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Invariant Method of Load Independent Pressure Control in Steam Boiler

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Abstract **–The paper considers the possibility of steam production and supply process improvement by perfection of the steam boiler control system, applying invariance principle that makes possible preemptive compensation of the influence of steam expenditure as a disturbance on the control process quality and efficiency. For the development of invariant control system, the mathematical modeling and simulation in MATLAB-SIMULINK environment is made. The control unit is low pressure steam boiler with one input impact to control – the heat flow of burning gas mixture fuel, one measured output parameter of the process – the steam pressure, and the main disturbance as a load impact – the steam expenditure. The mathematical and virtual models and block-diagrams for transient process simulation is compiled, allowing to start practical design and investigation of steam boiler invariant control system with high operation stability under essentially fluctuating load. The simulation results prove that the optimal solution for the transient process improvement in steam boiler, taking in account fluctuating load, is invariant PID-DPC two loop control system with disturbance impact on steam pressure preemptive compensation. Under invariant control the steam pressure overshoots decreases substantially in comparison with the traditional PID-feedback control method.**

Keywords **– Time invariant systems, pressure control, closed loop systems, computer simulation.**

I. INTRODUCTION

The steam boilers are energy conversion units transforming the combustion energy of fuel into steam heat and mechanical power [1]. High pressure steam boilers are applied in cogeneration plants for steam turbines operation and district central heating. Low pressure steam is utilized for technological needs and for autonomous heating of the administrative and manufacturing buildings, like the food production enterprises. The main tasks of the steam boilers design, operation and automatic control are as follows: 1) to minimize heat losses from the furnace and boiler room using economizers, increasing heat resistance and fuel combustion efficiency, as well as optimizing heat load control [2, 3, 4]; 2) to reduce flue gas emissions (CO_2, CO, NO_x, SO_2) using emissions reduction facilities and applying burners optimal control according to flue gas analysis [3, 4, 5]; continuous measurement, analysis and control of inner technological parameters – drum water level and flow, water and steam temperature, steam pressure and steam flow as an outer disturbance directly affecting boiler parameters [5, 6, 7].

Commonly, a steam boiler is characterized with changing sensitivity and inertia factors, highly variable disturbances, large thermal time constants and time delays, and several control loops with the mutual dynamics. Classical PID (proportional-integral-derivative) control is still the key tool for the steam boiler control. To increase operation stability and process control quality of the steam boiler the adaptive PID control and Fuzzy logic control combination are used [6]. Extreme overloads can be compensated by automatic reservation [7]. These methods do not allow reject an influence of the steam expenditure as a fluctuating load to the output steam pressure of the boiler timely.

New approaches on the subject of development of the heat power units-turbines control technology is complex control of continuous-discontinuous processes using linear hybrid automata [8] and invariance of multi-variable control [9]. General concept of steam boiler control improvement by active disturbance rejection is invariant control.

The main task of the given work is to develop and investigate the mathematical and virtual models of an invariant PID-DPC control system for steam pressure stabilization in a low pressure steam boiler VAPOR TTK-70, applying compensation of the steam load, as a disturbance, affect on the steam pressure. Main advantages of this control method are verified previously in the model of wastewater aeration control system [10].

II. MATHEMATICAL MODEL OF STEAM BOILER INVARIANT CONTROL SYSTEM

The research subject is the model of two loop invariant control system of the steam boiler VAPOR TTK-70 with two loops of steam pressure and steam expenditure control, developed in SIMULINK environment. The algorithm of the preemptive control circuit is compiled according to the invariant control principle in strong correlation with the algorithms of steam boiler and power supply unit to cancel out the affect of disturbance (steam load) fluctuations on the output variable.

The transfer functions and operational equations of the steam boiler control system components are composed using mathematical analyses, operator mathematics and Laplace transforms [11]. Transfer coefficients and time constants of the control system components are calculated according to their technical parameters and operation conditions.

For simplicity, heat transfer in the steam boiler is analysed as a process, where steam pressure changes uniformly with time, but not position. Then the transient process can be described by the ordinary differential equations. Using Laplace transforms to differential equations, the operational equations and transfer functions of automatic control system components is compiled.

