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Faculty of Mechatronics, Informatics
and Interdisciplinary Studies

Nonlinear process control - the method using derivatives

Diploma thesis

Study program: N2612 Electrical Engineering and Informatics
Specialization: Mechatronics

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1. Studying the basics of steam superheating in coal power plants.
2. Description of the nonlinear control method using derivatives of the plant variables.
3. The application of the method to the selected simulation example.
4. Description of the possibilities to apply this method to the superheater in power plant (pros & cons). Focus to the standard goals of control and their fulfilment by this method.
5. The simulation attempt to realize nonlinear control on the superheater simulation model.

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[1] **Vostrikov A., Frantsuzova G. Automatic control theory. Tutorial. - Novosibirsk: NSTU, pp.274-295, 2003. (in Russian).**

[2] **Hubka, L. Temperature Dynamic of Heat Exchangers in Boilers. In Eurosim 2010 - 7th EUROSIM Congress on Modelling and Simulation. Praha. CTU. 2010. p. 1-5. ISBN 978-80-01-04589-3.**

[3] **Hubka, L.; Modrlak, O., The practical possibilities of steam temperature dynamic models application, 13th International Carpathian Control Conference (ICCC), 2012, pp. 237-242. ISBN 978-1-4577-1867-0.**

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Abstract

The goal of this thesis is to present the nonlinear control system design algorithm named the localization method. Theoretical basics and method's capabilities in application for simple linear and nonlinear plants are shown.

The method is applied for earlier developed linear and nonlinear models of the coal power plant's once-through boiler's output superheater. There are descriptions of the plant features, elements and parameters.

The control of the plant is proceed by two control cascades; each of these cascades uses the localization controller and the special element for derivatives evaluating – the differentiating filter.

Through the research there were the different localization loop configuration developments. Simulation results for these variants of the localization loops are presented.

Key words: localization method, differentiating filter, output superheater of once-through boiler.

Content

1 Introduction

The control system synthesis – one of the main aims for the control theory. This aim becomes significantly complicated while being used for a nonlinear plant. Nowadays there are rather impressive numbers of different researches at this topic, but the most of them are usually connected only with correction of the nonlinear systems behavior. Despite the large number of researches, there are few regular algorithms for nonlinear control system design. Therefore, there is a need for new algorithms development. Nowadays existing algorithms for the nonlinear control systems synthesis: the big gains method, the sliding modes method, the robust control, the nonlinear model predictive control.

In this thesis alternative nonlinear control system design algorithm is presented. It has quite clear and regular design algorithm. Main idea of this method is the nonlinearities and disturbances influence localization in the inner fast processes subsystem. Therefore, it is called the localization method.

The design procedure and capabilities of the method will be demonstrated by processes simulation, applied to the models of the output superheater of the coal power plant's once-through boiler. Electrical energy field is very important nowadays, increasing prices for energy sources and power grid complexity growth put forward more and more requirements for control systems of all types of power plants, often absolutely new in comparison to the situation twenty or ten years ago. Therefore, the simulation model creation, the control system design based on these models and verification before the complementation into the real power plants are very important tasks for the control theory.

The once-through boiler itself by means of control theory is a very large complicated nonlinear plant with non-stationary parameters, which can be divided to many subsystems. The own control system is needed for each of these subsystem. Therefore, overall control system has huge number of parameters, controllers, etc. In this thesis it is considered only one element of the high-pressure part of the once-through boiler – the output superheater.

2 The controlled process description

2.1 The once-through boiler's output superheater

In this thesis, we will take the output superheater of coal power plant's once-through boiler as a plant for control system design. The once-through boiler has different technological parts – high-pressure and intermediate-pressure. Each of these parts consists of the set of heat exchangers, valves, spray attemperators, etc.The structure scheme of once-through boiler is presented on fig.2.1.

