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Power Plant Steam Superheater Control System

Preliminary Results and Experiences from the Field Tests

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Abstract—**This paper describes a newly developed steam superheater control system and its integration into the real power plant control system. The developed control system is based on the principles of the model predictive control. It is intended to replace one part of the existing classical control system that is based on gain scheduled PID controllers. The paper starts with a short description of the controlled plant and then it continues with the description of the predictive controller and its integration into the structure of the existing control system. The main focus is on the results of the functionality tests. The preliminary results hitherto achieved demonstrate the capability of the developed control system and its application potential. However, at the same time, they also show that extensive simulation testing of a controller for such a complex system does not necessarily guarantee perfect control performance and several modifications of the controller will be needed to make it really applicable.**

Keywords—predictive control; superheating; power plant

I. Introduction

The electrical energy market and the portfolio of electrical production sources are rapidly changing and the penetration of renewable generation is increasing. This results in higher demands on the performance of the control systems of the classical power plants that take part in keeping the electrical grid balance by providing the primary and secondary power control. The renewable sources become a standard production source and the total amount of the production should be around 25 % in the year 2040 [1]. The standard power plant operation has to be changed to fulfill all new tasks and to cover future goals on the electrical market. There are some disadvantages in the power plant controls. One of the problems is a strong nonlinear interaction between different parts of the plant and the nonlinear behavior of the steam at higher temperatures (and pressures, too). To focus on the new control strategy will be the essential thing [2, 3]. Actually, most of the new strategies stay only in the simulation version [4] because of some conservatism of power plant owners. Also, the built-in hardware is not prepared for the new control strategies and it is able to realize only some PID type control structures.

This paper should bring some important results from the new power plant control strategy tests. These tests were realized in the coal power plant rated at 200 MWe on one boiler-turbine unit. The concept of the control algorithm was described in [5] together with some simulation tests and the hardware and software implementation was described in [6].

The paper starts with a short description of the controlled power plant subsystem and it continues with a short description of the controller structure and its implementation. Next chapter is focused on the analysis of operation which leads to some adjustment in the controller and shows results from the field tests on the power plant.

II. Controlled System Description

The power plant has a once-through boiler. The steam is generated directly in tubes (not a drum conception) in a defined area in the once-through boiler. The economy of the water-steam-water circuit is improved by regenerative heat exchangers which are put between the low-pressure turbine output and the water to boiler inlet.

The focus of this improved control structure is on the inlet temperature of the high-pressure part of the turbine (so called main steam temperature) and the standard requirement is to hold a steady temperature for all operation regimes. The disturbance rejection is really important for the successful achievement of this goal. The disturbance can come from a changing heat intake to heat exchangers from combustion, another source is changing steam parameters of the inlet to the controlled part or uncertainties in the valve flow rates. Only parameters of the steam can be measured, all other has to be estimated or neglected by some mechanism.

Fig. 1 shows the internal structure of the heat exchanger system in the boiler. The area under new control is a superheating (marked as the HP controlled part in Fig. 1). The superheating consists of three heat exchangers. The outlet temperature of every heat exchanger in the HP part can be controlled via the spray attemperator valve on the inlet side. The physical realization of the system consists of the left and the right side. Heat exchangers on both sides are symmetrical and for a balancing of outlet temperatures from every exchanger's step the outlet steam is mixed from the left and the right side together in one tube – the mixture chamber.

The standard control uses PID controllers in a cascade structure. PID controllers are gain scheduled and some of them include also gain scheduled feedforward terms. Gain scheduling is necessary because of the strong nonlinearity of the superheater. The control structure is mirrored for the left

