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TIME DELAY COMPENSATING CONTROL OF FLUE-GAS OXYGEN-CONTENT IN FBB

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ABSTRACT

Flue-gas oxygen-content control is an important way to decrease emissions and increase thermal efficiency in fluidized bed boilers (FBB). Oxygen-content control is also stabilizing the burning process leading to more stable steam and electricity production. The oxygen-content is controlled normally by PI-controller. PI-controller is tuned to have a slow control performance, because of long time-delay in the burning process. In this paper, a robust delay compensating controller, filtered Smith-predictor, is used to improve the oxygen-content control performance Delay-compensating controller needs a model of the controlled process. For fluidized bed boilers, an accurate model is impossible to make because of unmeasured variation of fuel properties. The robust stability criterion is used to examine how robust the proposed control system is against modeling errors. Filtered Smith-predictor is compared to the PI-controller by simulations.

KEY WORDS
energy production, delay-compensation, boilers, control

1. Introduction

Biomass fuels (like wood) and peat, are important energy sources in the Finnish energy production. The intensive use of the mixture of such energy sources can be explained by a) the increasing demand of using domestic fuels (*e.g.* peat), b) the thermal utilisation of the high caloric-value paper-industry by-products (wood chips, sawdust, bark) which would be waste and c) diverting municipal solid wastes from landfill.

In fluidised bed boilers, low flue gas emission levels can be achieved and various types of solid fuels can be used either separately or mixed with each other. However, process disturbances such as variations in fuel feed rate and fuel quality lead to performance degradation and offset the advantage of having low-level average emission. It has been observed that increasing rate of municipal wastes in mixtures with biomass-fuels increases the probability for disturbances. One possible way to compensate the disturbance and stabilise the burning process is updating/improving the boiler's control system. It is also one of the economically and technically most feasible solutions.

Flue-gas oxygen-content control is an important way to decrease flue-gas emissions and maximize the thermal efficiency of a boiler in the stabilization level. The purpose of the oxygen-content control is to keep the measured oxygen-content close to its setpoint. There is an optimal setpoint for the content which can be defined using flue-gas losses and CO-losses as well flue-gas emissions. Decreasing the oxygen-content, thermal flue-gas loss decreases linearly and CO-loss increases exponentially. The optimal setpoint is dependent also on the load of a boiler, and the setpoint is usually slided ground on the load [1].

At the power plants, the flue-gas oxygen-content is controlled normally by PI-controllers. There is a significant delay between oxygen control signal and the oxygen measurement. Because of the delay, the PI-controller is tuned to have slow control performance to ensure stability of the system. PI-controller has problems to compensate the disturbances fast enough because of the tuning. If oxygen-content drops below a certain limit plant shutdown happens. To prevent the shutdown, the oxygen-content setpoint is usually set higher than the optimal setpoint would be. With a delay compensating controller, the performance of the oxygen-content control system can be improved and the oxygen-content setpoint can be lowered nearer to the optimum point. Another benefit is that the variation of the oxygen-content around the setpoint is decreasing. The benefits are resulting lower emissions, better thermal efficiency, more stable steam and electricity production and faster responses for power level changes.

A delay-compensating controller needs a model of the controlled process. The burning process is a nonlinear multivariable process with cross-effects and stochastic disturbances. For example, the fuel quality (humidity, consistency and heat value) is changing continuously despite the volumetric fuel flow is kept constant. Thus, it is difficult to make a model of the process which can describe the oxygen-content accurately. Therefore, a delay-compensating controller which is robust against modeling error is needed.

Normey-Rico et al. [2] have introduced a filter for IMC controller to improve stability of a system with high frequency modeling errors. In this paper, the same filter is used for Smith-predictor. A simulator of a 185 MW bubbling fluidized bed boiler was used to test the control performances of filtered Smith-predictor and PI-controller. The same simulator was earlier used to tune the oxygen control system of a power plant. More accurate description of the simulator can be found from [3] and [8].

2. Plant and control system description

The schematic picture of a bubbling fluidized bed (BFB) boiler is presented on the Fig. 1. The figure is modified from [4]. The fluidized bed is kept floating by primary air, which is fed from the bottom of the boiler. Secondary air is fed from the walls of the boiler to burn volatile components of fuel. Fuel is fed to the bed. The heat released during the burning process is used to heat feed water from water to steam. Steam pressure controller controls the amount of fuel and air to produce the needed power. Flue-gas oxygen content control is used to ensure that the burning process has always enough burning air.