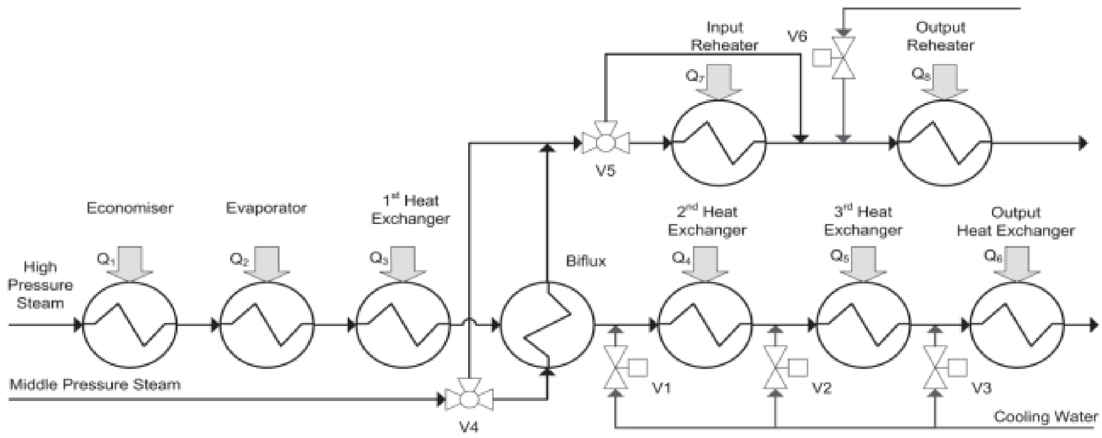

Figure 2.1 – The once-through boiler structure scheme

The detailed description of this structure can be found in [1]. While passing each heat exchanger or reheater, the steam is being heated by flue-gas burners. After passing the high-pressure part of a boiler, the steam is directed into the biflux heat exchanger, where it is again reheated.

Such system has multiple inputs and outputs (MIMO). The most important for this research are steam parameters: temperature, mass flux, pressure. Also, one of the most interesting input variables is the power plant load level. Electricity production from all types of sources in every moment must satisfy requirements of all consumers. Parameters of the electricity in a power grid, production-consumption rate, economical factors (such as energy cost price) – all these factors are taken into account during the current power load choice from different energy sources. Due to a situation in the power grid (for example, sharp increase or decrease in energy consumption), the load level of a power plant can be significantly changed. Changes in power load level, in turn, lead to changes in processes inside heat exchangers – the dynamic, the border conditions are not constant. In this research, we will focus on the control system for one part of the once-through boiler – the output superheater of the high-pressure part. The main aim for such system is obtaining and maintenance of set of desired steam parameters – mainly, the temperature.

Each presented subsystem – heat exchanger, reheater, evaporator, etc. – can be described by its own simulation model. In this thesis, we are interested only in the output superheater model. The structure scheme of the output superheater with a control element is presented on fig. 2.2.

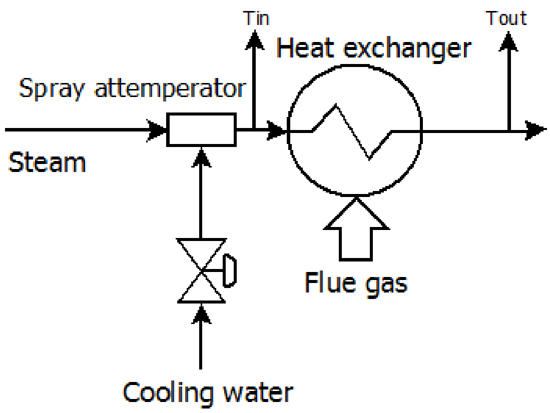

Figure 2.2 – The structure scheme of the superheater

The steam is fed to input of the spray attemperator, where it is mixed with cooling water according to the valve position. After mixing, precooled steam goes to the heat exchanger. Steam heating is made by a flue gas burning. Amount of heating energy depends on current plant's load level (it is also called heating energy level – Q-level). In this case, the control system actuator is the valve – by changing its position we can change the parameters of steam on the output of heat exchanger. One of important system features is the possibility to measure the steam temperature on the input of the heat exchanger.