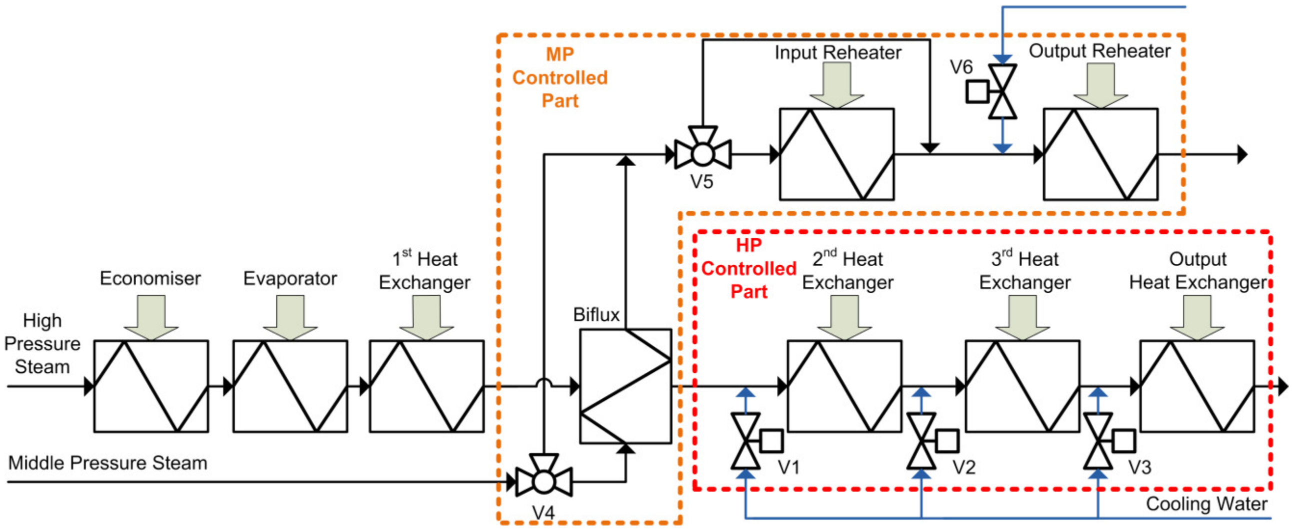

Fig. 1. The structure of the technology, superheaters are under new control

and right side. The middle-pressure part has a similar structure but actually, it is not in the scope of our aims.

The mathematical model of the selected controlled high-pressure part is based on the general Euler equations for the non-isothermal system. The initial equations are redesigned into the specific form, where the enthalpy of the medium is the output. Moreover, the relation for the heat exchange between the medium and the material of the pipe is added.

$$\frac{\partial h}{\partial t} = -\frac{\dot{m}}{F\rho}\frac{\partial h}{\partial z} + \frac{1}{F\rho}\frac{\partial \dot{Q}}{\partial z} \qquad (1)$$

$$\frac{dT_w}{dt} = \frac{1}{m_w c_w}\left(\dot{Q} - \alpha S(T_{Fe} - T)\right) \qquad (2)$$

where ρ - density, m – flow rate, h – enthalpy, Q – input heat, F – cross-section area, c – heat capacity, T – temperature, S – heat exchange area, α – heat exchange coefficient, t – time, z – space coordinate.

Eq. (1) can be transformed using the basic relation between enthalpy and temperature and after $\partial z \rightarrow \Delta z$ into

$$\frac{dT_i}{dt} = -\frac{\dot{m}}{F\Delta z\rho}(T_i - T_{i-1}) + \frac{\alpha}{L\rho c_p}(T_{w,i} - T_i) \quad (3)$$

where $\Delta z = L/N$, i=1,.. N, N – number of elements, L – tube length.

The steam tables are used to calculate the relation between temperature, enthalpy, and pressure. The very detailed mathematical description of the simulation model is presented in [5] and [7].

III. Controller Structure and Implementation

The innovated controller is based on the model-predictive control. This type of control usually needs a mathematical model to realize the control. A nonlinear mathematical model of the steam heating/superheating was created and verified in [7,8] and briefly introduced in the previous chapter. The model describes the temperature dynamic in the whole operating range and it includes all important nonlinearities. The implemented predictive controller is based on a set of linearized models and the natural system nonlinearity is accounted for by controller switching.

