SIMULATION OF MULTI-LINK INVARIANT CONTROL SYSTEM FOR STEAM BOILER

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Abstract. The paper discusses the procedures and results of development and investigation of the mathematical and virtual models for transient process simulation in multi-link invariant control system for steam pressure stabilization in a low pressure steam boiler, applying preemptive compensation of the steam flow and feed water supply affect on the steam pressure. The research subject is the virtual model of three-link invariant control system of the steam boiler VAPOR TTK-70, developed in SIMULINK environment. To obtain a mathematical model of the invariant control system with steam pressure closed loop PID (proportional-integral-derivative) control link and steam expenditure (as a load), and feed water supply affect compensation DPC (disturbance preemptive compensation) control links, an algorithmic block-diagram and operational equation of the steam boiler invariant control system are compiled. To simulate response of steam pressure $p(t)$ in the steam boiler with invariant PID-DPC control system and preemptive compensation of steam flow - $q_s(t)$ and feed water supply – $q_w(t)$ affect on steam pressure, an algorithm of the disturbance controller DPC is developed and parameters are calculated, using invariant control principle. Simulation of the steam boiler invariant PID-DPC control system in SIMULINK shows that the process parameter $p(t)$ remains practically constant under any type of disturbances. Due to high speed preemptive operation of disturbance controller, the disturbances affect on boiler steam pressure is timely compensated by effective regulation of the furnace heat power.

Key words: steam boiler, disturbances, invariant control system, simulation model.

Introduction

The steam boilers are energy conversion units which transform the combustion energy of fuel into steam heat and mechanical power. High pressure steam boilers are applied in cogeneration plants for steam turbine operation and district central heating. Low pressure steam is utilized for technological needs and for autonomous heating of administrative and manufacturing buildings, like food production enterprises. The main tasks of the steam boiler design, operation and automatic control are as follows: 1) to minimize heat losses from the furnace and boiler room using economizers, increasing the heat resistance and fuel combustion efficiency, as well as optimizing the heat load control; 2) to reduce flue gas emissions using emission reduction facilities and applying burners optimal control according to flue gas analysis; 3) continuous measurement, analysis and control of inner technological parameters – steam pressure and temperature, and drum water level and temperature, as well as outer disturbances – feed water flow and steam expenditure what directly affect the boiler parameters.

Commonly, a steam boiler is characterized by changing sensitivity and inertia factors, highly variable disturbances, large thermal time constants and time delays. Classical PID (proportional-integral-derivative) control is still the current tool for the steam boiler control [1]. The main control loop with only PID controller cannot eliminate the affect of disturbances to the transition process of the steam parameters enough effectively because of delayed response on variable steam expenditure and feed water flow. To increase operation stability and the process control quality of the steam boilers and power plants, wide investigations of long-range control methods are made recently: an active disturbance rejection control method, using multi variable robust controllers with optimal settings and robustness against uncertainties and disturbances [1; 2]; cascade control of drum water level and feed water flow [3]; an adaptive PID & Fuzzy logic control for transient process optimization [4]; automatic reservation, to compensate extreme overloads [5]. New approaches on the subject of development of the heat power unit-turbine control technology are complex control of continuous-discontinuous processes using linear hybrid automata [6] and invariance of multi-variable control [7]. A general concept of steam boiler control improvement by active disturbance rejection is invariant control [8].

The main task of the given work is to develop and investigate the mathematical and virtual model of three-link invariant PID-DPC control system for steam pressure stabilization in a low pressure steam boiler VAPOR TTK-70, applying preemptive compensation of the steam expenditure (load) and feed water supply, as the disturbances, affect on the steam pressure. The main advantages of this control method are verified previously in the virtual model of two-link invariant control system [8].

Research subject and methods

The research subject is the model of three-link invariant control system of the steam boiler VAPOR TTK-70 with closed loop control link of steam pressure $p(t)$, open loop control link of steam expenditure $q_s(t)$ as the first disturbance of steam pressure and open loop control link of feed water supply $q_w(t)$ as the second disturbance of steam pressure. An algorithmic block-diagram of invariant PID-DPC control system is shown in Fig. 1. The algorithms of the disturbance preemptive compensation (DPC) controller are compiled according to the invariant control principle in strong correlation with the algorithms of steam boiler and power supply unit, as well as the steam flow and feed water flow affect on steam pressure. The transfer functions and operational equations of the steam boiler control system components are composed using mathematical analyses, operator mathematics and Laplace transforms.