Nowadays, several simulation models of the superheater has been developed [2,3]. Real mathematical model of superheater is high-ordered and strongly nonlinear, therefore, for the beginning of control system design we will use linearized simplified model. Obtained controller, after several parameters tuning, will be subsequently used for nonlinear model simulation.

2.2 The linearized model of the superheater

The set of superheater linearized models was developed by the Institute of Mechatronics and Computer Engineering in Technical University of Liberec [3]. Usual purpose of linearization is control algorithm synthesis or state observer design. Primary aim of this development was the decreasing of computation requirements for the processes simulation in nonlinear model. It was proofed, that plant's dynamic and state properties in linearized models are relatively accurately correspond to same properties in nonlinear model. The detailed process analysis is presented in [3].

Inputs and outputs of the output superheater, important for the control circuit, are:

- Inputs:
  - V – cooling valve position (controller output from 0 to 1);
  - Q – source of heat (flue gas);
  - Input steam parameters – temperature, pressure, mass flow;
  - Parameters of cooling water;
- Measured outputs:
  - T_{in} – steam temperature on the input of heat exchanger (after mixing with cooling water);
  - T_{out} –the output steam temperature (main controlled parameter).

Operating mode for boiler is between 50% and 100% of the power load (which is equal to 0% to 100% of electrical power output). Power level value influences all superheater inputs. Temperature of the output steam must remain constant (575°C) – it is the primary aim for the control system design.

The linearized model has only two input values – valve position and input steam temperature, and two outputs – steam temperatures after mixing and on the output of heat exchanger. All other inputs depend on current power load level, therefore, they are not realized as input signals, but they are considered as transfer functions parameters. Thus, model in each operating point (which is defined by power load level) has different parameters. The structure of linearized model is presented on fig. 2.3.

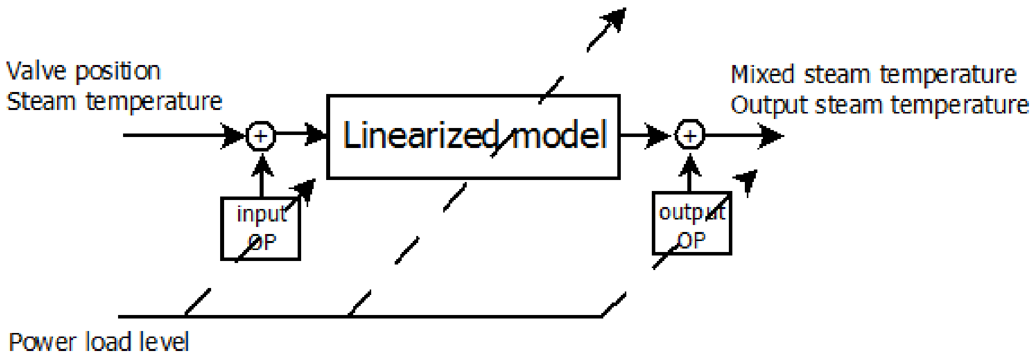

Figure 2.3 – The linearized model structure

It is necessary to choose set of operating points before using linearization. In this thesis, chosen operation points are 50 %, 70 %, 90 % and 100 % of power load.

