Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 2, 2017, vol. LXIII
article No. 2033

Radim HÝL[*], Renata WAGNEROVÁ[**]

MPC CONTROL FOR SUPERHEATED STEAM TEMPERATURE

PREDIKTIVNÍ ŘÍZENÍ TEPLOTY PŘEHŘÁTÉ PÁRY

Abstract

This contribution deals with design and implementation of control system for superheated steam temperature, which is most often carried out by injection of the feed water. In the proposed control system, a common cascade control system is replaced by a predictive controller. This can quickly respond to rapid and unpredictable changes in steam consumption. The accuracy of the predictive controller design has been verified not only by digital simulation but directly in real process. The quality of the newly designed controller was compared to the originally implemented cascade control.

Abstrakt

Článek se zabývá návrhem a realizací regulačního obvodu pro řízení teploty přehřáté páry, která je dnes nejčastěji prováděna vstřikem napájecí vody. V navrženém regulačním obvodu je běžný rozvětvený regulační obvod s pomocnou regulovanou veličinou nahrazen prediktivním regulátorem. Tím lze rychle reagovat na rychlé a nepředvídatelné změny ve spotřebě páry. Správnost návrhu prediktivního regulátoru byla ověřena nejen pomocí číslicové simulace, ale přímo v běžném provozu. Kvalita řízení nově navrženého regulátoru byla porovnána s původně implementovaným kaskádovým řízením.

Keywords

Predictive control, internal model, superheater, MPC, PLC

1 INTRODUCTION

Predictive control (MPC) is one of the most modern control methods, which is widely used in various areas of industry. For calculating future values of action interventions, the knowledge of the discrete mathematical model of the controlled system is used, which also serves to obtain the future responses of the system to the given set-point signal. The advantage of predictive control over other approaches is that the future value of the set-point is considered when calculating the action (controller output) and the optimization criterion, also called the cost function, is taken into account. From the calculated sequence of action interventions, only the first value is applied in the given step and in the next step the whole calculation procedure is repeated, the so-called moving horizon strategy. One of the advantages of predictive control is the possibility of including limitations on the range of input, state or output variables (temperatures, pressures, valve positions, temperature gradients, etc.) directly into the calculation of action interventions. Thanks to this, the quality of the

---

[*] Ing., Department of Control Systems and Instrumentation, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, 17. listopadu 13, Ostrava, tel. (+420) 59 732 1280, e-mail radim.hyl.st1@vsb.cz

[**] doc. Ing. Ph.D., Department of Control Systems and Instrumentation, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, 17. listopadu 13, Ostrava, tel. (+420) 59 732 4113, e-mail renata.wagnerova@vsb.cz

control is higher than that of the PID controller. The MPC controller is basically design as multidimensional and worked with a larger number of controls and controlled variables. For this reason, the deployment of internal-based control methods in the industry continues to grow, see [1]. In [2], MPC is used to control the waste incineration process and [3] in industrial biomass combustion plants.

2 DESCRIPTION OF CHOSEN TECHNOLOGY - BIOMASS POWER PLANT

An important renewable energy source is biomass that houses solar energy. The oldest method of obtaining energy from biomass is combustion. The highest efficiency is achieved from biomass when used for heat production - more than 90%. Very often, biomass is used in cogeneration - combined heat and power (50-90% efficiency). In pure electricity production, the efficiency is below 50%. [4], [5]

Based on previous experience, it can be expected that the largest use of biomass will also be associated in the future with decentralized sources of smaller output, especially with cogeneration units. The cogeneration units operate on a simple principle of combustion as in a coal power plant. Biomass-based chemical energy is converted to thermal energy by a common combustion process in the boiler. This is then transformed through the kinetic energy of steam into the mechanical energy of rotation and that of the electric energy. Heat-carrying medium is common steam produced in the boiler. The steam is fed to a turbine which is mechanically connected by a common shaft with an electric generator. The mechanical energy of the rotation is then transferred by means of the generator to the electrical energy that is transferred to the electricity grid. The heat, not used for water heating, usually serves to heat and warm hot service water.

2.1 The superheated temperature control

At present, the most widely used flow-through boiler can be presented in a simplified form as a pipe in which the water is converted into steam, and this adds additional energy to the superheaters. The steam superheater is actually a flow-through heat exchanger where one medium is a steam and the other medium (heating) is usually flue gas.

