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Improvement of load-following capacity of grate boilers based on the combustion power soft-sensor

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Abstract

For improving the load-following capacity of existing grate boiler units, a model predictive control concept based on the combustion power soft-sensor is developed. Because the combustion power estimation has a very quick response to the primary air flow input, the load-following speed of the boiler control system will be improved considerably. The proposed model predictive control strategy is tested with the BioPower 5 combined heat and power plant data and the results are presented, analyzed, and discussed.

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Keywords: combustion; power; soft-sensor; grate; load; capacity

1. Main text

Renewable energy sources are considered on the priority level of energy policies in Europe and many other countries worldwide. The European commission has endorsed a mandatory target of a 20 % share of energy from renewable sources in overall consumption by 2020. This leads to an introduction of an increasing share of energy produced from natural resources, such as hydro power, wind, solar, wave, geothermal, waste fuels, as well as biomass and waste heat, into the existing energy networks. With more and more wind power and solar power units integration on power systems, there has been an increased demand on the load-following capabilities of the other power units.

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In [1], Wang et al. proposed an improved coordinated control strategy (CCS) combined with cold flow adjustment on account that cold source parameter has rapid and large influence on the turbine power output. The control strategy utilizes cold source flow adjustment (CSFA) to accelerate the load following capability, coal feeder rate to ensure the control accuracy of turbine load, and the turbine governor valve to avoid large fluctuation of main steam pressure. The simulation studies on the 300 MW unit showed that after 10 MW step order of turbine power is given, the turbine power with improved strategy reached its equilibrium state after about 7 seconds. However, it took over 50 seconds when using the traditional CSS. In addition, the improved strategy had a much smaller overshoot than traditional CSS.

Mortensen et al. [2] developed a control concept based on a scheduled linear-quadratic-Gaussian (LQG) controller with coordinated feedforward from the boiler load demand to fuel flow and feedwater flow for the purpose of improving the load-following capability of existing power-plant units. Field tests on the 265 MW coal-fired power plant unit revealed that the maximum allowable load gradient can be increased from 4 to 8 MW/min without further plant stress.

Wang et al. [3] developed a new method for the boiler control system based on radiation intensity for improving the load-following capacity of a coal-fired power plant. Field tests on a 300 MW coal-fired plant revealed that the improved boiler control system increased the load-following capacity. Also, indirect methods have been used to measure radiation intensity or combustion power in the furnace. According to the theoretical studies and practical tests by Kortela and Lautala [4] at the coal power plant, the fuel combustion power can be estimated on the basis of the measured oxygen consumption. The method assumed a constant fuel moisture content, although the relative ration of oxygen in flue gas is affected by the variation of the fuel moisture content, which introduces the error to the estimation.

Recently, the above mentioned combustion power method was improved by Kortela and Jämsä-Jounela [5] who estimated the fuel moisture content from the dynamic energy balance of the secondary superheater involving the combustion power estimation. Because the combustion power estimation has a very quick response of less than 1.5 minutes to the primary air flow input, the load-following speed of the boiler control system will be improved considerably.

In this paper an improvement of load-following capacity of BioPower 5 combined heat and power (CHP) plant is presented. The paper is organized as follows: Section 2 presents the BioPower 5 CHP process. The developed model predictive control (MPC) 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 transferred by the heat exchangers to the steam-water circulation, where superheated steam is generated [6].

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.