The structure scheme of the output superheater, obtained by using identification method [4], is presented on fig. 2.4:

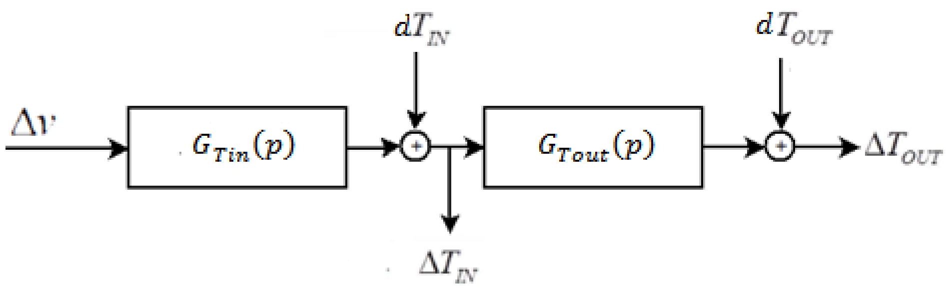

Figure 2.4 – The structure scheme of the linearized superheater model

On this scheme there are $\Delta v, \Delta T_{IN}, \Delta T_{OUT}$ – changes of valve position and steam temperatures; dT_{IN}, dT_{OUT} – temperature disturbances.

Dynamic and static effects of front-end spray on change of the steam temperature T_{IN}after the spray attemperator are approximated by the transfer function (2.1):

$$G_{Tin}(p) = \frac{k_{Tin}}{(T_{Tin1}p + 1)(T_{Tin2}p + 1)(T_{Tin3}p + 1)}; \tag{2.1}$$

where parameters $k_{Tin}, T_{Tin1}, T_{Tin2}, T_{Tin3}$ are changing due to selected operating point.

Dynamic and static effects of input steam temperature change on the output steam temperature T_{OUT} are approximated by the transfer function (2.2):

$$G_{Tout}(p) = \frac{k_{Tout}}{(T_{Tout1}p + 1)(T_{Tout2}p + 1)(T_{Tout3}p + 1)}; \quad (2.2)$$

where parameters $k_{Tout}, T_{Tout1}, T_{Tout2}, T_{Tout3}$ are changing due to selected operating point.

Identification of transfer functions parameters was based on the data from the original nonlinear model experiments in the neighborhood of required power load levels. Different parameters values choices according to operation point are presented in Table 1.

Table 1.Model parameters values in different operating points

Q level	k_{Tin}	T_{Tin1}	T_{Tin2}	T_{Tin3}	k_{Tout}	T_{Tout1}	T_{Tout2}	T_{Tout3}
50%	-118.7	1.69	1.82	3.8	1.0675	51.4641	51.2095	53.5572
70%	-73.69	1.69	1.82	3.8	1.1313	39	39	39
90%	-48.99	1.69	1.82	3.8	1.1723	28	28	28
100%	-40.63	1.69	1.82	3.8	1.1948	25	25	25

Simulation linearized model is developed in MATLAB *Simulink*. Parameters values switching is made through *Lookup Table* block. This block uses the input values to generate outputusing the linear interpolation and extrapolation method. Simulation scheme is presented on fig. 2.5.