The transfer coefficients and time constants of the control system components are determined according to their technical parameters and operation conditions. For simplicity, heat transfer in the steam boiler is analysed as a process, where the steam pressure changes uniformly with time, not position. Then the transient process can be described by the ordinary differential equations. A simplified linear model of steam boiler is used for no load mode ($q_s(t) = 0$ and $q_w(t) = 0$), as well as linear models of disturbances affect on steam pressure for limited area of their changes.

The technical parameters of the steam boiler VAPOR TTK-70: heat power – 2 MW; rated steam capacity – 50 kg·min^{-1}; max steam pressure – 10 bar; drum water capacity – 7700 kg; steam temperature – 184 ºC; feed water temperature – 90 ºC; OILON burner GKP- 250M – (0.37-2.6) MW.

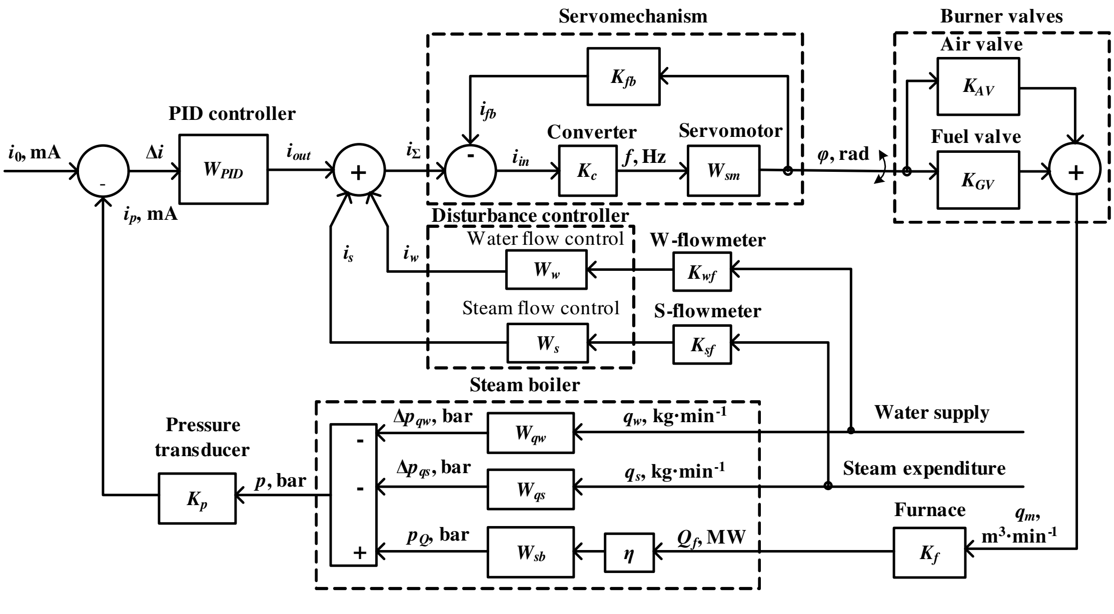

Fig. 1. **Algorithmic block-diagram of steam boiler invariant PID-DPC control system:** i_0 – input setup, mA; i_p – steam pressure feedback output, mA; i_{out} – PID output, mA; i_s, i_w – DPC outputs, mA; φ – servomotor shaft angle, rad; q_m – gas mixture flow, m^3·min^{-1}; Q_f – furnace output, MW; $p = (p_Q - \Delta p_{qs} - \Delta p_{qw})$ – steam pressure, bar; p_Q ,Δp_{qs} ,Δp_{qw} – components of heat, steam and feed water affect

The main control loop of the invariant PID-DPC control system consists of the PID controller, the frequency controlled electrical servomechanism for burner valve operation, the furnace, the steam boiler and the pressure transducer. To implement invariant control of the boiler output steam pressure, apart from the steam flow (expenditure) and feed water flow (supply) fast variations, the two links disturbance controller is introduced. According to the measurement results of the steam flow (*S* – flowmeter) and feed water flow (*W* – flowmeter), the disturbance controller produces output signals i_s and i_w for preemptive adjustment of servomechanism input signal: $i_\Sigma = i_{\text{out}} + i_{\text{s}} + i_{\text{w}}$. Thereby, the activated actuator (servomechanism + burner valves + furnace) eliminates the steam pressure change in time.