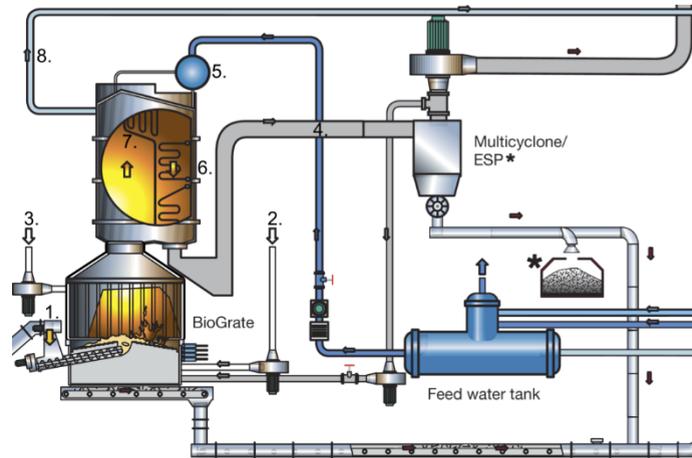


Fig. 1. 1. Fuel, 2. Primary air, 3. Secondary air, 4. Economizer, 5. Drum, 6. Evaporator, 7. Superheaters, 8. Superheated steam

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 [7].

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. Model predictive control for the BioGrate boiler

The objective of the MPC strategy is to improve the load following capacity of existing grate boilers. 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, the combustion power, and the steam pressure are the controlled variables (y). The MPC 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 [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 improves the load-following capacity of the boiler during the transitions. In addition, the thermal decomposition rate is used in the calculations of the fuel bed height. In order to design the MPC a sample data model of the process has been obtained by zero-order hold discretization with sampling time $T_s = 1$ s. Hence, from now on, we will refer to the following discrete-time system:

$$x_{k+1} = Ax_k + Bu_k + Ed_k \tag{1}$$

$$z_k = C_z x_k$$

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. The system of Eq(1) is formulated as:

$$z_k = C_z A^k x_0 + \sum_{j=0}^{k-1} H_{k-j} u_j \tag{2}$$

where H_{k-j} are impulse response coefficients. Therefore – using the Eq(2) the MPC optimization problem with input – the input rate of movement, and output constraints are:

$$\min \phi = \frac{1}{2} \sum_{k=1}^N \|z_k - r_k\|_{Q_z}^2 + \frac{1}{2} \|\Delta u_k\|_S^2$$

$$s.t. \quad x_{k+1} = Ax_k + Bu_k + Ed_k, \quad k = 0, 1, \dots, N-1$$

$$z_k = C_z x_k, \quad k = 0, 1, \dots, N \tag{3}$$

$$u_{\min} \leq u_k \leq u_{\max}, \quad k = 0, 1, \dots, N-1$$

$$\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, \quad k = 0, 1, \dots, N-1$$

$$z_{\min} \leq z_k \leq z_{\max}, \quad k = 1, 2, \dots, N$$

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 $\Delta u_k = u_k - u_{k-1}$.

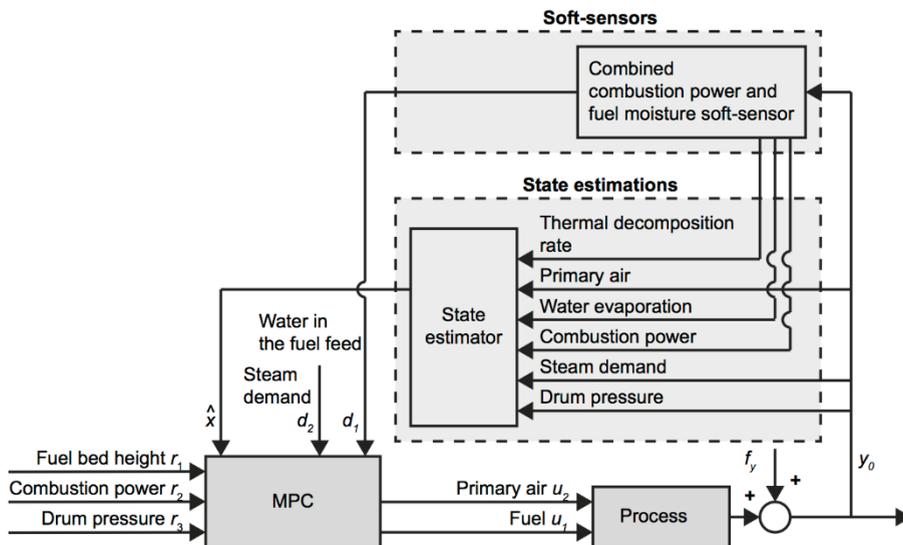


Fig. 2. Model predictive control of the BioGrate boiler.