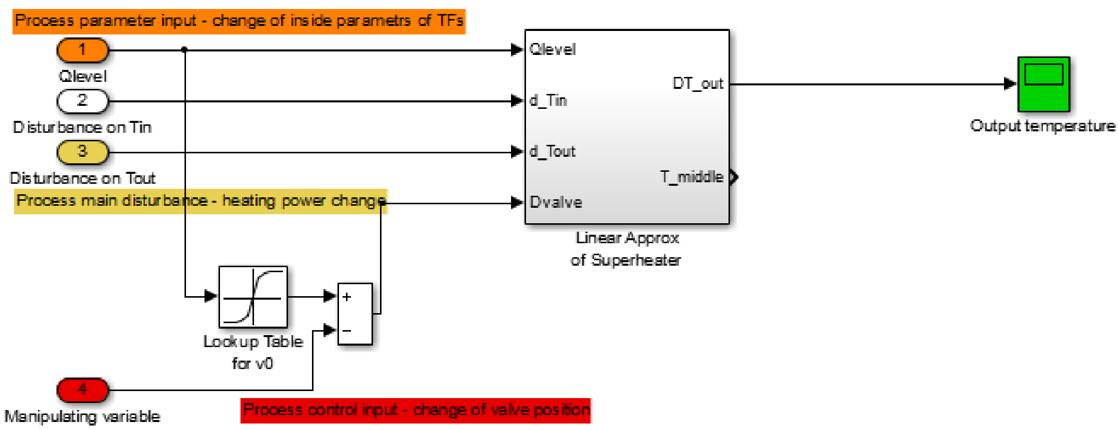

Figure 2.5 – The simulation scheme of linearized superheater model

2.3 The nonlinear model of the superheater

The nonlinear simulation model was developed by Faculty of Mechatronics, Informatics and Interdisciplinary Studies of Technical University of Liberec. This model is complicated, has high order. It is proofed [1], that temperature dynamics of output superheater can be described by equations:

$$\frac{dT_{Fe}}{dt} = \frac{1}{m_{Fe}c_{Fe}} \times \left(\dot{Q}_{input} - \alpha S(T_{Fe} - T)\right);$$
$$\frac{dT}{dt} = -\frac{\dot{m}}{\Delta V \overline{p}} r^* T + \alpha \frac{S}{V\overline{p}\bar{c}_p}(T_{Fe} - T) + \Omega \frac{\dot{m}}{\Delta V}\frac{T_{in}}{p_{in}}. \quad (2.3)$$

In these equations there are T_{Fe} – the temperature of barrier (tube wall); T – the steam temperature; m_{Fe}, c_{Fe} – barrier's mass and heat capacity; $\dot{Q}_{input}$ – the input heat power; α – heat exchange coefficient; S – the heat exchange area; $\dot{m}$ – the steam mass flow; V – inner tube dimension; $\Delta V = F * \partial z$, where F – the cross-section area, z – space coordinate; $\overline{p}, \bar{c}_p$ – mean values of steam density and heat capacity in whole tube;

$$r^* = \begin{bmatrix} 1 & 0 & . & . & 0 \\ -1 & 1 & 0 & . & 0 \\ 0 & . & . & . & . \\ . & . & . & . & 0 \\ 0 & . & 0 & -1 & 1 \end{bmatrix}; \ \Omega = [1 \quad 0 \quad . \quad 0]^T.$$

The accuracy of such solution is enough high. The difference between simulation and real plant's values is very small both in the steady state, and in dynamic. The structure scheme of nonlinear simulation model is shown on fig. 2.6.