Mathematical and simulation models

The conventional algorithm of the PID controller with parallel connections of proportional, integral and derivative circuits, available in SIMULINK, is used. All constants of PID controller are tuned automatically during the simulation process (Fig. 2). For no load mode ($q_s = 0$, $q_w = 0$) the steam boiler is considered as a two component volume (water + steam) unit with constant sensitivity and response parameters. In that case the transient process of pressure alteration can be described by second-order transfer function:

$$W_{sb} = \eta \cdot \frac{p_Q(s)}{Q_f(s)} = \eta \cdot \frac{K_{sb}}{T_w \cdot T_s \cdot s^2 + (T_w + T_s) \cdot s + 1} = \eta \cdot \frac{11.5}{95 \cdot s^2 + 24 \cdot s + 1}, \quad (1)$$

where Q_f (s), p_Q (s) – Laplace transforms of furnace heat flow and steam pressure at no-load mode;
$\eta = 0.93$ – efficiency factor of boiler using economiser;
$K_{sb} = 11.5$ bar·MW^{-1} – transfer coefficient of steam boiler at ideal no load mode;
$T_w = 5$ min, $T_s = 19$ min – time constants of water and steam volumes.

Variable steam expenditure q_s as a load (disturbance) has a directly negative affect on common steam pressure in the boiler. Load growth causes pressure decrease for transient volume Δp_{qs} (Fig. 1). That can be described by the following second order transfer function:

$$W_{q_s} = \frac{\Delta p_{qs}(s)}{q_s(s)} = \frac{K_{qs}}{\tau_{qs} \cdot T_{qs} \cdot s^2 + (\tau_{qs} + T_{qs}) \cdot s + 1} = \frac{0.135}{35 \cdot s^2 + 12 \cdot s + 1}, \quad (2)$$

where $q_s(s)$, $\Delta p_{qs}(s)$ – Laplace transforms of steam flow and steam pressure change;
$K_{qs} = 0.135$ bar·min·kg^{-1} – transfer coefficient of steam flow affect on steam pressure;
$\tau_{qs} = 4.5$ min, $T_{qs} = 7.7$ min – dead time and time constant of steam flow affect.

Feed water flow q_w is regulated by a frequency controlled centrifugal pump in correlation with the steam expenditure and causes additional change of common steam pressure in the boiler for transient volume Δp_{qw} (Fig. 1), what can be described by the following second order transfer function:

$$W_{q_w} = \frac{\Delta p_{qw}(s)}{q_w(s)} = \frac{K_{qs}}{\tau_{qw} \cdot T_{qw} \cdot s^2 + (\tau_{qw} + T_{qw}) \cdot s + 1} = \frac{0.038}{14 \cdot s^2 + 9 \cdot s + 1}, \quad (3)$$

where $q_w(s)$, $\Delta p_{qw}(s)$ – Laplace transforms of feed water flow and steam pressure change;
$K_{qw} = 0.038$ bar·min·kg^{-1} – transfer coefficient of feed water flow affect on steam pressure;
$\tau_{qw} = 2$ min, $T_{qw} = 7$ min – dead time and time constant of feed water flow affect.