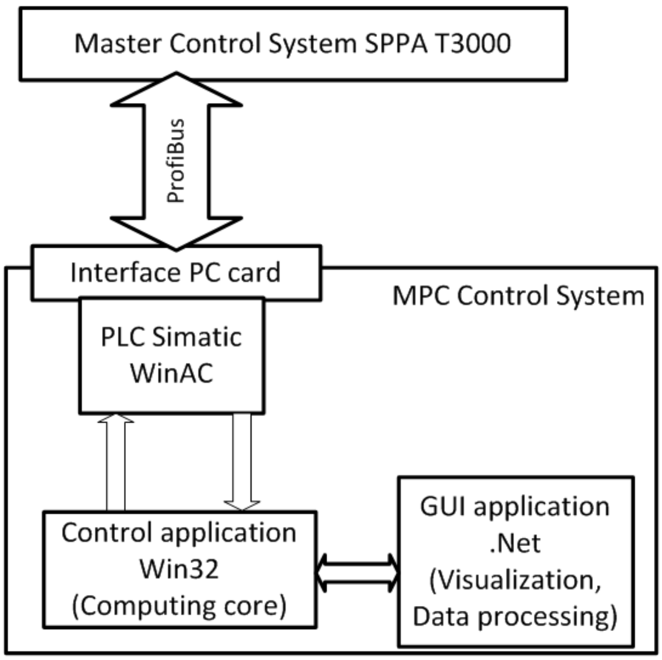

Fig. 2. The structure of developed control system.

The nonlinear model predictive controller was tested, too [9]. The results are acceptable but some danger and discomfort are presented for this type of control on the real process. The problem is in the solution of the criteria searching for the minimum. The minimization task shouldn't give results in all cases. The next important problem is time needed for the calculation. Tests showed the real-time operation is almost impossible.

The final choice for the implementation was a linear version of predictive control with seven soft switched linear models covering the whole operating range of the plant [7,10,11,12].

The model predictive controller is realized in C using qpOases library [13] to solve the quadratic programming problem. The core is implemented as a standard win32 application that runs together with software PLC on one computer. Software PLC is Simatic WinAC RTX and this PLC allows connection and communication with the master control system in the power plant. The PLC is in the position of an interface between the master control system and the new control algorithm. The visualization, the monitoring and the data management are realized in the LabView program. The internal structure is in Fig. 2. The hardware for the model predictive control system is an industrial computer (i5, 4GB RAM) that is equipped with the Siemens Profibus card. The hardware configuration gives enough flexibility in the program code and secures the connection compatibility with the master control system Siemens SPPA T3000.

IV. Analysis of Operation and Tests

A. Valve Flow Characteristics

The valves' operation range is closely connected with the operation regime of the power plant. The power plant is mostly used on the maximum power level because the total efficiency of this power plant is high. It is possible to conclude the power plant operates more than 80 % of the operation time on power level over 90 % of maximum. In the ideal case, the narrow operation zone of the power plant should indicate narrow operation range of spray attemperator valves. It the reality, the operation range of valves is really mostly around some ideal working point but often it falls down to zero. The expected characteristics described by the valve manufacturer are known but the real operation creates another condition than during laboratory tests so the real characteristics and the real flow rate dependency on the valve opening are different. The valve characteristic is important for the right setting of the control system. The online measurement created a good background for such an analysis.

The valve should be characterized by a standard function

$$m = \frac{m_{\max}}{\sqrt{\left(1 + a \cdot \left(\left(\frac{1}{q \cdot e^{n \cdot h}}\right)^2 - 1\right)\right)}} \qquad (1)$$

where a is the authority, q is the proportional flow rate ratio, h is the travel, n is the slide, m is the flow rate. The max index means maximal flow rate.

The characteristics of the form (1) based on measurement data from monitoring the operation of the power plant control system are in Fig. 3. It can be seen that in general (1) is an appropriate functional form to describe the real behavior of the valves. However, as the valves (in particular the 2nd valve) work just in a part of their operating range, some uncertainty in the description arises as the characteristics must be extrapolated to those valve opening ranges where no measurement data are available. The Fig. 4 shows the comparison of temperatures beside the 3rd valve from the real operation and as the model output.

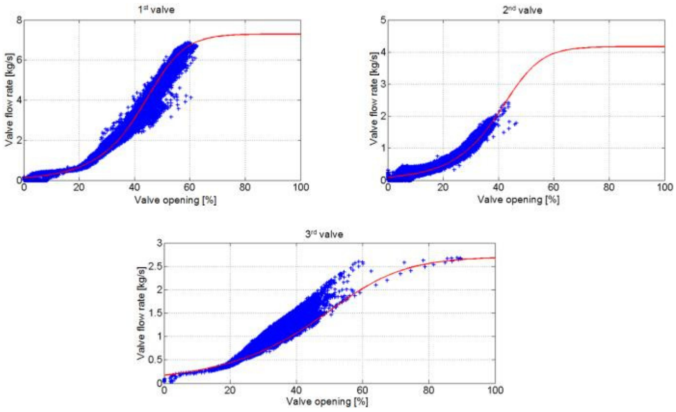

Fig. 3. Flow rate characteristics for valves, measured values (blue points) and approximation (red line)