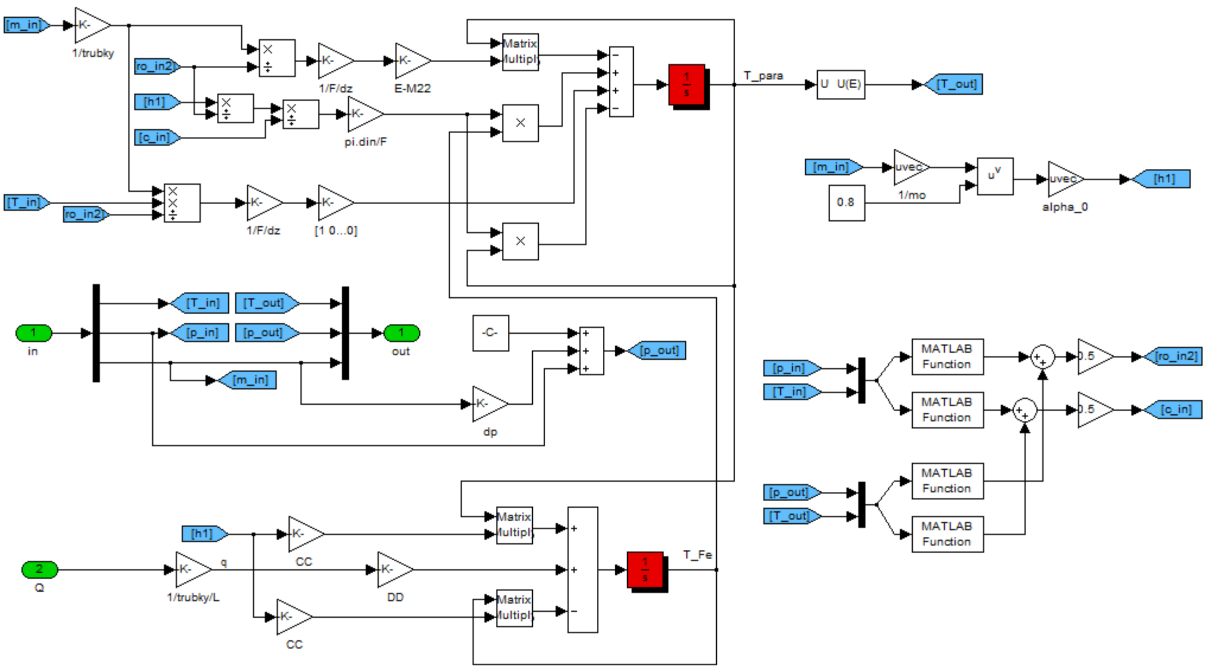

Figure 2.6 – The simulation scheme of nonlinear superheater model

The nonlinear simulation model also makes heating level recalculation with *Lookup Table* blocks, as input parameters it takes output steam temperature reference point (usually 575°C) and power load level Q. Nonlinearities of this model are contained in changes of time constants and gains. In this thesis we won't go deeply into analysis of structure and processes in nonlinear model. We will use controllers, designed for the linearized models, and tune them in order to make them robust.

2.4 The control system design task

Plant for a control system design can be described by two ways:

- Linearized model: is described in subchapter 2.2, presented by transfer functions (2.1) and (2.2) and linear simulation model.
- Nonlinear model: is described in subchapter 2.3, presented by nonlinear simulation model.

The actuating variable limitation is as follow:

$$0 \leq U \leq 1. \tag{2.4}$$

There are control system aims for the linearized model.

- Making output variable (steam temperature) equal to input reference point. Initial point for output variable is equal to zero. The output steam temperature disturbance is equal to zero. The system functionality must be checked for every chosen operating point ($Q = [50,70,90,100]\%$). Q level during processes passing remains constant. Requirements for steady state and dynamics:

$$t_p \leq 1000s, \sigma \leq 10\%, \Delta \leq 5\%; \tag{2.5}$$

where t_p – setting time, σ – overshoot, Δ – steady state error.

- Neglecting the output steam temperature disturbance in the steady state (reference remains constant). Disturbance has a ramp form. The system functionality must be checked for every chosen operating point. Qlevel remains constant.
- Suppression of the Q level changes influence in the steady state. Switching between operating points can be made by step between nearest ones (for example 50%→70%), or by ramp in whole operating range. Disturbance is equal to zero.

For nonlinear model simulation the only aim is to suppress operating point changes in the steady state and with zero disturbances. Operating points changing is made by the same way, as for the linearized model.

3 The nonlinear control system synthesis, based on the localization method

3.1 General control aims

The control system synthesis implies controller addition to the plant in order to obtain needed steady and dynamic properties.

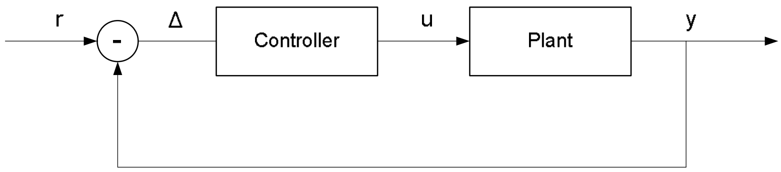

Figure 3.1 – The functional scheme of a SISO control system

Plants, considered in this chapter, can be described by the output equation:

$$y^{(n)} = f\big(t, y, \dots, y^{(n-1)}\big) + b\big(t, y, \dots, y^{(n-1)}\big)u. \quad (3.1)$$