The heat power actuator of heat production and heat flow regulation consists of a frequency converter; servomechanism with servomotor and feedback for stability improvement, gas and air valves; and furnace. According to the block-diagram (Fig. 1) the transfer function of the actuator input-output link for transient process simulation is compiled:

$$W_A = \frac{Q_f(s)}{i_a(s)} = \frac{K_{fb}^{-1} \cdot (K_{GV} + K_{AV}) \cdot K_f}{(K_c \cdot K_{sm} \cdot K_{fb})^{-1} \cdot s + 1} = \frac{K_A}{T_A \cdot s + 1} = \frac{0.24}{1.4 \cdot s + 1}, \quad (4)$$

where $i_a(s)$, $Q_f(s)$ – Laplace transforms of actuator input signal and furnace heat flow;
$K_c = 2.5$ Hz·mA^{-1} – transfer coefficient of frequency converter;
$K_{fb} = 4.5$ mA·rad^{-1} – transfer coefficient of servomechanism feedback;
$K_{sm} = 0.063$ rad·min^{-1}·Hz^{-1} – speed coefficient of servomotor;
$K_{GV} = 2.5$ m^3·min^{-1}·rad^{-1} – transfer coefficient of gas valve;
$K_{AV} = 24$ m^3·min^{-1}·rad^{-1} – transfer coefficient of air valve;
$K_f = 0.043$ MW·m^{-3}·min – transfer coefficient of furnace;
$K_A = 0.24$ MW·mA^{-1} – transfer coefficient of actuator;
$T_A = 1.4$ min – time constant of actuator response.

The main task of the steam boiler control system is to ensure perfect compensation of the physical affect of variable steam expenditure $q_s(t)$ and feed water flow $q_w(t)$ on steam pressure $p(t)$ by use of the disturbance preemptive compensation controller, which operates under the invariant control principle.

To obtain the mathematical model of the three links invariant control system containing steam pressure closed loop PID control and steam expenditure, and feed water flow open loop DPC control, the following operational equation of the system (Fig. 1) is obtained:

$$p(s)=\frac{i_0(s)\cdot W_{PID}\cdot W_A\cdot W_{sb}+(K_{sf}\cdot W_s\cdot W_A\cdot W_{sb}-W_{qs})\cdot q_s(s)+(K_{wf}\cdot W_w\cdot W_A\cdot W_{sb}-W_{qw})\cdot q_w(s)}{K_p\cdot W_{PID}\cdot W_A\cdot W_{sb}+1}, \quad (5)$$

where $q_s(s)$, $q_w(s)$ – Laplace transforms of main disturbances (steam flow and feed water flow);
K_{sf}, K_{wf}= 0.2 mA·kg^{-1}·min – transfer coefficients of steam and feed water flowmeters;
W_s, W_w – unknown transfer functions of steam and feed water disturbances controller.

In conformity with the invariant control principle, the following conditions of invariance can been formulated: if $K_{sf}\cdot W_s\cdot W_A\cdot W_{sb}-W_{qs}=0$ and $K_{wf}\cdot W_w\cdot W_A\cdot W_{sb}-W_{qw}=0$, then the disturbances $q_s(t)$ and q_w (t) do not affect the transient process in the steam boiler. Therefore, the algorithms of DPC controller should be composed according to such transfer functions:

$$W_s=\frac{W_{qs}}{K_{sf}\cdot W_A\cdot W_{sb}}=\frac{0.135}{0.2\cdot 0.24\cdot 11.5}\cdot\frac{95\cdot s^2+24\cdot s+1}{35\cdot s^2+12\cdot s+1}\cdot(1.4\cdot s+1)\approx 0.245\cdot\frac{129\cdot s^2+25.4\cdot s+1}{35\cdot s^2+12\cdot s+1} \quad (6)$$

$$W_w=\frac{W_{qw}}{K_{wf}\cdot W_A\cdot W_{sb}}=\frac{0.038}{0.2\cdot 0.24\cdot 11.5}\cdot\frac{95\cdot s^2+24\cdot s+1}{14\cdot s^2+9\cdot s+1}\cdot(1.4\cdot s+1)\approx 0.069\cdot\frac{129\cdot s^2+25.4\cdot s+1}{35\cdot s^2+12_1\cdot s+1} \quad (7)$$

The transfer functions (6, 7) describe the conditions of the disturbance affect on steam boiler preemptive compensation. The block-diagram is compiled in SIMULINK for the steam boiler control system simulation and transient process comparative analysis of conventional PID control model and invariant PID-DPC control model with disturbance controller (Fig. 2).