The boiler is constructed and operated in such a way that the change from water to steam occurs before the superheaters and only steam flows. The parts before and behind the key element of the boiler (evaporator) are first used by the economiser, which is commonly located in the rear part. Evaporator tubes are usually included along all the walls of the boiler furnace where the flue gas has the highest temperature. Then the superheaters are located and supply the steam with enough energy that is ultimately usable on the turbine. The injection valves in the superheater section control the output temperature of high-pressure steam. The steam passes on energy to turbine and the temperature and pressure will be lost. [6]

The most common way to control steam temperature is to regulate the steam temperature by injection of water. It has the lowest realization costs because the steam is cooled with water in the heat exchanger, which is part of the connecting steam pipe as in Fig. 1.

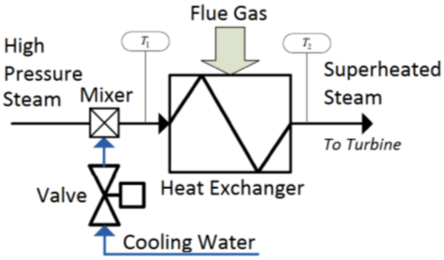


Fig. 1 Schema of steam superheater

2.2 Internal model identification

As has been mentioned above, the most common way of control steam temperature is now the regulation of injection water supply. This technology was also installed in a heating plant for which predictive control was proposed. The original steam temperature control system was arranged according to Fig. 2.

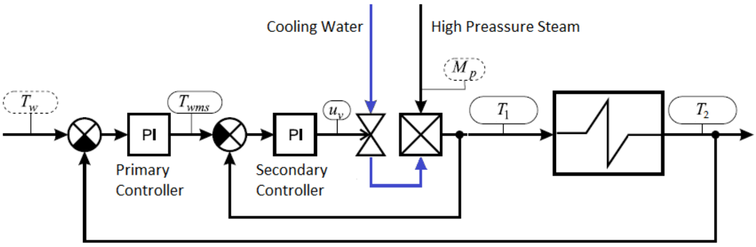
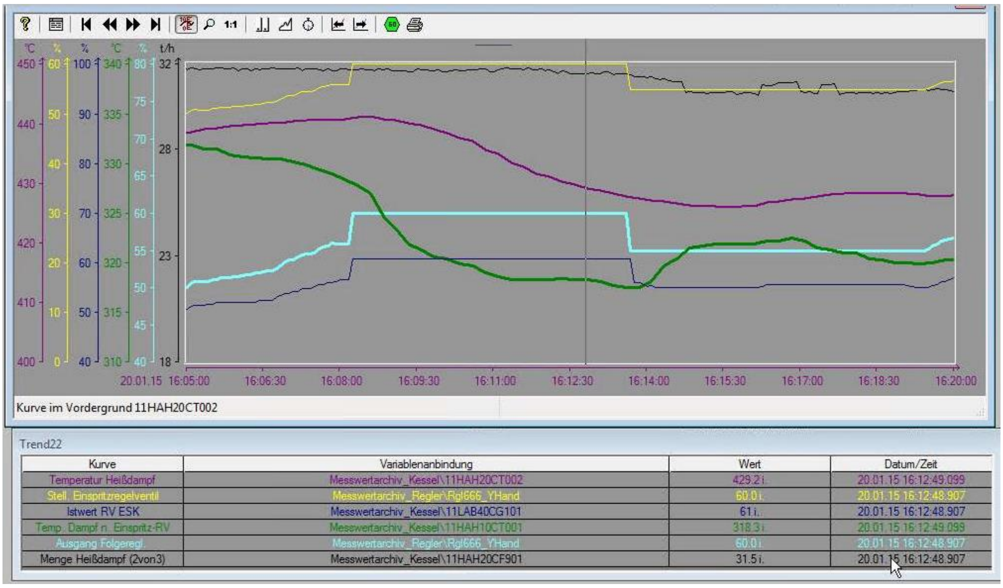


Fig. 2 Schema of cascade control system

The controlled variable is the steam temperature T_2 behind the superheater. The master controller handles the control error (T_w-T_2) and is usually of the PI type, sometimes even the PID is used, although this control quality improves little. Because the temperature change transmission T_2 (beyond the superheater) is dynamically disadvantageous (the transition characteristic is of a higher order with a long transition time), it is advisable to measure the temperature T_1 before the superheater and use it as an auxiliary controlled variable.

The identification of the controlled process for predictive control was carried out in full operation at steady flow of steam M_p = 30 t/h, which corresponds to the maximum boiler output. The control was switched to manual mode and a 5% step change of the control value (valve position) was initiated in the usual valve operating range. During the experiment, the temperatures T_1 and T_2 were measured. The change of the control variable was up and down and the whole test was repeated once more to improve the accuracy.