The rated technical parameters of the prototype – steam boiler VAPOR TTK-70 are as follows: heat power – 2 MW; steam capacity – 3000 kg per hour; steam pressure – 10 bar; water capacity – 7700 kg; steam temperature – 184 ^{0}C; gas fuel heat power of OILON burner GKP- 250M – (0.37-2.6) MW[1].

A. Transfer functions of PID control system components

General algorithmic block-diagram of PID-DPC control system for the steam pressure invariant stabilization in a steam boiler is presented in Fig.1.

The transfer function of PID controller applying Laplace transforms and SIMULINK model is as follows:

$$W_{PID}=\frac{i_{out}(s)}{\Delta i(s)}=\frac{(D\cdot N^{-1}+P\cdot I^{-1}\cdot N^{-1})s^2+(P\cdot I^{-1}+N^{-1})s+1}{s(I^{-1}\cdot N^{-1}\cdot s+1)}, \quad (1)$$

where Δi(s) and i_{out} (s) – Laplace transforms of input and output signals, mA; P – proportional link coefficient; I – integral link coefficient, min^{-1}; D – derivative link time constant, min; N- filter coefficient, min^{-1}. s – Laplace variable, min^{-1}. All constants are tuned automatically during the simulation process (Fig. 2).

The steam boiler is considered as two component volume (water + steam) unit with constant sensitivity and response parameters. In that case the transient process of pressure alteration can be described with second-order differential equation with constant coefficients. Applying Laplace transform, the transfer function of the steam boiler for transient process simulation is obtained:

$$W_{SB}=\frac{p_Q(s)}{Q_F(s)}=\frac{\eta\cdot K_{SB}}{T_w\cdot T_s\cdot s^2+(T_w+T_s)\cdot s+1}, \quad (2)$$

where Q_F(s) – Laplace transform of furnace heat flow, MW; p_Q(s) - Laplace transform of efficient output steam pressure, bar; η = 0.93 – efficiency factor of the boiler using economiser; K_{SB} = 6.5 bar·MW^{-1} – transfer coefficient (gain) of input-output link (Q → p_Q); T_w = 5 min – time constant of water temperature rise; T_s = 19 min – time constant of steam pressure rise.

Rated conditions of steam boiler for modelling are as follows: input water temperature – 90 ^{0}C; water volume – 7500 kg; steam pressure – 6 bar; steam expenditure – 50 kg· min^{-1}. Heat power at rated steam expenditure is 1.5 MW.

Steam expenditure as a load (disturbance) has a directly negative effect on common steam pressure in the boiler. Load growth causes pressure decrease for transient volume p_q (Fig.1). The following transfer function describes it:

$$W_q=\frac{p_q(s)}{q(s)}=\frac{K_q}{\tau_q\cdot T_q\cdot s^2+(\tau_q+T_q)\cdot s+1}, \quad (3)$$

where q(s) – Laplace transform of steam flow, kg · min^{-1}; p_q(s) - Laplace transform of appropriate steam pressure change, bar; K_q = 0.065 bar·min·kg^{-1} – transfer coefficient of disturbance; τ_q = 2 min and T_q = 7 min – dead time and time constant of disturbance affect on steam pressure.

The heat power actuator for heat production and heat flow regulation consists of several devices: frequency converter (rated input – 20mA, rated output – 50 Hz); servomechanism SQM50.482A2Z3 with synchronous motor (rated input - 220 V, 50 Hz, rated output – 3.14 min^{-1}, shaft max revolution angle – 2.4 radians) and feedback potentiometer, gas valve (max input – 2.4 radians, max output – 4.3 m^3·min^{-1}), air valve (max input – 2.4 radians, max output – 57.6 m^3·min^{-1}); burners and furnace (rated gas mixture input – 46.5m^3·min^{-1}, rated heat power output – 2 MW).