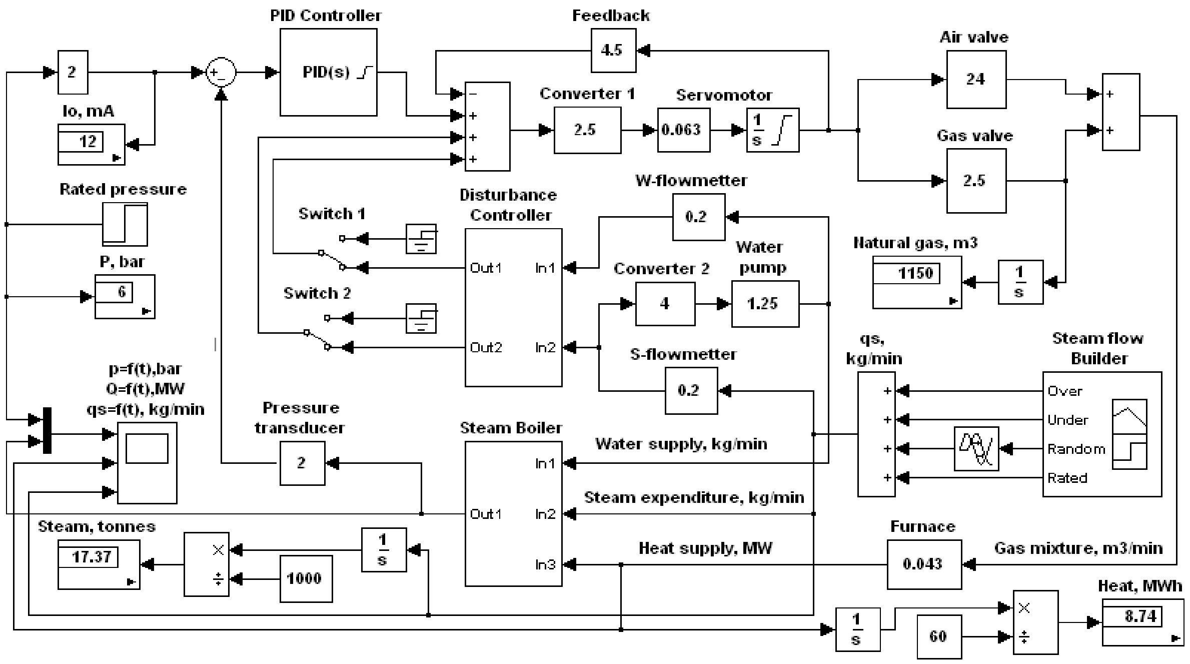

Fig. 2. **Simulation model of steam boiler invariant PID-DPC control system in SIMULINK**

The main closed loop control circuit consists of the following models: **PID Controller** model with limited output (± 20 mA) and auto-tuning of control circuits parameters; actuator model for heat power supply regulation with operation algorithm (4) (**Converter 1**, **Servomotor** with **Feedbac**k to improve the control stability; **Air Valve** and **Gas Valve** of gas mixture flow regulation on to

Furnace); **Steam boiler** model with operation algorithms of heat flow affect (1), steam flow disturbance affect (2) and feed water flow disturbance affect (3) on to speed pressure; **Pressure transducer** with the transfer coefficient K_p = 2mA·bar^{-1} for steam pressure continuous measurement. To perform constant, linear, pulse case and randomly changing components of variable disturbance – steam expenditure $q_s(t)$ the **Load Builder** and **Transport Delay** blocks are applied.

The model of **Disturbance Controller** is performed accordingly to algorithms (6, 7) as coupled second order differential filters. The steam flow and feed water flow are measured by ***S* – flowmeter** and ***W* – flowmeter** in kg·min^{-1}. To minimize disturbance on to steam pressure, the feed water flow is regulated continuously in strong correlation with the steam expenditure flow, using a frequency regulated water **Pump** (1.25 kg·min^{-1}·Hz^{-1}) with **Converter 2** (4 Hz·mA^{-1}).