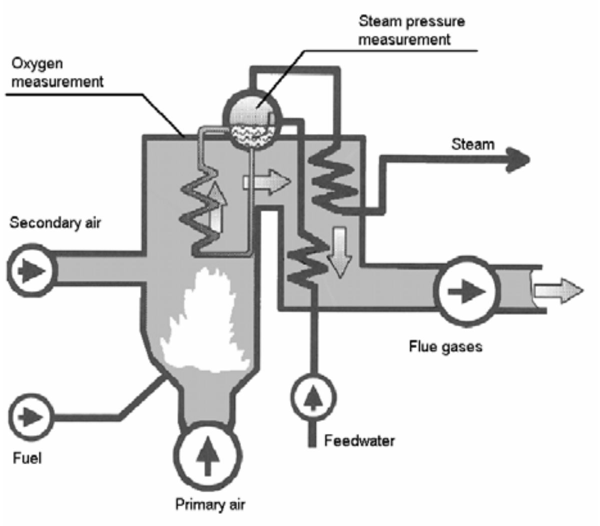

Fig. 1. Schematic picture of a BFB boiler. Modified from [4].

A block diagram of oxygen-content control system with delay compensation is presented on Fig. 2. The main amounts of fuel and air are determined by the steam pressure controller. The flue-gas oxygen-content control signal is used to correct the amount of secondary air of the boiler. The output of the controller is limited for example between 0.7-1.3 and it is multiplied with the secondary air setpoint. The flue-gas oxygen-content control is actually fine-tuning of the ratio of fuel and air. This ratio is changing all-the-time because of the variation of energy-content in the fuel flow. The delay compensator is used to modify the oxygen-content measurement signal.

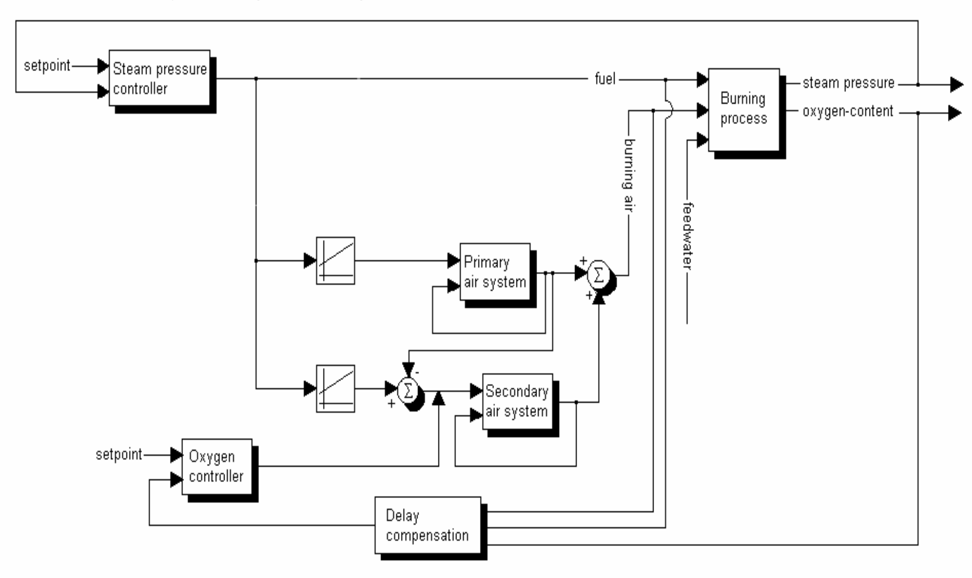

Fig. 2. Simplified oxygen-content control structure.

3. Delay-compensating controllers

A basic Smith-predictor structure was chosen for the application. Smith-predictor can be installed to power plant's automation system quite easily. The traditional PI-controller is one part of the controller and operators have possibility to tune the controller manually by trial-and-error methods. A drawback of the Smith-predictor is the amount of parameters to determine. There are Smith-predictor-based dead-time compensating controllers such as IMC- and PPI-controllers, which have less parameters to tune. On the other hand, these controllers have restrictions on the process model, which can be a drawback in the sense of control performance [5]. With the simulator, it is possible to tune the filtered Smith-predictor quite easily despite of the amount of parameters to tune.