According to block-diagram (Fig.1) the transfer function of the actuator input-output link for transient process simulation has been compiled:

$$W_A(s)=\frac{Q_F(s)}{i_a(s)}=\frac{K_f\cdot W_{Sm}\cdot(K_{GV}+K_{AV})\cdot K_F}{K_f\cdot W_{Sm}\cdot K_{Fb}+1}, \quad (4)$$

where i_a(s) – Laplace transform of actuator input signal, mA; K_f = 2.5 Hz·mA^{-1} – transfer coefficient of frequency converter; K_{GV} = 1.8 m^3·min^{-1}·radians^{-1} – transfer coefficient of gas valve; K_{AV} = 24 m^3·min^{-1}·radians^{-1} – transfer coefficient of air valve; K_F = 0.043 MW·m^{-3}·min – transfer coefficient of furnace; K_{Fb} = 4.5mA·radians^{-1} – transfer coefficient of motor feedback; $W_{Sm}(s)=\omega(s)/f(s)=K_{Sm}/s-$ the transfer function of the synchronous motor; $\omega(s)$ - Laplace transform of angular speed, radians·min^{-1}; $f(s)$- Laplace transform of voltage frequency, Hz; K_{Sm} = 0.063 radians · min^{-1} · Hz^{-1} – speed coefficient of synchronous motor.

B. Operational equation of invariant PID-DPC control system

The main task of the steam boiler control system is to ensure perfect compensation of the physical affect of steam load *q (t)* on steam pressure *p (t)* by the use of the disturbance preemptive compensation circuit operating under the invariant control principle. If the action is made correctly, the controlled variable should remain undisturbed even if the load changes substantially.

To obtain the mathematical model of the two loop invariant control system – steam pressure closed loop feedback (PID) control and disturbance (steam expenditure as a load) preemptive compensation (DPC) control loop, the following system of operational equations has been solved:

$$\begin{cases} i_{out}(s)=W_{PID}\cdot[i_0(s)-K_p\cdot p(s)] \\ Q_F(s)=W_A\cdot[i_{out}(s)+i_c(s)] \\ i_c(s)=K_{Fl}\cdot W_C\cdot q(s) \\ p(s)=W_{SB}\cdot Q_F(s)-W_q\cdot q(s)] \end{cases}, \quad (5)$$

where p(s) - Laplace transform of actual output steam pressure, bar; i_0(s) – Laplace transform of control system's

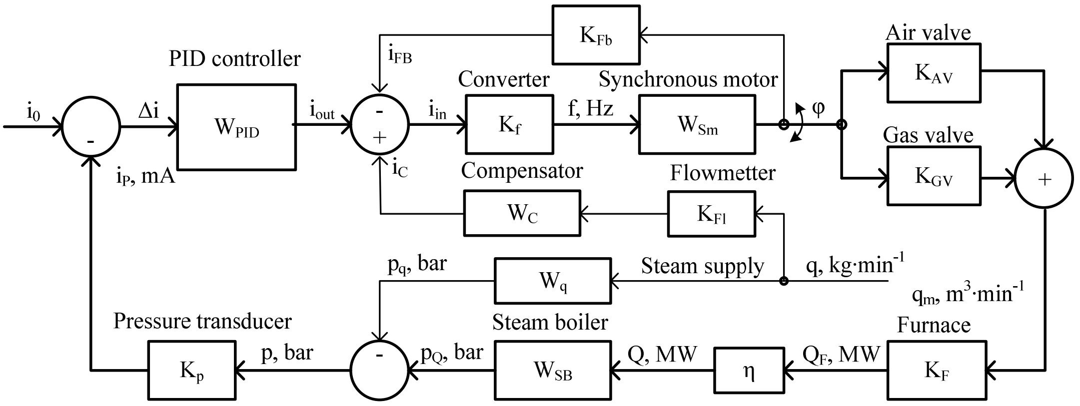

Fig. 1. Algorithmic block-diagram of steam boiler PID – DPC invariant control system: i_0 – input setup, mA; i_p – steam pressure transducer output, mA; i_{out} – PID output, mA; i_C – DPC output, mA; q_m – gas mixture flow, m^{3}min^{-1}; Q_F – furnace output, MW; Q – effective heat flow, MW; p – steam pressure, bar .