Simulation procedures and results

The simulation comparative results of the steam boiler conventional PID control system and invariant PID-DPC control system are presented in Figure 3. To search wide spectrum of steam flow $q_s(t)$ influence on the steam pressure $p(t)$, the simulation time should be enough long because of high transient process inertia (t_{sim} = 400 min). Simulation is started at ideal no load mode, when the main disturbances – $q_s(t) = 0$ and $q_w(t) = 0$. After the transient steam pressure reaches the set point – 6 bar and becomes stable, the linear growing load from zero to rated value 50 kg·min^{-1} is activated. To search for the steam boiler reaction on the steam flow large and fast perturbations, a linear growing overload (+40 % of rated value) and linear changing under load (–40 % of rated value) are added. After 300 minutes from the start, a random component with amplitude ±20 % of the rated value and frequency 0.5 min^{-1} is added. Simulated response of the steam pressure $p(t)$ change in the steam boiler feedback control system with optimally tuned PID controller shows, that the overshoot of the steam pressure run up process is lower than 8 % and response time does not exceed 20 minutes.

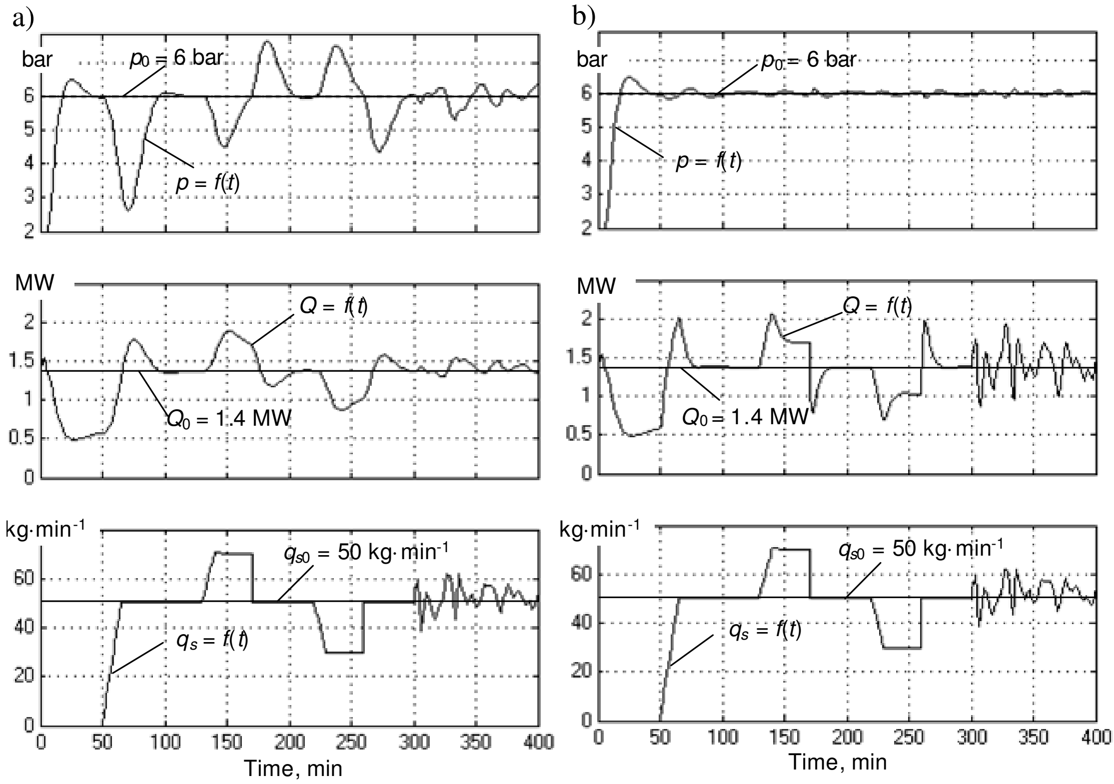

Fig. 3. **Transient characteristics of the steam boiler model in SIMULINK:** a – PID control system; b – invariant PID-DPC control system ($p = f(t)$ – steam pressure, bar; $Q = f(t)$ – heat flow, MW; $q_s = f(t)$ – steam flow as main disturbance of the boiler, kg·min^{-1}; p_0, Q_0, q_{s0} – rated values of the variables)

Under fast growing load from zero to the rated value, the steam pressure response curve has the maximal deviation up to 50 %. Under linear and step case load variations (± 40 % of rated value) $p(t)$

maximal deviations reach up to ± 25 % of the rated value. It testifies that the feedback control system with PID controller is sufficiently stable and fast in operation under no load or constant load conditions, but the operation quality is insufficient under substantially variable load. Due to response inertia of PID controller, the heat power regulation is delayed and disturbance rejection is too late, what causes great deviations of the control parameter $p(t)$ (Fig. 3-a).