Filtered Smith-predictor control scheme is presented in Fig. 3, where C is a PI oxygen controller, G_{Air} is the nonlinear model of the secondary air system (including its own control loops), P_n is the nominal combustion process model, G_n is the delay free model of the combustion process, P is the "true" model of the combustion process and $F(s)$ is a filter, and d_2 is the dead-time of the combustion process. The P, P_n and G_n are nonlinear MISO models, including a linear transfer functions, and a nonlinear MISO characteristics. The control input is the air flow (M_{air}), while the fuel (M_{fuel}) acts as a disturbance.

Compared to the original Smith-predictor structure, the controller is extended with the filter proposed by Normey-Rico *et al* [2]. This filter improves the robustness of the system at a desired frequency region.

The *F(s)* filter is typically a unity gain, one parameter low-pass filter and it has been proven to be sufficient for control design by Normey-Rico *et al.* [2] and Ingimundarson and Hägglund [7]. There is another extension as well: the predictor uses a MISO process model. Introducing the fuel flow signal into the predictor, a feed-forward action is incorporated into the control structure. A robust stability criterion can be used to examine the effect of modeling error to the stability of a system in different frequencies. This criterion will be discussed next.

4. Robust stability criterion

The robustness of the control loops is nowadays a fundamental requirement. The robustness analysis has even more importance in case of model predictive applications, where the predictor includes the nominal process model. In this paper, the robust stability criterion based on Nyquist stability criterion is used for stability analysis. The details for the criterion can be found from [6].

Based on the Nyquist stability criterion, it is possible to derive a robust stability limit for a control system described by the open-loop transfer function *C(s)Y(s)*, where the *C(s)* is the controller and *Y(s)* is the nominal process model. The behaviour of the process is assumed to be described by a family of linear models from now on.

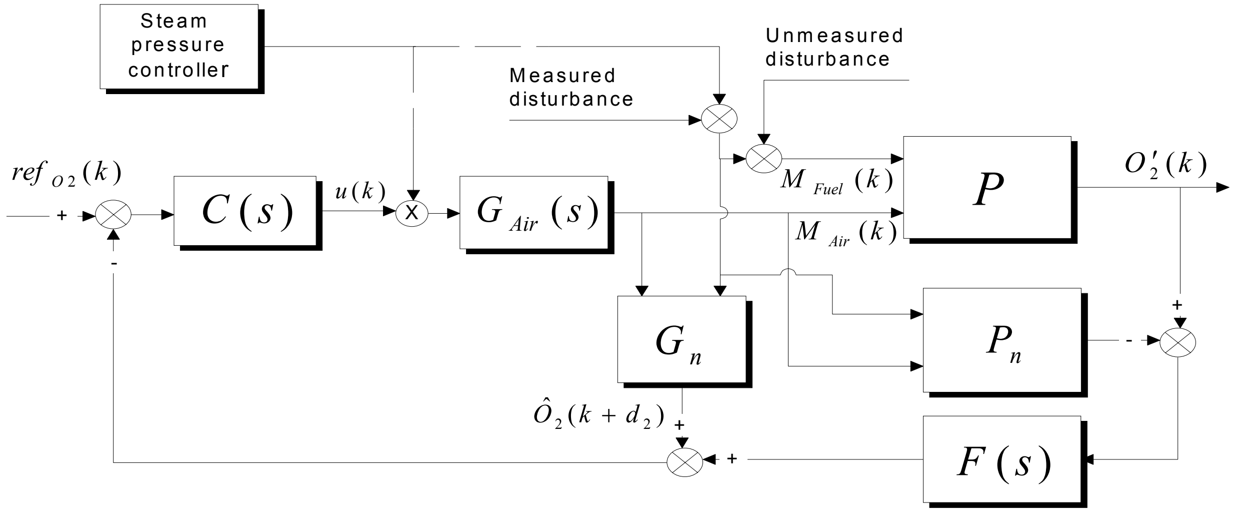

Fig. 3. The Smith predictor based control scheme of the BFBB. The dashed signal flow represents further signal conditioning.