input (reference) signal, mA; $K_p = 2$ mA·bar^{-1} – transfer coefficient of steam pressure transducer; $K_{Fl} = 0.2$ mA·min·kg^{-1} – transfer coefficient of steam flow (supply) transmitter; W_C - unknown transfer function of disturbance preemptive compensation (DPC) circuit. After solution of the equation system (5) an operational equation (6) has been obtained:

$$p(s)=\frac{i_0(s)\cdot W_{PID}\cdot W_A\cdot W_{SB}+(K_{Fl}\cdot W_C\cdot W_A\cdot W_{SB}-W_q)q(s)}{K_p\cdot W_{PID}\cdot W_A\cdot W_{SB}+1}. \quad (6)$$

In conformity with the invariant control principle, the expression of the transfer function W_C for DPC control loop is obtained. From expression (6) the condition of invariance can be formulated: if $K_{Fl}\cdot W_C\cdot W_A\cdot W_{SB}-W_q=0$, then the disturbance q (t) does not affect the transient process in the steam boiler. To compensate disturbance affect on the steam pressure the DPC algorithm should be composed according to such transfer function:

$$W_C=\frac{W_q}{K_{Fl}\cdot W_A\cdot W_{SB}}=K_C\cdot\frac{T_w\cdot T_s\cdot s^2+(T_w+T_s)\cdot s+1}{\tau_q\cdot T_q\cdot s^2+(\tau_q+T_q)\cdot s+1}\cdot(T_A\cdot s+1), \quad (7)$$

The time constant of the actuator T_A and the transfer coefficient of the compensator K_C can be expressed with system parameters:

$$T_A=\frac{1}{K_f\cdot K_{Fb}\cdot K_{Sm}}=\frac{1}{2.5\cdot 4.5\cdot 0.063}=1.41\text{min.},$$

$$K_C=\frac{K_q\cdot K_{Fb}}{\eta\cdot K_{SB}\cdot K_{Fl}\cdot K_F(K_{AV}+K_{GV})}=$$
$$\frac{0.065\cdot 4.5}{0.93\cdot 0.65\cdot 0.2\cdot 0.043\cdot(24+1.8)}=0.22.$$

Development of the compensator's model according to the algorithm (7) is problematic because of higher order of numerator expression in comparison with the denominator one. Since the time constant of the actuator is substantially lower than that of control process and of disturbance influence, some simplifications of (7) can be applied. Ignoring inertia of servo-mechanism ($T_A \approx 0$), the compensator can be composed according to the algorithm:

$$W_C=K_C\cdot\frac{T_w\cdot T_s\cdot s^2+(T_w+T_s)\cdot s+1}{\tau_q\cdot T_q\cdot s^2+(\tau_q+T_q)\cdot s+1}=0.22\cdot\frac{95\cdot s^2+24\cdot s+1}{14\cdot s^2+9\cdot s+1}, \quad (8)$$

Expression (6) describes the transient process of steam pressure stabilization in a closed loop PID-DPC control system of the steam boiler, invariant to the load as a disturbance.

Transfer function (8) describes sub-invariance conditions for the disturbance influence preemptive compensation on steam pressure change. It is in close correlation with the steam boiler (2) and steam load (3) operation algorithms.

III. Simulation of Steam Boiler Invariant Control

The block-diagram (Fig.2) of the steam boiler control system simulation is compiled for comparative analysis of conventional PID control model and invariant PID-DPC control model, using functional blocks from SIMULINK libraries. The main closed loop control circuit consists of *PID controller* with limited output (± 20mA) and operation algorithm (1), actuator for heat power supply with operation algorithm (4), *Steam boiler* as a steam production unit with operation algorithm (2) and *Pressure transducer* with transfer coefficient K_p = 2mA·bar^{-1} for steam pressure continuous measurement. *Saturation* is installed for steam pressure limitation up to 15bar. Efficiency of the steam boiler TTK-70 with economizer is up to 93%. An actuator consists of: servomechanism with *Converter* (K_f = 2.5 Hz·mA^{-1}), *Synchronous motor* (K_{Sm} = 0.063 radians·min^{-1}·Hz^{-1}) simulated by integrator with limited output (shaft max revolution angle – 2.4 radians) and *Feedback* potentiometer (K_{Fb}= 4.5 mA·radians^{-1}) to improve the control stability; *Air valve* (K_{AV}=24m^3·min^{-1}· radians^{-1}) and *Gas valve* (K_{GV} =1.8 m^3·min^{-1}·radians^{-1})- controlled by servomechanism simultaneously; *Furnace* (K_F = 0.043 MW· min·m^{-3}) for gas mixture burning.