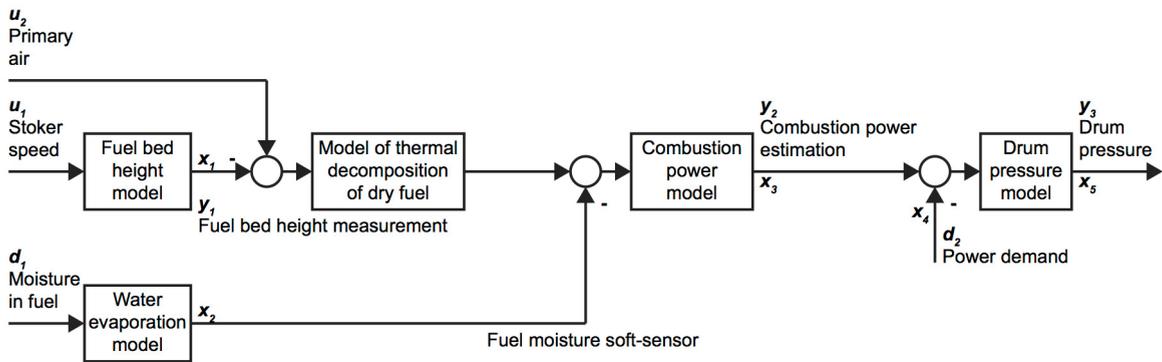


Fig. 3. The models of the BioGrate boiler.

4. Test results of the load-following capacity of the MPC strategy

4.1. Description of the simulation and testing environment

To test the load-following capacity of the developed MPC strategy, a simulation model of the BioPower 5 CHP plant was built and the code for the MPC was developed in MATLAB environment. 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.

4.2. Test results of the load-following capacity of the MPC strategy

The developed MPC strategy was compared with the conventional MPC strategy where the heat signal as a feedback signal is determined only by the steam pressure and the steam flow. 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 developed strategy, 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. In the conventional MPC strategy, the output limits were $y_{3,\min} = 0$, $y_{3,\max} = 55$ [bar] for the drum pressure.

Table 1. The time delays calculated using the Pearson cross-correlation function and the time constants of the first order transfer functions based on the estimated combustion power values and various measurements.

An example of a column heading	Time delay(s)	Time constant(s)
Moisture content in fuel flow, CP	1309	380
CP, drum pressure	0	1819
Primary air, oxygen content	50	N/A
Secondary air, oxygen content	36	N/A
Primary air, steam temperature	86	N/A
Secondary air, steam temperature	26	N/A

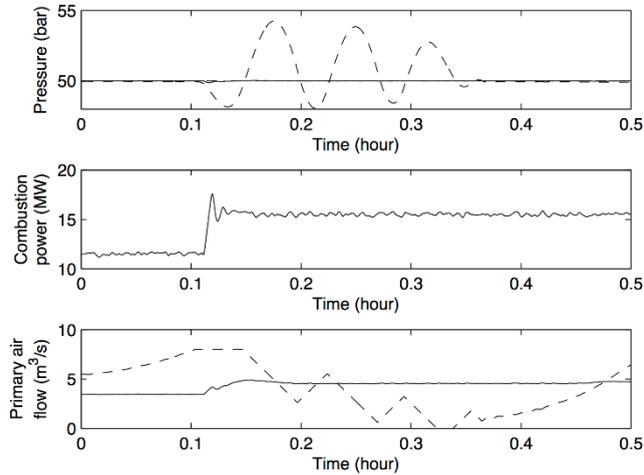


Fig. 4. The improved MPC control strategy (solid line) and the conventional control strategy (dashed line) responses for the change in steam demand.