Applying the additive uncertainty description any member of the family satisfies the equation:

$$P(j\omega) = P'_n(j\omega) + L_a(j\omega) \tag{1}$$

$$\text{with } |L_a(j\omega)| < |\bar{L}_a(\omega)| \tag{2}$$

where: $L_a(j\omega)$ is the additive error and
$\bar{L}_a(\omega)$ is the bound on the additive error.

Morari and Zafirou [6] showed that the robust stability boundary can be defined as:

$$|\bar{L}_a(\omega)| < \left|\frac{1 + C(j\omega)Y(j\omega)}{C(j\omega)}\right| \qquad \forall\omega \tag{3}$$

The robust stability boundary for the Smith-predictor was presented by Normey-Rico [2], where the *Y(s)* is the delay-free nominal process model. It shows an important feature that the robust stability boundary is independent of the delay of the nominal model. For the filtered Smith-predictor, the stability criterion is as follows:

$$|\bar{L}_a(\omega)| < \left|\frac{1 + C(j\omega)Y(j\omega)}{F(j\omega)\cdot C(j\omega)}\right| \qquad \forall\omega \tag{4}$$

The robust stability boundary of the oxygen control loop with the filtered Smith predictor is given in the following form:

$$|\bar{L}_a(\omega)| < \left|\frac{1 + C(j\omega)\cdot G_{Air}(j\omega)\cdot G_n(j\omega)}{F(j\omega)\cdot G_{Air}(j\omega)\cdot C(j\omega)}\right| \qquad \forall\omega \tag{5}$$

The calculated robust stability limits of the control loop are shown in Fig. 4 with different filter time constants. The modelling error is also illustrated in case where the nominal model has -10% errors in both gain and time-delay.

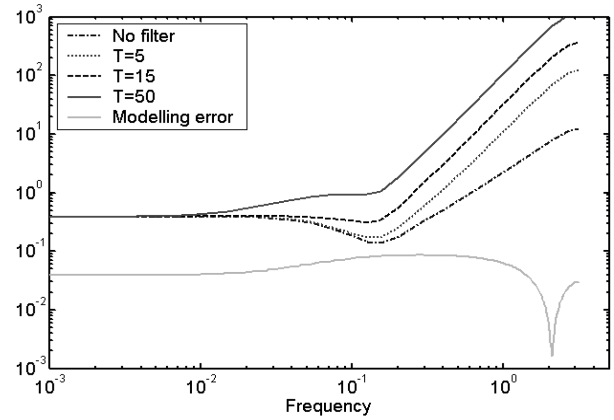

Fig. 4. Robust stability boundary for filtered Smith predictor

From Fig. 4 it can be clearly seen, that increasing the filter time constant results in more robust control loop, which has especially importance at mid-frequencies where the modelling error is close to the robust stability limit. On the other hand, the filter time constant has an opposite effect to the control performance of the system. In practise filter time constant should be chosen as small as possible but large enough to ensure stability of the system. This can be done by plotting the largest possible modelling error and then finding a suitable filter time constant to get the stability limit above the modelling error for all frequencies.

5. Simulation results

The Smith predictor and PI controller were compared with several simulations. The parameters of the controllers' were optimized based on ITAE criterion. The perfect model for Smith predictor was used during the optimization. The filter time constant of the filtered Smith predictor was chosen to be 15 s. Choice was based on the variation of the process properties (gain and delay) of the real process. The simulations were made using 30% load level of the boiler, because the nonlinearities of the processes are steepest around this level.

Unmeasured (t=100, t=1600s) and measured (t=600 s, t=2100 s) disturbances (see Fig. 5) were introduced in the simulations. The feed forward connection of the filtered Smith-predictor can utilize the measured disturbances. The power level of the boiler was changed +5 MW at time step t=1100 s. The reference value of O_2 content was set to be 4 %. The results of the simulation are shown in Fig. 5.

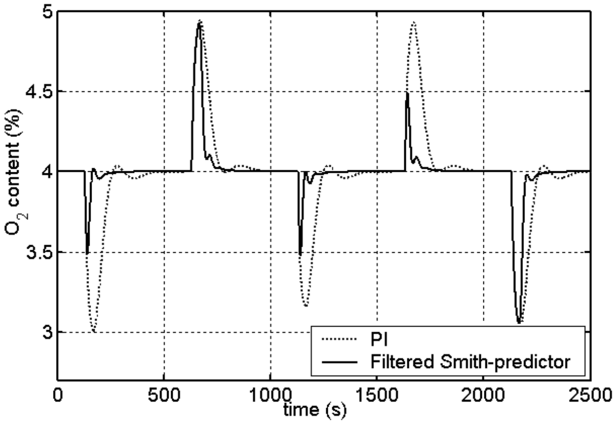

Fig. 5. The controllers' performances with perfect model matching.

