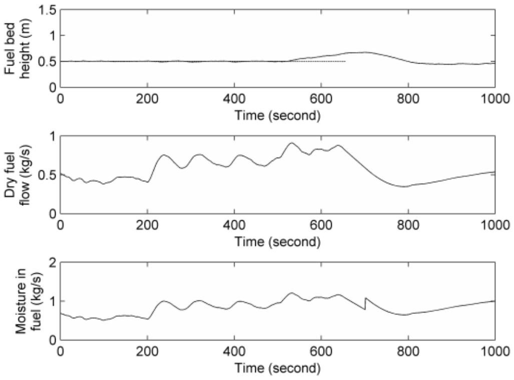

Figure 5: Reactions of moisture in fuel, dry fuel flow, and fuel bed height to drift fault in the fuel bed height sensor with the FTMPC active

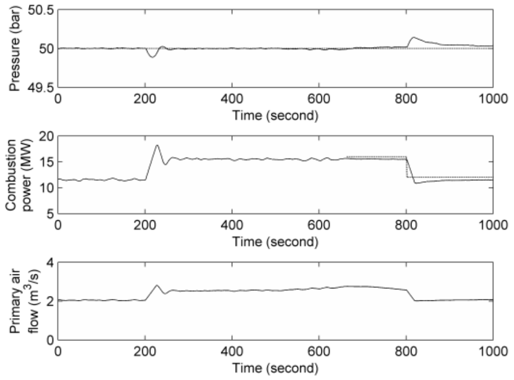

Figure 6: Reactions of pressure, combustion power, and primary air flow to drift fault in the fuel bed height sensor with the FTMPC active

Figure 7 shows RMSEP index of different fuel bed height state values of MPC 1 and MPC 2. The detection threshold value was chosen so – to be twice as high as the fuel bed height state differences caused by power demand changes in different MPC configurations.

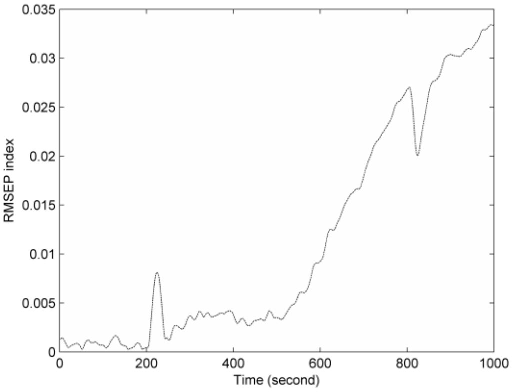

Figure 7: RMSEP index of fuel bed height state values of MPC 1 and MPC 2

6. 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.

References

Bauer R., Grölles M., Brunner T., Dourdoumas N. Obernberger I., 2010, Modelling of grate combustion in a medium scale biomass furnace for control purposes, Biomass. Bioenerg., 34(4), 417-427.

Boriouchkine A., Zakharov A., Jämsä-Jounela S-L., 2012, Dynamic modeling of combustion in a BioGrate furnace: The effect of operation paramets on biomass firing, Chem. Eng. Sci., 69(1), 669-678.

Grölles M., Reiter S., Brunner T., Dourdoumas N., Obernberger I., 2014, Model based control of a small-scale biomass boiler, Control. Eng. Pract., 22, 94-102.

Johansson R., Thunman H., Leckner B., 2007, Influence of intraparticle gradients in modeling of fixed bed combustion, Combust and Flame., 149(1-2), 49-62.

Kortela J., Jämsä-Jounela S-L., 2012, Fuel-quality soft sensor using the dynamic superheater model for control strategy improvement of the BioPower 5 CHP plant, J. Electr. Power Energy. Syst., 42(1), 38-48.

Zhang Y., Jiang J., 2008, Bibliographical review on reconfigurable fault-tolerant control systems, Annu. Rev. Contr., 32(2), 229-252.

Sourander M., Vermasvuori M., Sauter D., Liikala T., 2009, Fault tolerant control for a dearomatisation process, J. Process. Contr., 19(7), 1091-1102.

Jain T., Yamé J.J., 2013, A Novel Approach to Real-Time Fault Accommodation in NREL's 5-MW Wind Turbine Systems, IEEE Transactions on Sustainable ener., 4(4), 1082-1090.

Kettunen M., Jämsä-Jounela S-L., 2011, Data-Based, Fault-Tolerant Model Predictive Control of a Complex Industrial Dearomatization Process, Ind. Eng. Chem. Res., 50(11), 6755-6768.

Maciejowski J.M., 2002, Predictive Control with Constraints. Harlow, UK: Prentice Hal.