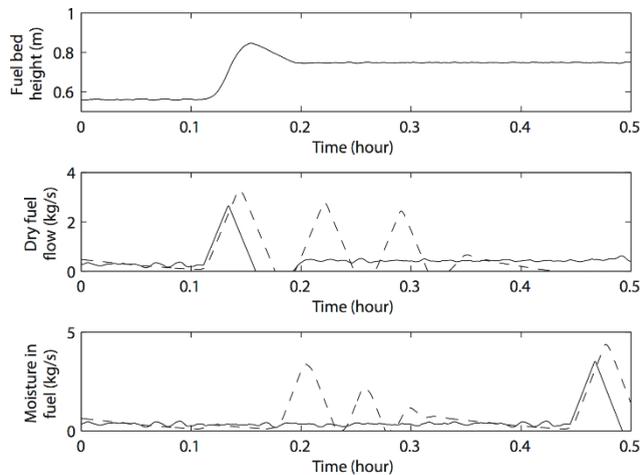


Fig. 5. The improved MPC control strategy (solid line) and the conventional control strategy (dashed line) responses for the change in steam demand.

In the simulation test, the steam demand was changed from 12 MW to 16 MW while the moisture content in the fuel feed was kept at 57 %. From the simulation curves Figs. 4-5 it can be seen that change in the steam demand had almost no effect on the drum pressure. However, it would take almost half an hour to make a new balance at 16 MW when using the conventional control strategy.

Table I shows the time delays calculated using the Pearson cross-correlation function and the time constants of the first order transfer functions based on the combustion power softsensor value and various measurements. The time delay and time constant between the measurement values of the fuel flow moisture and the measurement values of the evaporating moisture were 1309 seconds and 380 seconds respectively. The time constant between the

estimated combustion power values and the drum pressure measurements was 1819 seconds due to the large volume of the drum. On the other hand, the time delays between the measurements that are utilized to estimate the combustion power values are less than 90 seconds. Therefore, the utilization of the combustion power soft-sensor improves the load-following capacity of the grate boiler.

5. Conclusions

For improving the load-following capacity of existing grate boiler units, an MPC control concept based on the combustion power soft-sensor was developed. Based on the simulation results, significant improvements in the control of critical process variables were obtained during load changes. Because the combustion power estimation had a very quick response to the primary air flow input, the load-following speed of the boiler control system would be improved considerably. Due to the general applicability of the method, it could be used for similar processes and thus the same advantages could be achieved in other plants regardless of the fuels and burning methods used.

References

- [1] Wang W, Liu J, Zeng D, Niu Y, Cui C. An improved coordinated control strategy for boiler-turbine units supplemented by cold source flow adjustment. *Energy* 2015;88:927-34.
- [2] Mortensen JH, Moelbak T, Andersen P, Pedersen TS. Optimization of boiler control to improve the load-following capability of power-plant units. *Control Engineering Practice* 1998;6:1531-39.
- [3] Wang F, Huang Q, Liu D, Yan J, Cen K. Improvement of Load-Following Capacity Based on the Flame Radiation Intensity Signal in a Power Plant. *Energy & Fuels* 2008;22:1731-38.
- [4] Kortela U, Lautala P. A new control concept for a coal power plant. *Control Science and Technology for the Progress of Society* 1982;6:3017-23.
- [5] Kortela J, Jämsä-Jounela S-L. Fuel moisture soft-sensor and its validation for the industrial BioPower 5 CHP plant. *Applied Energy* 2013;105:66-74.
- [6] Boriouchkine A, Zakharov A, Jämsä-Jounela S-L. Dynamic modeling of combustion in a BioGrate furnace: The effect of operation parameters on biomass firing. *Chemical Engineering Science* 2012;69(1):669-78.
- [7] Yin C, Rosendahl LA, Kær SK. Grate-firing of biomass for heat and power production. *Progress in Energy and Combustion Science* 2008;34(6):725-54.
- [8] Kortela J, Jämsä-Jounela S-L. Modeling and model predictive control of the BioPower combined heat and power (CHP) plant. *International Journal of Electrical Power & Energy Systems* 2015;65:453-62.
- [9] Pannocchia G, Rawlings JB. Disturbance Models for Offset-Free Model-Predictive Control *AIChE Journal* 2003;49 (2):426-37.