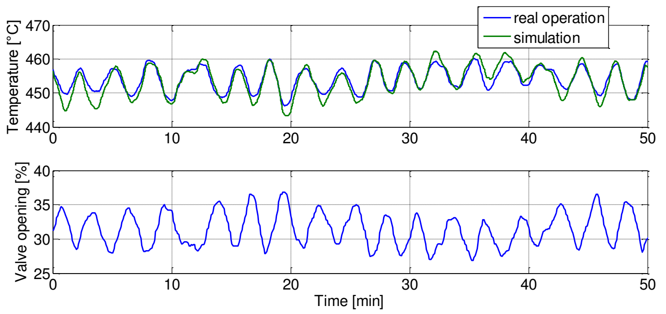

Fig. 4. The valve opening effect on the temperature – comparison of the simulation model and the real operation

B. Control Algorithm Development

The development of control algorithm consists of several steps. In the beginning, the deep analysis of the problem and technology was made. This analysis showed some possibilities for improvement in the actual state and necessary inputs for the next work. The next step was the setup and building of the simulation model. The advantage of innovation of running technology was used in this phase because the model could be compared with the real system and fitted to cover all important nonlinearities and uncertainties. The simulation model creates the right conditions for a very detailed test of a new control algorithm. The nonlinear character of the system requires the application of an extended version of the basic model-predictive control. The idea of linear predictive control was kept but it was connected with model switching strategy. After some tuning, the final version was prepared for the real application. The algorithm was transferred from the simulation tool and software into the C language and equipped with necessary add-ons as graphical user interface, database administration, communication interface etc.

The safety was a key for the real application so a safety algorithm structures were implemented not only in a new part of control but also into the existing one. Firstly the safety routines were tested. The new control algorithm was started after that. The first set of tests showed the process is stable but some important disturbance corrupted the control process and the output temperature.

The predictive algorithm should be able to reject all disturbances and to keep the main steam temperature as constant as possible, preferably also with minimum changes of the manipulated variables (valve positions). One important disturbance is the boiler thermal power output. This disturbance cannot be directly measured but it can be estimated from several boiler variables. This estimation introduces some error and time delay. The use of this estimated disturbance was considered and tested already in the initial controller design.

A more serious problem is the fact that there are unmeasured and probably unmeasurable disturbances due to the variations of the hot flue gasses temperatures and flow directions. This problem was not initially considered and it is quite difficult to describe as the disturbance propagates in ways that are not adequately captured by the purely serial structure of Fig. 1. As a result of it, the control algorithm had to be improved to cope with the unmeasured disturbances, so the prediction of the disturbance was added into the model to cover the difference between the model and the real process. The disturbance prediction tries to estimate the future differences between the model and the real process on the basis of a series of past measurements.

Finally, after some tests, it is possible to say this is the right way to improve the control performance of the real plant and how to construct the predictive controller for such a type of systems, where the disturbances have strong influences on the measured output but cannot be directly measured.

C. Preliminary Results of the Field Tests

A huge set of the different test has been conducted in order to study the behavior of the new control algorithm under different operation conditions. The structural test window was as follows. The basic structure of the test set was first to test switching on and switching off the new control algorithm to show that both algorithms are ready for the switching and for tracking the control outputs of each other. The next test was made on the high power level to observe the stability and ability of the controller to deal with standard disturbances (oscillating heat exchange in exchangers, etc.). The last step was focused on the readiness of the controller to realize step or slope changes in the desired electrical power level in the standard framework of the secondary control of the electrical grid.

The results from one of the latest test are shown in Fig. 5 and Fig. 6. Figure 5 shows temperatures on one side of the high-pressure heat exchangers in all important measured points. These points are always directly at the output of the heat exchanger to measure the actual steam temperature and at the input of the heat exchanger to measure the effect of the water spray valve positioning on the exchanger inlet. The blue line represents the measured temperature; the red line is the reference. The yellow frame highlights a part where the new control algorithm was in operation. In the beginning and in the end the standard PID structure realizes the control of steam temperature. The vertical axis is in percent, and the 0.005 means approximately 2.5÷3 °C.

