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Linear MPC utilizing combustion power and fuel moisture soft-sensor for the BioPower 5 CHP plant

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Abstract

This paper presents a linear MPC for the BioPower 5 CHP plat. To enable the use of linear MPC, this method utilizes combustion power estimation in conjuction with the fuel moisture soft-sensor. The performance of the linear MPC is evaluated on the BioPower 5 CHP plant simulator. Finally, the results are presented, analyzed and discussed.

Keywords: biopower, fuel quality, MPC, moisture, control, power plant

1. Introduction

Increasing utilization of renewable energy has created new energy efficiency challenges in industry where biomass is one of the most important raw materials for renewable energy. Grate firing is one of the main technologies that are currently used in biomass combustion for heat and power production. Though the grate firing of biomass has been tried and tested over many years, there are still some problems for further studied, for instance, the conversion of biomass in the fuel bed on the grate, mixing in both the fuel bed and the freeboard, deposit formation and corrosion and their control, and pollutant formation and control (Yin et al. (2008)). One of the latest successful processes developed, which use wood waste as fuel, is a BioGrate boiler technology developed by MW Power. At the plant grate boilers are used as steam generation units to control a steam network. Rapid steam load changes necessitate good stability and load following properties in the system. Therefore, both drying and combustion in the grate must be controlled properly (Kortela and Marttinen (1985)). The main disturbances to the boiler are caused by fuel quality variations. Even for the same type of bio fuels, their chemical properties may differ greatly; for example – due to harvesting, storing and transporting conditions (Yin et al. (2008)). Compensating variations in the fuel quality plays thus a key role in a control of the combustion process.

As an early step for a control strategy development it has been essential to develop a method for estimating fuel flow as well as combustion power of the furnace. Referring to the theoretical studies and practical tests by Kortela and Lautala (1981) for a coal power plant, the fuel combustion power in the furnace can be estimated on the basis of the measured oxygen consumption. It is reported that the amplitude and the settling time of the response of the generator power decreased to about one third of the original when this cascade compensation loop was added to the present system.

The model-based predictive control has been used by Havlena and Findejs (2005) to enable tight dynamical coordination between air and fuel to take into account variations in power levels. The results showed that this approach could be used to increase boiler efficiency while considerably reducing the production of (NO_x) emissions. Similar results

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are also reported on an application of a local model networks (LMN) based multivariable long-range predictive control (LRPC) strategy for a simulation of 200 MW oil-fired drum-boiler thermal plant (Prasad et al. (1998)).

The fuel quality soft-sensor that utilizes combustion power and the energy balance of the boiler has been developed in (Kortela and Jämsä-Jounela (2010)). Based on the previous work of the authors, this paper sets forth to introduce a linear MPC using these previously developed methods. The paper is organized as follows. In Section 2, the BioPower 5 CHP plant process, the linear MPC and models of the boiler are presented. The process experiments with varying fuel quality and the diagnosis results are given in Section 3, followed by the conclusions in Section 4.

2. Linear MPC of Biopower 5 CHP plant

In the BioPower 5 CHP plant, the heat used for steam generation is obtained by burning solid biomass fuel: bark, sawdust and pellets, which are fed to the steam boiler together with combustion air. As a result combustion heat and flue gases are generated. The heat is then used in the steam-water circulation process.

In order to take into account fuel quality, thermal decomposition of dry fuel, water evaporation and drum pressure are chosen as states, primary air and fuel flow are manipulated variables, moisture in fuel feed is measured disturbance, and power of the boiler and drum pressure are the outputs of the system.

2.1. Plant

The plant is assumed to be a linear state space system

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

where x are states, u are manipulated variables (MVs), and d measured disturbances. z denote controlled variables (CVs).

2.2. Regulator

The process is described by linear time invariant state space model

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

where H_i are impulse response coefficients. Using the Equation (2), the regularized l_2 output tracking problem with input and output constraints is formulated as (Maciejowski (2002))

$$\begin{aligned} \min \phi &= \frac{1}{2}\sum_{k=1}^{N} \|z_k - r_k\|_{Q_z}^2 + \frac{1}{2}\|\Delta u_k\|_S^2 \\ s.t. x_{k+1} &= Ax_k + Bu_k + Ed_k, k = 0, 1, \ldots, N-1 \\ z_k &= C_z x_k, k = 0, 1, \ldots, N \\ u_{\min} &\leq u_k \leq u_{\max}, k = 0, 1, \ldots, N-1 \\ \Delta u_{\min} &\leq \Delta u_k \leq \Delta u_{\max}, k = 0, 1, \ldots, N-1 \\ z_{\min} &\leq z_k \leq z_{\max}, k = 1, 2, \ldots, N \end{aligned} \tag{3}$$