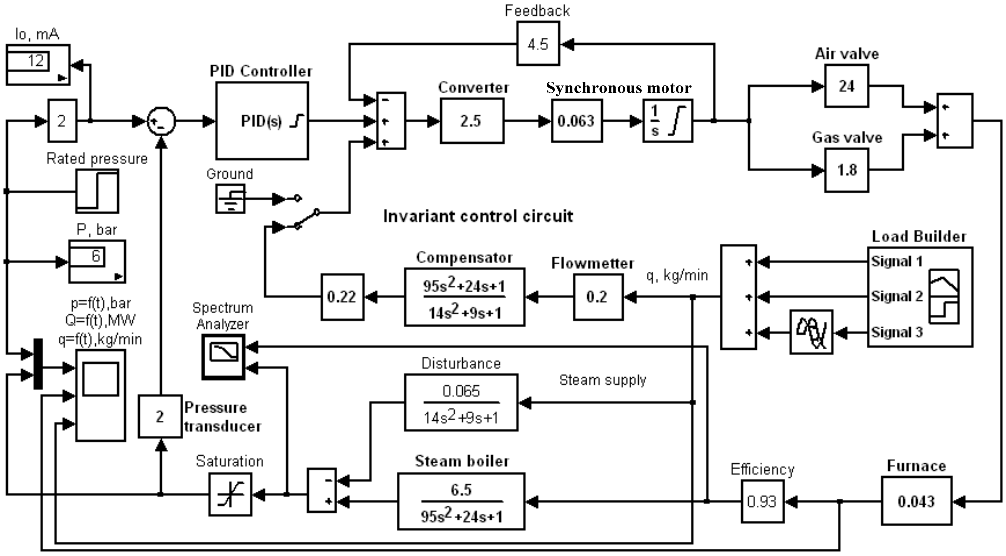

Fig.2. Simulation block - diagram of steam pressure invariant PID – DPC control system in MATLAB-SIMULINK environment.

To perform constant, linear, pulse case and randomly changing components of variable disturbance - steam load q(t) the *Load Builder*, *Transport Delay* and *Sum* blocks are applied.

The steam load impact *Compensator* is performed as a second order differential filter accordingly to algorithm (8). The steam supply is measured by *Flow-meter* (K_{Fm} = 0.2 mA·min·kg^{-1}).

For *Disturbance,* as a variable steam supply (load) affect on the steam boiler output parameter (the steam pressure), simulation the transfer function block with appropriate algorithm (3) is used.

For the control system starting and *Rated pressure* setup the step block is installed. Digital displays are set up for numeric values visualization: p – pressure set point, 6bar; i_0 – system input, 12mA. *Spectrum Analyzer* enables to search steam boiler input-output signals magnitude, frequency spectrum and phase.

For visualization of main input-output variables, such as steam pressure *p(t)*, heat flow *Q(t)* and load *q(t)*, the scope is set up.

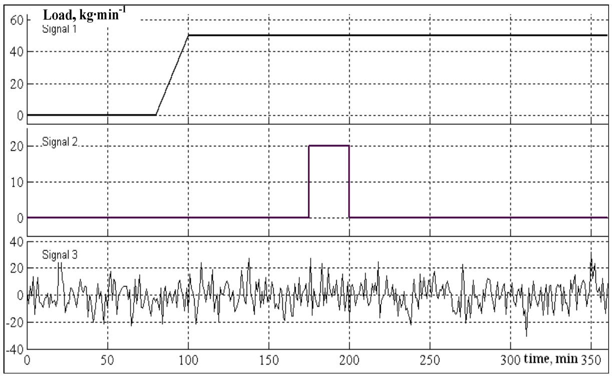

Fig. 3. Steam load as a main disturbance builder output signals, simulated in MATLAB-SIMULINK environment: Signal 1 - linear growing and constant component; Signal 2 – pulse case overload component; Signal 3 – random fluctuating component (Gaussian probability distribution).