It is possible to see that the main steam temperature at turbine inlet deviates maximally by 2 °C from the reference during the time when the predictive controller is in operation. Hence it can be said that it performs better than the original control system. It is not so important to reach the references on both internal temperatures (outlets of the 2nd and 1st heat exchangers). These lines mainly express the complexity of the plant and the controller activity. It can be seen that the 3rd heat exchanger is probably influenced by disturbances that do not affect the first two exchangers. There is a little apparent correlation between deviations of the temperature at the output of the 2nd heat exchanger and at the turbine inlet.

The controller activity is shown in detail in Fig. 5. It is interesting that the frequency of the valve position change does not directly correspond to the frequency on the measured temperature. The 2nd valve is closed for a most of time because of the reference setting and operation condition. The bottom graph shows the actual power level, the reference electrical power on the generator output. The experiment covers both the steady state with no changes on the power level and also the time window with power level decrease and increase. The maximum on the electrical power output is a standard for this power plant, so more than 70 % of operation time is working at power levels close to 200 MWe. The improvement is mainly in the valve operation and in the amplitude of the temperatures remarkable in the comparison of the MPC and the PID control structure in real operation. The oscillation of temperatures still hold and the research is actually focused on this problem, to find the potential source of the oscillation, and to increase the power of the MPC controller in the fight with this type of a disturbance.