Kurve im Vordergrund 11HAH20CT002

Trend22

Kurve	Variablenanbindung	Wert	Datum/Zeit
Temperatur Heißdampf	Messwertarchiv_Kessel\11HAH20CT002	429.2 i.	20.01.15 16:12:49.099
Stell. Einspritzregelventil	Messwertarchiv_Regler\Rgl666_YHand	60.0 i.	20.01.15 16:12:48.907
Istwert RV ESK	Messwertarchiv_Kessel\11LAB40CG101	61 i.	20.01.15 16:12:48.907
Temp. Dampf n. Einspritz-RV	Messwertarchiv_Kessel\11HAH10CT001	318.3 i.	20.01.15 16:12:49.099
Ausgang Folgeregl.	Messwertarchiv_Regler\Rgl666_YHand	60.0 i.	20.01.15 16:12:48.907
Menge Heißdampf (2von3)	Messwertarchiv_Kessel\11HAH20CF901	31.5 i.	20.01.15 16:12:48.907

Fig. 3 Measured data during the identification process

From the measured data, two transfer functions of this system were identified using the System Identification Toolbox. Injection temperature T_1 was approximated by a first-order proportional system, its transfer function $G_{T_1}(s)$ was determined as

$$G_{T_1}(s)=\frac{-2{,}733}{133{,}5s+1} \tag{1}$$

Further, this transfer function was discretized to

$$G_{T_1}(z)=\frac{-0{,}0204}{z-0{,}9925} \tag{2}$$

From which it can be determined differential equation for output value

$$y_{T_1}(k)=0{,}9925y_{T_1}(k-1)-0{,}0204u_v(k-1) \tag{3}$$

The final equation for prediction is

$$\hat{y}_{T_1}(k+1)=0{,}9925y_{T_1}(k)-0{,}0204u_v(k) \tag{4}$$

The temperature T_2 behind the superheater was approximated by a proportional 2nd order system with the same time constants and converted to the desired discrete equations as follow

$$G_{T_2}(s)=\frac{1{,}2}{(200s+1)^2} \tag{5}$$

$$G_{T_2}(z)=\frac{1{,}495\cdot10^{-5}z+1{,}49\cdot10^{-5}}{z^2-1{,}99z+0{,}99} \tag{6}$$

$$y_{T_2}(k)=1{,}99y_{T_2}(k-1)-0.99y_{T_2}(k-2)+1{,}495\cdot10^{-5}y_{T_1}(k-1)+1{,}49\cdot10^{-5}y_{T_1}(k-2) \tag{7}$$

$$\hat{y}_{T_2}(k+1)=1{,}99y_{T_2}(k)-0.99y_{T_2}(k-1)+1{,}495\cdot10^{-5}y_{T_1}(k)+1{,}49\cdot10^{-5}y_{T_1}(k-1) \tag{8}$$

Since these two transfer functions are placed in series and the output of the first is the input to the second, then their differential equations can be rewritten into one matrix differential equation, which can be denoted as a discrete state description of the controlled system.

$$\mathbf{x}(k+1)=\mathbf{A}\mathbf{x}(k)+\mathbf{b}u(k) \tag{9}$$

$$y(k)=\mathbf{c}^T\mathbf{x}(k) \tag{10}$$

where:

$$\begin{bmatrix}\hat{y}_{T_1}(k+1)\\ y_{T_1}(k)\\ \hat{y}_{T_2}(k+1)\\ y_{T_2}(k)\end{bmatrix}=\begin{bmatrix}0{,}9925 & 0 & 0 & 0\\ 1 & 0 & 0 & 0\\ 1{,}495\cdot10^{-5} & 1{,}49\cdot10^{-5} & 1{,}99 & -0{,}99\\ 0 & 0 & 1 & 0\end{bmatrix}\cdot\begin{bmatrix}y_{T_1}(k)\\ y_{T_1}(k-1)\\ y_{T_2}(k)\\ y_{T_2}(k-1)\end{bmatrix}+\begin{bmatrix}-0{,}0204\\ 0\\ 0\\ 0\end{bmatrix}\cdot u_v(k)$$

$$y_{T_2}(k)=\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}\cdot\begin{bmatrix}y_{T_1}(k)\\ y_{T_1}(k-1)\\ y_{T_2}(k)\\ y_{T_2}(k-1)\end{bmatrix}$$

The matrix ***A*** and vectors ***b*** and ***c*** are then used in the predictive controller to calculate predictions of future responses of the desired variable. Since the predictive algorithm is described in incremental form, the state vector $\boldsymbol{x}(k)$ consists of not only current measured variables T_1 and T_2 but also contains the temperatures from the previous step.