The vectors Z, R, U, and D are defined as

$$Z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_N \end{bmatrix} R = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_N \end{bmatrix} U = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix} D = \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_{N-1} \end{bmatrix} \tag{4}$$

and the predictions by the Equation (2) are expressed as

$$Z = \phi x_o + \Gamma U + \Gamma_d D \tag{5}$$

ϕ, Γ and Γ_d are assembled as

$$\phi = \begin{bmatrix} C_z A \\ C_z A^2 \\ C_z A^3 \\ \vdots \\ C_z A^N \end{bmatrix} \Gamma = \begin{bmatrix} H_1 & 0 & 0 & \dots & 0 \\ H_2 & H_1 & 0 & \dots & 0 \\ H_3 & H_2 & H_1 & & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ H_N & H_{N-1} & H_{N-2} & \dots & H_1 \end{bmatrix} \tag{6}$$

$$\Gamma_d = \begin{bmatrix} H_{1,d} & 0 & 0 & \dots & 0 \\ H_{2,d} & H_{1,d} & 0 & \dots & 0 \\ H_{3,d} & H_{2,d} & H_{1,d} & & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ H_{N,d} & H_{N-1,d} & H_{N-2,d} & \dots & H_{1,d} \end{bmatrix} \Lambda = \begin{bmatrix} -I & I & 0 & 0 & 0 \\ 0 & -I & I & 0 & 0 \\ 0 & 0 & -I & I & 0 \\ 0 & 0 & 0 & -I & I \end{bmatrix} \tag{7}$$

For the case $N = 6$, the matrices Λ is

$$Q_z = \begin{bmatrix} Q_z & 0 & 0 & 0 \\ 0 & Q_z & 0 & 0 \\ & & \ddots & \\ 0 & 0 & & 0 \\ 0 & 0 & 0 & Q_z \end{bmatrix} H_S = \begin{bmatrix} 2S & -S & 0 & 0 & 0 \\ -S & 2S & -S & 0 & 0 \\ 0 & -S & 2S & -S & 0 \\ 0 & 0 & -S & 2S & -S \\ 0 & 0 & 0 & -S & 2S \end{bmatrix} M_{u_{-1}} = - \begin{bmatrix} S \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

Then the objective function is expressed as

$$\begin{aligned} \phi &= \frac{1}{2}\sum_{k=1}^{N} \|z_k - r_k\|_{Q_z}^2 + \frac{1}{2}\|\Delta u_k\|_S^2 \\ &= \frac{1}{2}U'HU + g'U + \rho \end{aligned} \tag{9}$$

where

$$H = \Gamma' Q_z \Gamma + H_S \tag{10}$$

$$g = \Gamma' Q_z \phi x_0 - \Gamma' Q_z R + M_{u_{-1}} u_{-1} + \Gamma' Q_z \Gamma_d D \tag{11}$$

The MPC regulator problem Equation (3) can be solved by the solution of the following convex quadratic program

$$\begin{aligned} \min_U \psi &= \frac{1}{2}U'HU + g'U \\ U_{\min} &\leq U \leq U_{\max} \\ \Delta U_{\min} &\leq \Lambda U \leq \Delta U_{\max} \\ \bar{Z}_{\min} &\leq \Gamma U \leq \bar{Z}_{\max} \end{aligned} \tag{12}$$

2.3. Models of the boiler

Bauer et al. (2010) showed that the overall effect of the primary air flow rate on the thermal decomposition rate is multiplicative. Therefore, the thermal decomposition of dry fuel is as follows

$$\frac{dm_{ds}}{dt} = -\alpha_{thd} * m_{ds} + m_{ds,in}(t - T_d) + \alpha_{pa} * m_{pa} \tag{13}$$

where α_{thd} is decomposition rate coefficient of fuel flow, and α_{pa} decomposition rate coefficient of primary air flow. Water evaporation is

$$\frac{dm_w}{dt} = -\alpha_{wev} * m_w + m_{w,im}(t - T_d) \tag{14}$$

where α_{wev} is dimensionless scaling factor. The linear model for the pressure is presented by Åström and Bell (2000). The combustion power and fuel-quality soft-sensor are described detailed in (Kortela and Jämsä-Jounela (2010)) and (Kortela and Jämsä-Jounela (2012)).

3. Test results

The performance of the MPC is evaluated on the BioPower 5 plant simulator. The integrator of the MPC is disabled in order to see the affect of the fuel moisture soft-sensor. Initially, the power demand of the boiler is 18MW. The power demand is changed to 16MW at a time step 500 seconds and back to 18MW at time step 700 seconds. The power demand and the actual power match really well due to both states, thermal decomposition rate of fuel and evaporation rate of water, are estimated. To compare, there is a offset in the results where the MPC assumes that moisture content is constant. The moisture content of fuel is initially 1.3 kg/s. At a time step 250 seconds it is changed to1.8

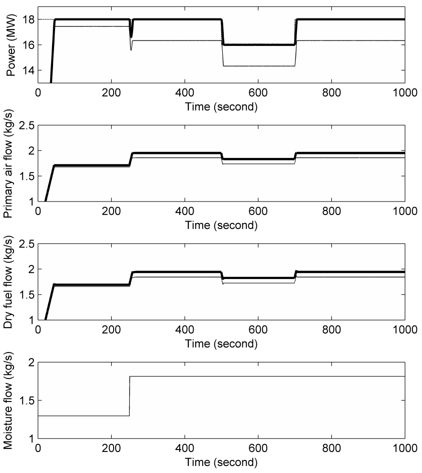

Figure 1. The simulation results of the MPC with both fuel flow estimation and fuel moisture soft-sensor (thick line), and the MPC with only fuel flow estimation (thin-line).

kg/s. The actual power of the boiler has small cap due to change rate constraints of fuel feed and primary air.

4. Conclusions

The linear MPC for the BioPower 5 CHP plant was presented in this paper. To enable the use of linear MPC, this method utilizes combustion power estimation in conjuction with the fuel moisture soft-sensor. The test results show that the power demand and the actual power match really well when the both states, thermal decomposition rate and evaporation rate of water, are estimated.

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