As it was expected, improvement was achieved by the filtered Smith predictor compared to the original PI controller for all types of disturbances. The improvement is relatively small for unmeasured disturbances, because the disturbances enter to the Smith-predictor after a delay of the process. The small improvement in control performance is due to the faster tuning, which is allowed for the Smith-predictor. The power level change (at t=1100 s) caused deviation from the setpoint because the air curve (ratio of amounts of fuel and air in certain power level) was not exact, which is a normal situation in boilers. The feedforward connection helps to correct faster the deviations caused by power level changes. The changes are daily in the boilers, which are producing steam to the paper plants.

To further explore the performances of the controllers, operational conditions were simulated: the main steam control signal, fuel flow, the air flows except the secondary air flow were taken from measured data belonging to the load level shown in Fig. 6. Additional disturbance was generated to approximate the fuel quality changes. The control performances of the PI-controller and Smith-predictor are compared in Fig. 7.

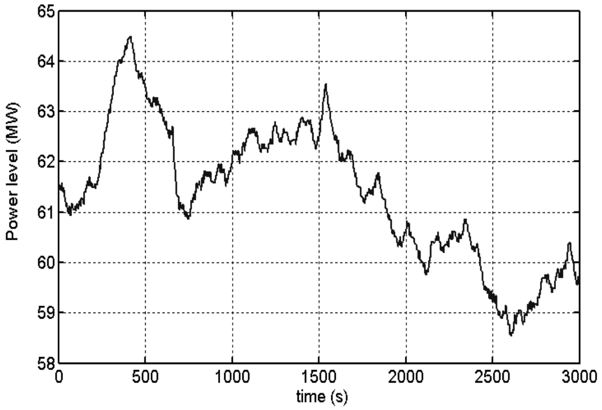

Fig. 6. The applied power level in the simulation.

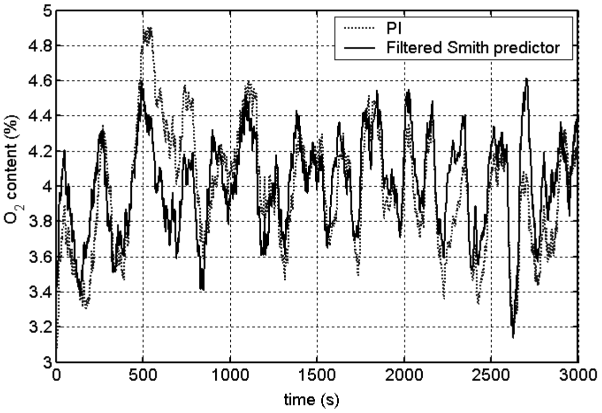

Fig. 7. The controllers' performances on measurement data.

The presented results in Fig. 7 are not conclusive. Therefore the average absolute errors are used to distinguish the three different performances, which were in case of the PI controller 0.33 and in case of filtered Smith predictor 0.234.

The robustness against modeling errors are presented in the final two simulations. In first simulation (Figs. 8 and 9), the process delay is 1.3 times larger than the delay in the nominal model.

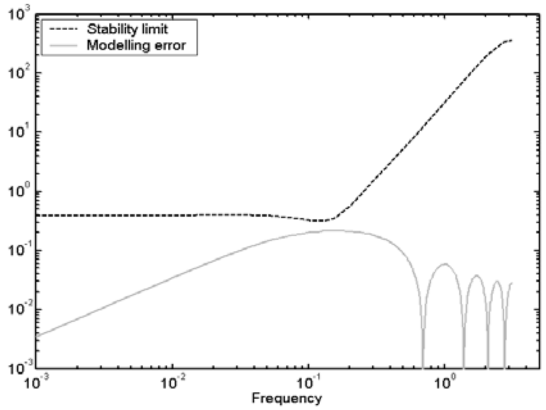

Fig. 8. Robust stability boundary and modeling error in case of pure delay error.