In general case, functions $f_0(.)$ and $b_0(.)$ can be unknown, the dependence on$t$ represents disturbance and plants parameters unsteadiness influence. We will assume only that the range of possible $f_0(.)$ and $b_0(.)$ values is known (for example: $|f_i(.)| \leq f_{imax}, |b_i(.)| \leq b_{imax}, i = \overline{1, n}$), and the speed of these functions changes is significantly (at least, by one order) lower than main processes in a plant.

Control aim is to obtain such an actuating action $u = u(.)$, which will satisfy the condition

$$\lim_{t\to\infty} y = r. \quad (3.2)$$

The condition (2.2) must be fulfilled with given steady state accuracy

$$|\Delta(\infty)| = |r - y(\infty)| \leq \Delta^0. \quad (3.3)$$

Together with steady state requirements (3.2),(3.3), there are also requirements to the system dynamic behavior:

$$t_p \leq t_{p\_max}; \sigma \leq \sigma_{max}, \quad (3.4)$$

where t_p is setting time, σ is overshoot.

In order to meet the steady state requirement (3.3) and the dynamic requirement (3.4), the closed loop desired equation should be constructed. It can be defined through output variable (3.1):

$$y^{(n)} = F\left(y, \dot{y}, \dots, y^{(n-1)}, r\right). \tag{3.5}$$

The desired equation can be relatively easy constructed as a linear differential equation for most types of plants (3.2). Firstly, one should choose desired root values – thus to satisfy requirements (3.3). Secondly, desired characteristic equation (3.5) is constructed accordingly to chosen roots.

3.2 The method description

The localization method as a nonlinear control system synthesis method has been researched by Automatics department of Novosibirsk State Technical University for more than 30 years [5]. The main idea of this method is highest-order output variable derivative usage in case of plant description (3.2) in a feedback loop. Supposed actuating equation is:

$$u = u(x, \dot{x}, r). \tag{3.6}$$

Using of $\dot{x}$ in this equation (or output variable derivatives) allows to obtainthe indirect evaluation of the right-hand side of the plant's differential equation, giving the actual information about nonlinearities and disturbances.

The simplest actuating equation (3.6) is proportional:

$$u = K(F_x(x, r) - \dot{x}), \tag{3.7}$$

where K is the controller gains matrix.

Capabilities of actuating equation (3.7) can be illustrated on nonlinear first-order plant. The mathematical model of such a plant:

$$\dot{y} = f(t, y) + b(t, y)u, \;\; y \in R^1, \tag{3.8}$$

where$|f(.)| \le f_{max}$, $|b(.)| \le b_{max}$ and $b(t, y) \ne 0$.

The desired differential equation must be constructed according to requirements (3.4) and (3.5):

$$\dot{y} = F(y, r). \tag{3.9}$$

We will use the first-order actuating equation (3.7)

$$u = k(F(y, r) - \dot{y}). \tag{3.10}$$

Substituting (3.10) into (3.8), we will obtain closed loop equation:

$$\dot{y} = f(t, y) + b(t, y)k(F(y, r) - \dot{y}),$$

resolving to $\dot{y}$, we will obtain:

$$\dot{y} = \frac{f(t,y)}{1+b(t,y)k} + \frac{b(t,y)k}{1+b(t,y)k} F(y, r). \tag{3.11}$$