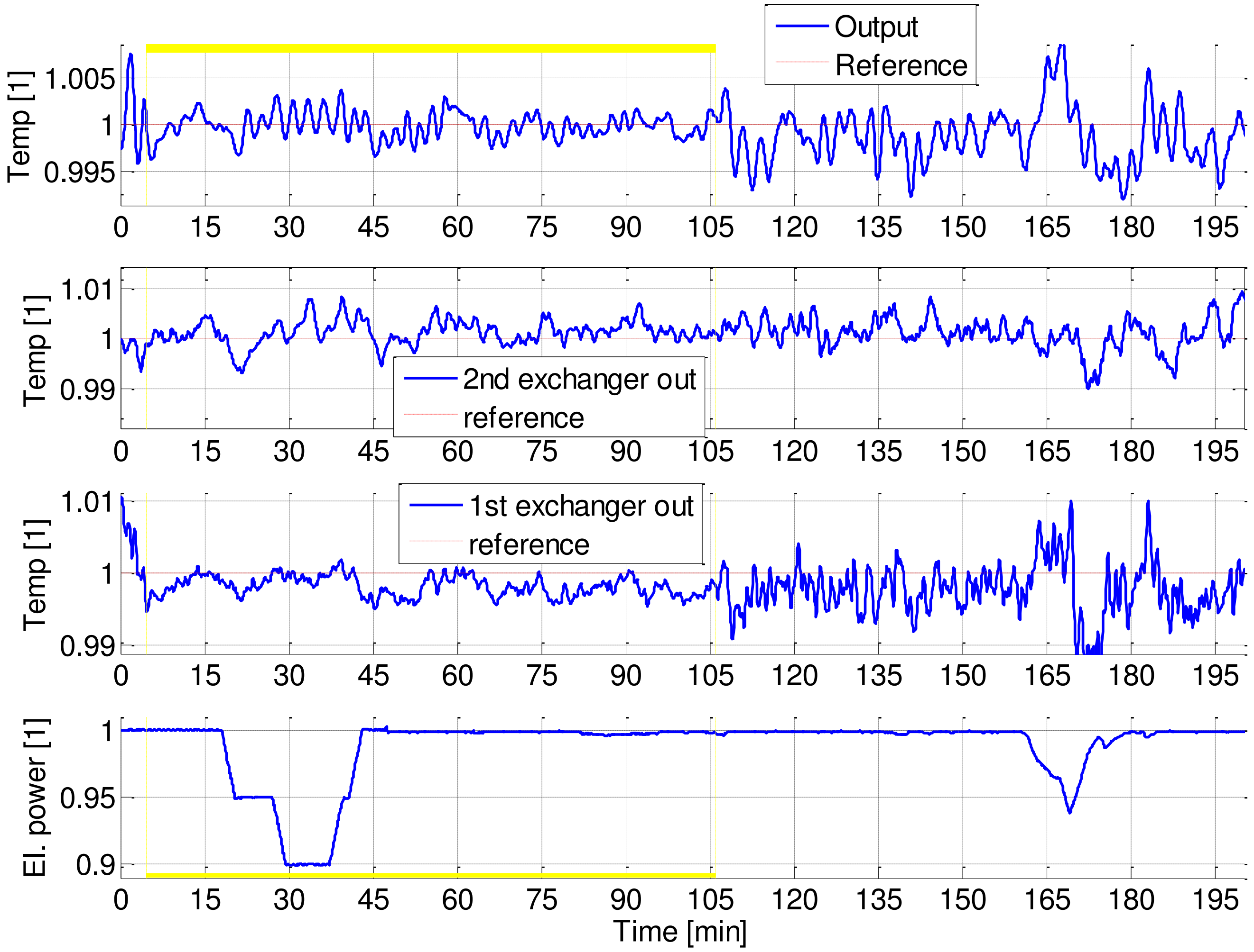

Fig. 5. Temperatures of steam on heat exchangers outlets (top) and desired electrical power level (bottom)

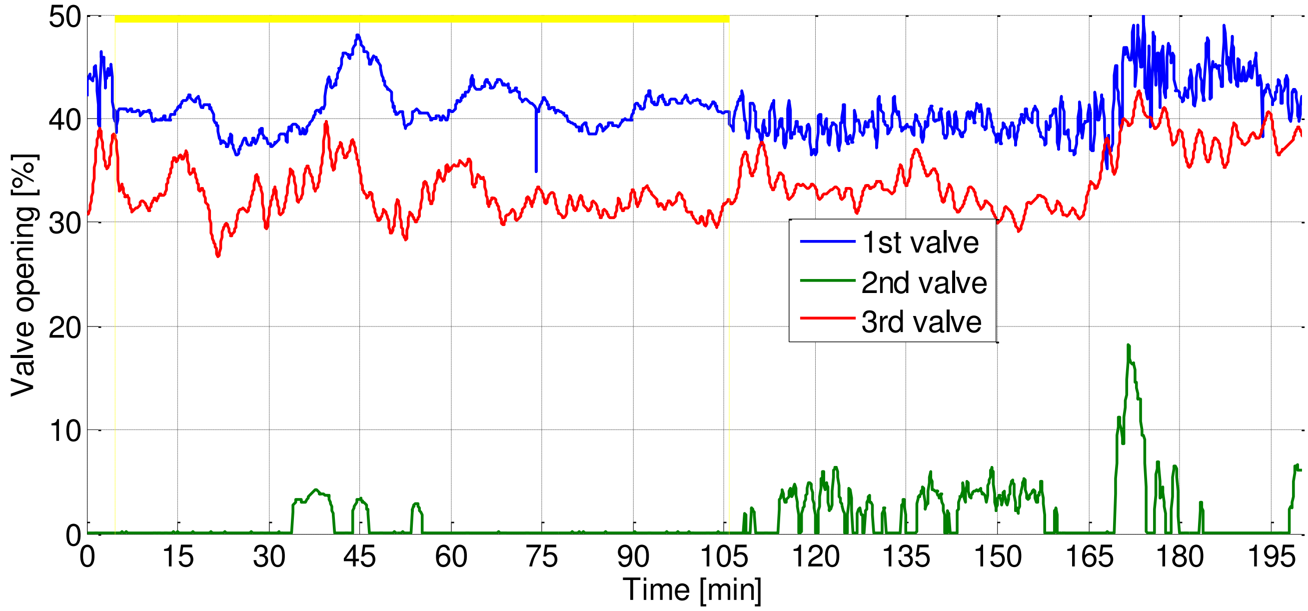

Fig. 6. Valves positions

V. Conclusion

This paper shows one possibility how to change the standard and traditional controller in the power plant to a new one based on the model predictive strategy. The controlled subsystem is a relatively small part of the whole power plant. However, it is a very important part where smaller fluctuations of the main steam temperature can potentially enable increasing this temperature and hence also the power plant overall efficiency. Further tests will be focused on testing in extended operating range and full replacement of the superheater PID control.

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