IV. SIMULATION PROCEDURES AND RESULTS

Load values used during simulation of the steam boiler control system are presented in Fig. 3. To search wide spectrum of load q(t) influence on the steam pressure p(t), the simulation time should be long enough because of high transient process inertia (t_{sim} = 350 min).

Simulation of the steam boiler control system is started at no load mode, when the main disturbance - $q = 0$. After the transient steam pressure reaches the set point – 6 bar and becomes stable, the steady growing load with slope 2.5 kg·min^{-1} per minute is activated. The load growth limit is 50 kg·min^{-1} - the rated value for steam boiler Vapor TTK-70 (Signal -1, Fig.3). When the steam pressure becomes stable the pulse overload = 20 kg·min^{-1} is added (Signal-2). After 230 minutes from the beginning, random component with amplitude ± 20 kg·min^{-1} and frequency 0.5 min^{-1} is added. The final load is (50 ± 20) kg·min^{-1}.

Simulated response of steam pressure *p(t)* change in the steam boiler feedback control system with optimally tuned PID controller shows, that the maximal overshoot of the steam pressure run up process is lower 8% and response time does not exceed 25 minutes (Fig. 4). Therefore, the feedback control system of the steam boiler with PID controller is sufficiently stable and fast in operation under no load or constant load conditions. Under steady growing load and short-term overload, the response curve has a great deviation – up to 25%. Under random fluctuating load the maximum amplitude of controlled variable oscillations is up to ± 8% (Fig. 4).

Simulation results testify that the steam boiler feedback PID control system operation quality is insufficient under variable load. Due to response inertia of PID controller, the heat power actuator fails to change the heat flow in time, the heat power regulation is delayed and disturbance rejection is too late.

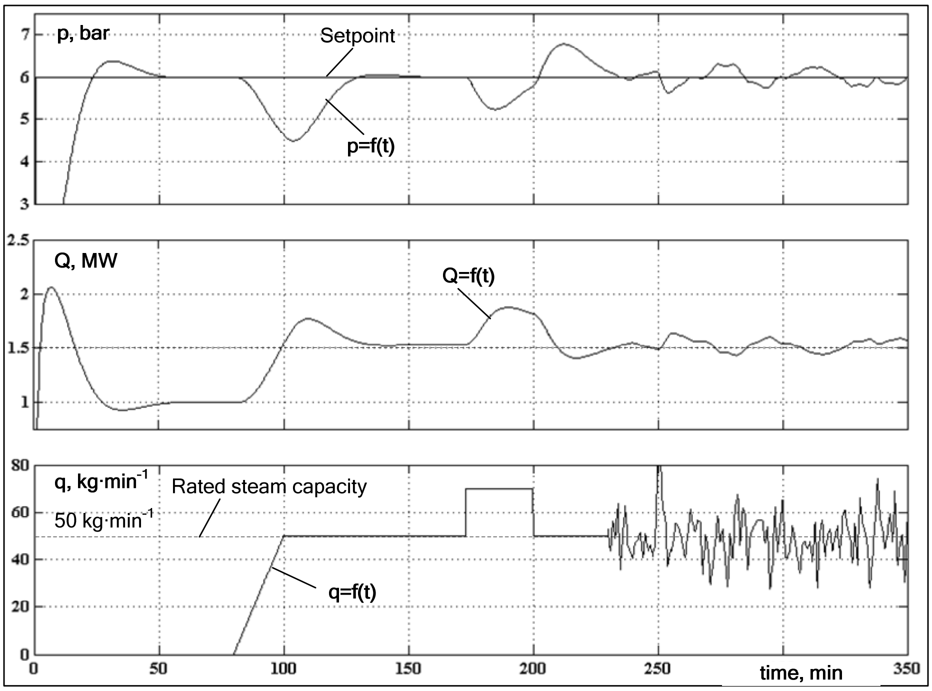

Fig.4. Simulated transient characteristics of traditional PID control system in MATLAB-SIMULINK environment under determinate variable load and randomly fluctuating load: p(t) – steam pressure, bar; Q(t) – heat flow, MW; q(t) – steam flow as a load and disturbance of the boiler, kg·min^{-1}.