Based on robust stability boundary (Fig. 8), the Smith-predictor is satisfactory in the sense, that the modeling error does not exceed the stability limit. The behaviors of the control loops are presented in Fig. 9.

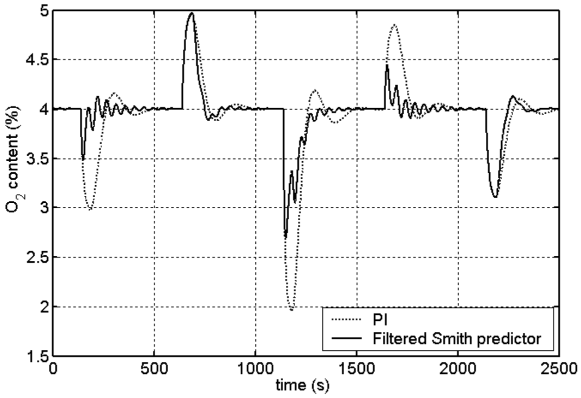

Fig. 9. Control performances in case of pure delay error.

The control loops are still stable, but compared to Fig. 5 it can be easily observed that the control performance largely degraded because of the modeling error. The PI controller does not result in such a heavy oscillation as the filtered Smith predictor.

In the second simulation (Figs. 10 and 11), the real combustion process has 1.3 times higher gain and 1.3 longer delay as in the nominal model.

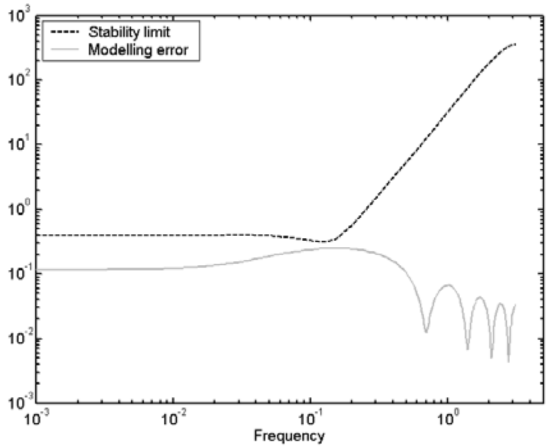

Fig. 10. Robust stability boundary and modeling error in case of gain and delay errors.

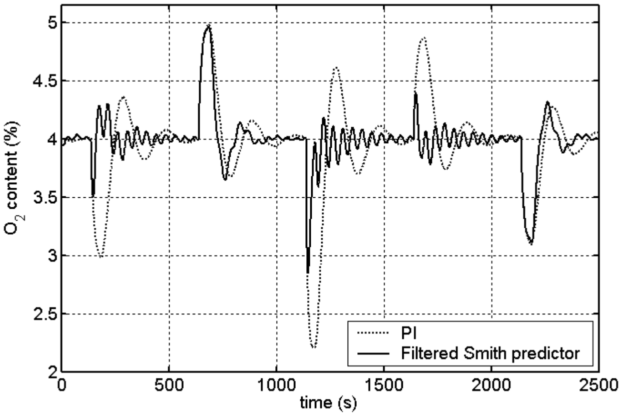

Fig. 11. Control performance in case of gain error and delay error.

The modeling error is still under the limit, but the responses for the disturbances are badly damped. If this case was reasonable in power plant, the retuning of the both control systems would be recommended.

6. Conclusion

Control performance of a Smith-predictor based control system is significantly better than it is for PI-controller for boiler's oxygen control system. With faster and more accurate control, it is possible to decrease the flue-gas oxygen setpoint nearer the optimum without risking the safe operation. Also the oxygen content variation around the setpoint is decreasing. The natural consequence of these results is an improvement in the boilers' thermal efficiency, decrease of the flue gas emissions and more stable steam/electricity generation.

Based on simulations, the filtered Smith-predictor was stable in the normal operating conditions of a BFBB. The simulations were done for both delay and gain errors. Robust stability criterion was used to examine the stability of the system during modeling errors. It is also useful in choosing appropriate filter time constant for filtered Smith-predictor.

The filtered Smith-predictor is modifying the measurement signal of a PI-controller. Thus, it is quite easy to implement to real plant. Also operator's can accept the new control structure easier, because the same tuning rules are valid as for a PI-controller. In the future, the filtered Smith-predictor will be implemented in a real application.

7. Acknowledgement

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