3 COMPARISON OF THE ORIGINAL CASCADE CONTROL WITH PREDICTIVE CONTROL

To compare the original control system with the newly installed predictive controller, there will be shown and evaluated the process variables from day when the switch between the original cascade control and the predictive control has occurred. The main adjustable parameters of the predictive controller are always shown to the right of the screen with the measured data. Furthermore, the action of the predictive controller included a limitation of the action quantity range, which is 0 to 100% of the valve position, as well as a limitation of the change of the action quantity, which corresponded to a change of 1% between the steps. The sampling period was 1 second.

The measured data is from 6. 4. 2017 and the recording time is 8 hours (Fig. 4). After four hours of active cascade control, predictive control was activated. The switch itself occurred in the middle of the record in Fig. 4. The comparison of both types of control will thus serve recorded data of 4 hours with active cascade control and a follow-up 4 hour record when predictive control was active.

Improvements are apparent from trends, as well as from the main tracking parameters, overshoot (Cascade – 11%, MPC – 7.3%), undercut (cascade – 10%, MPC – 6.8%) and mean deviation from zero value (MVD – Fig. 5).

🟥 sw_T_ESK [°C]	440.00	🟩 iw_T_Fhrgrgl [°C]	447.30	🟧 ra_Fhrgrgl [°C]	349.20
🟩 iw_T_Flgrgl [°C]	349.20	■ ra_Flgrgl [%]	21.22	🟪 iw_mp_Dampf [t/h]	20.63
■ esk_stoergr [t/h]	0.00	🟦 iw_y_ESK [%]	47.19		

Plant and Controller Settings

Execution Interval:	0	(Seconds)	Set-point:	440.0
Prediction Horizon:	500	(Periods)	Y offset:	0
Control Horizon:	50	(Periods)	Qy:	1
Number of Plant Inputs:	1	(-)	Qu:	100000

Fig. 4 Measured data from 6. 4 2017

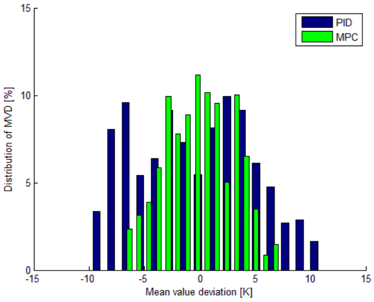


Fig. 5 Distribution of Mean Value of Deviation (MVD)

4 CONCLUSIONS

The result of this work is the use of predictive control for superheated steam temperature control in a biomass power plant. The predictive algorithm used was implemented in C ++ and installed in an existing PLC system under full power plant operation.

The control quality in the use of predictive control was then compared with the control quality of the cascade control system, where two PI controllers were used. From the comparison of the measured waveforms of the selected variables it was evident that during the implementation of the predictive control, the deviation of the controlled variable from the set quantity showed smaller absolute values. The comparison of the action variables shows that the predictive control also shows less activity of the actuator.

ACKNOWLEDGMENT

This research has been elaborated in cooperation with research company VOIGT+WIPP Industrial Research in the framework of the project No: SP 2017/106 - “Advanced Method of Machines and Processes Control” supported by the Ministry of Education, Youth and Sports.

REFERENCES

[1] AGACHI, P. S., NAGY Z. K., et al., Model Based Control: Case Studies in Process Engineering, New York: John Wiley Sons, 2007. ISBN 9783527315451

[2] PEHRSON, Havard, Modelling and Control of Brobekk Waste Incineration Plant, Norwegian University of Science and Technology, 2010. available from: http://www.nt.ntnu.no/users/skoge/diplom/diplom10/pehrson/rapport.pdf

[3] HAFFNER, L., VOIGT, A., High dynamic process control of a large scale industrial incineration power plant, IASTED Software Engineering: Control Applications, Greece, 2012.

[4] Obnovitelné zdroje, 2017. ČEZ, a. s. [online]. [cit. 2017-04-30]. Available from: https://www.cez.cz/cs/vyroba-elektriny/obnovitelne-zdroje/biomasa.html (in Czech)

[5] OENERGETICE.cz: Biomasa [online], [cit. 2017-04-30]. Available from: http://oenergetice.cz/technologie/obnovitelne-zdroje-energie/biomasa-vyuziti-zpracovani-vyhody-a-nevyhody/ (in Czech)

[6] MENKINA, Michal. Advanced algorithms for controlling elements and groups of power blocks. Liberec: Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Technical University in Liberec, 2011. 140 p. Dissertation thesis, Supervisor: doc. Ing. Osvald Modrlák, CSc. (in Czech)