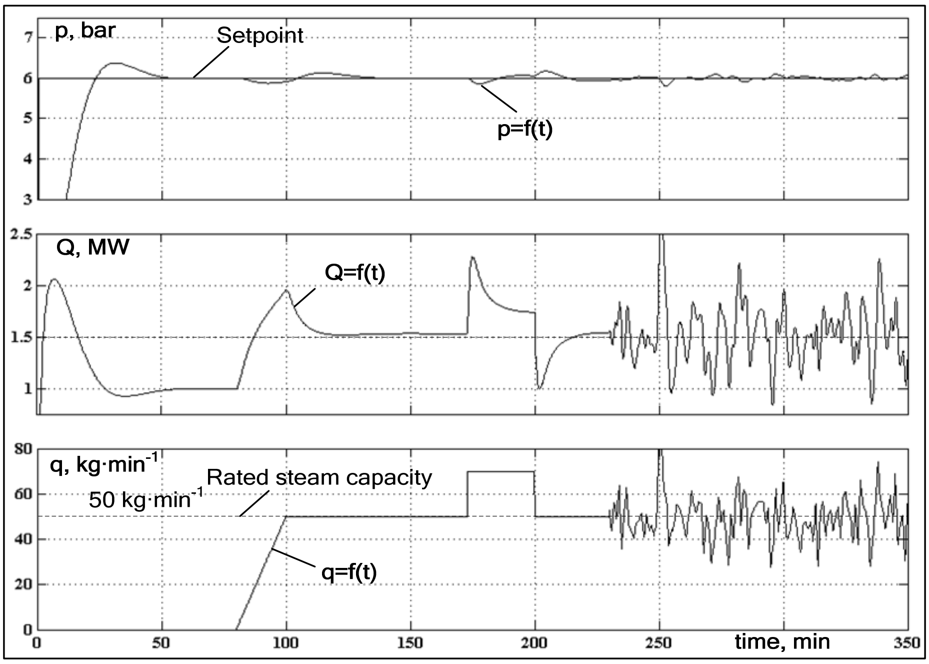

Fig.5. Simulated transient characteristics of invariant PID-DPC control system in MATLAB-SIMULINK environment under determinate variable load and randomly fluctuating load: p(t) – steam pressure, bar; Q(t) – heat flow, MW; q(t) – steam flow as a load and disturbance of the boiler, kg·min^{-1}

If the parameters of the steam boiler and the load exchange, steam pressure control quality becomes worse.

The simulated response of steam pressure *p(t)* in the steam boiler invariant PID-DPC control system with disturbance *q(t)* preemptive compensation circuit, the parameters of which are correctly calculated using the invariant control algorithm (8), shows that the process parameter *p(t)* remains practically constant under any type of load – constant, steady changing, pulse or randomly fluctuating (Fig. 5). If the steam load deviates from the rated value for ± 25 %, deviation of the steam pressure is only ± (1.5 - 3) % of set point value. Due to high speed preemptive operation of invariant control circuit, the disturbance is timely rejected by effective control of heat power (Fig.5).

The parameters of the PID controller are the same as for only feedback control. Close conformity of the parameters of invariant controller and technological part of the system is relevant. Therefore, an adaptive self-tuning controller is needed.

V. CONCLUSIONS

Invariant PID-DPC control system with a Preemptive compensating circuit, the algorithm and parameters of which are correctly calculated according to the invariant control principle, cancel out the affect of main disturbance – the fluctuating steam expenditure *q(t)* as a load on the steam boiler output variable – steam pressure *p(t)*.

Simulations show that for feedback control system with PID Controller and optimally tuned parameters the overshoot of the control variable *p(t)* reaches - 25% under linear growing load (from no load to rated value $q=50\ kg\cdot min^{-1}$), but under randomly fluctuating load with amplitude ±25 % and frequency 0.5 min^{-1} it is ±8% - showing overall unacceptable control quality (Fig. 4).

Introduction in practice the invariant PID-DPC control system with sub-optimally tuned parameters of disturbance *q(t)* preemptive compensation circuit the output variable *p(t)* overshoot and fluctuations decreases up to ± (1.5 – 3)% (Fig. 5), and through this makes the process of the steam boiler operation more stable and more efficient.

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