Simulated response of steam pressure $p(t)$ invariant PID-DPC control system with the disturbance controller, the parameters of which are correctly calculated using the invariant control algorithms (6, 7), shows that the process parameter $p(t)$ remains practically constant under any type of steam load – constant, steady changing, pulse or randomly fluctuating (Fig. 3-b). If the steam flow deviates on ±25 % from the rated value, deviations of the steam pressure do not increase ±3 % of the set point value. High quality of steam pressure stabilisation is reached due to fast operation of the disturbance controller. The disturbance affect on the steam pressure is timely eliminated by effective regulation of the heat power.

Conclusions

1. Invariant PID-DPC control system with disturbances preemptive compensation controller, the algorithm and parameters of which are correctly compiled according to the invariant control principle, cancel the affect of main external disturbances – the fluctuating steam expenditure $q_s(t)$ and the feed water flow changes $q_w(t)$ on the steam boiler output variable– steam pressure $p(t)$.
2. Simulations show that for the feedback control system with only PID Controller and optimally tuned parameters the overshoot of the control variable - steam pressure $p(t)$ is up to 50 % under linear growing rate of steam expenditure from no load to the rated value, showing overall unacceptable control quality and inability to compensate fast variable disturbances (Fig. 3-a).
3. The simulation results make it possible to forecast that introducing in practice the invariant PID-DPC control system with disturbances $q_s(t)$ and $q_w(t)$ preemptive compensation controller, the overshoot and fluctuations of the boiler steam pressure $p(t)$ do not exceed ±3 % of the rated value because of high sensitivity and high-speed response of the disturbance controller to disturbances change (Fig. 3-b).

References

1. Qinling Z., Zhiqiang G., Wen T. Disturbance Rejection in Thermal Power Plants. Proceedings of the 30th Chinese Control Conference, July 22-24, 2011, Yantai, China, pp. 6350-6355.
2. Ivezic D., Petrovic T. Robust IMC Controllers with Optimal Set-points Tracking and Disturbance Rejection for Industrial Boiler. Journal of Mechanical Engineering, vol. 56, 2010, pp.565-574.
3. Byun S.H, Kim B.C., Kim H.Y.Tuning of Boiler Drum Level Controller in Power Plant. The 55th Annual ISA Power Industry Division Symposium, June 4-6, 2012, Texas, USA, 19 p.
4. Шнидерс, А., Рунгулис, Д. Адаптивное управление паровой установки для технологических нужд пищевого предприятия (Adaptive Control of the Steam Boiler for Process Needs in Food Production Plant). В ж: Промышленная теплотехника, Националъная Академия Наук Украины ,Киев, 2001, № 23, том 3, с. 89-95. (In Russian).
5. Šnīders, A. Nestacionāro procesu stabilizācija tvaika katlā (Non-Stationary Process Stabilization in Steam Boiler). RTU Zinātniskie Raksti "Enerģētika un Elektrotehnika", 4. sērija, 9. sējums, Rīga, Latvia, 2003, 166.-171. lpp. (In Latvian).
6. Henzinger, A., Wong-Toi, H. Using HYTECH to Synthesize Control Parameters for Steam Boiler. Lecture Notes in Computer Science, University of California, Berkeley, Springer-Verlag, 1996, pp. 265-282.
7. Navritil, A., Pekar, L., Masaryka, T.G. Possible Solution of Decoupling and Invariance of Multi-variable Control Loop by Using Correction Members. WSEAS Transactions on Circuits and Systems, issue 6, vol. 10, pp. 209-219.
8. Sniders A., Komass T. Invariant Method of Load Independent Pressure Control in Steam Boiler. Proceedings of the 53rd International Scientific Conference dedicated to the 150th anniversary of Riga Polytechnic Institute „Power and Electrical Engineering", October 11-12, 2012, Riga, Latvia. Available at: https://ortus.rtu.lv/science/lv/publications/15315/fulltext.pdf.