Increasing of the gain k to the limit of $k \to \infty$ transforms (3.11) to

$$\dot{y} \to F(y, r).$$

Thus, the appropriate choice of controller parameters allows obtaining desired properties (3.9) in the closed loop. Steady state error can be calculated through the equation:

$$\Delta \approx \frac{f(t,y)}{1+b(t,y)k}. \tag{3.12}$$

All nonlinearities and disturbances, described by functions $f(t, y)$and $b(t, y)$, can be compensated by big values of k. Due to the localization method recommendations, values of k should be chosen according to equation

$$b_{min}k \approx (20 \dots 100). \tag{3.13}$$

In case of choosing controller parameters according to (3.13) the steady state accuracy (3.12) can by evaluated by the equation

$$\Delta \approx (0.05 \dots 0.01)f(t, y). \tag{3.14}$$

This effect appears due to the disturbance localization, which is illustrated on the closed loop structure scheme:

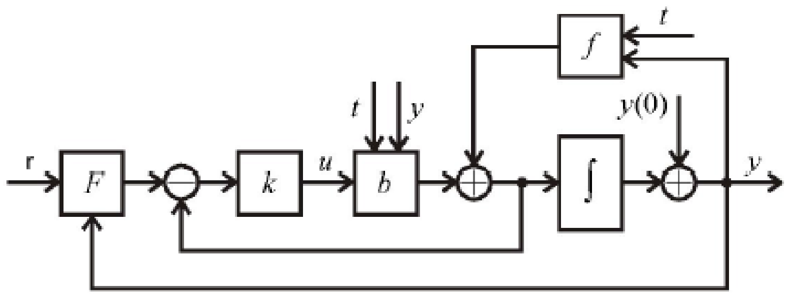

Figure 3.2 – The structure scheme of a closed loop

This scheme has two circuits. Outer circuit is usual output variable feedback loop, while inner circuit is formed by output derivative feedback. The influence of functions $f(t, y)$ and $b(t, y)$, suppressed by the big gain k, is localized in this inner circuit. Also, inner circuit is non-inertial structure (doesn't have any inertial elements).

In order to realize actuating equation (3.10) in practice, we need to make sure that actuating variable values won't go over plant actuating limitations. Taking equation (3.8) into the right-hand side of (3.10), we will obtain:

$$u = k(F(.) - f(.) - b(.)u).$$

After few transformations this equation forms as follows:

$$u = \frac{k}{1+b(.)k}\big(F(.) - f(.)\big). \tag{3.15}$$

The asymptotic actuating equation in case of $k \to \infty$ in closed loop has a form:

$$u = b^{-1}(.)[F(.) - f(.)]. \tag{3.16}$$

Some conclusions, following from (3.15) and (3.16):

1. The asymptotic actuating equation (3.15) corresponds to accurate control task solution. By equating right-hand sides of output equation (3.8) and desired equation (3.9), after few transformations we will obtain accurate actuating equation, similar to (3.16).

2. Actuating variable values in the closed loop stay finite even in case of infinite controller gain k.

3. The equation (3.16) allows calculating the maximum actuating variable value in worst case – when all functions reach their limits:

$$u_{max} = \left|b_{min}^{-1}\right|(|F_{max}| + |f_{max}|).$$

This is the maximum limitation of the actuating value in a closed loop. Desired processes (3.9) can be acquired in the closed loop control system, if the following requirement is met:

$$u_{max} = \left|b_{min}^{-1}\right|(|F_{max}| + |f_{max}|) \leq |\bar{U}|. \tag{3.17}$$

3.3 The differentiating filter

The system must be able to evaluate the output derivative $\dot{y}$ in order to realize the actuating equation (3.10) in practice. Proposed solution is the special structure implementation. This structure is called differentiating filter, and it is realized on integrators. The differential filter (in case of first-order plant) can be defined as the dynamic structure of a first order

$$\mu\dot{\hat{y}} + \hat{y} = y \tag{3.18}$$

or of a second order

$$\mu^2\ddot{\hat{y}} + 2d\mu\dot{\hat{y}} + \hat{y} = y, \tag{3.19}$$

In dependency on the measurement noise level. In these equations $\hat{y}$ is estimated output value; μ is the parameter, which describes the filter's lag, d is damping coefficient. Second-order differentiating filter structure with zero initial conditions has a following form:

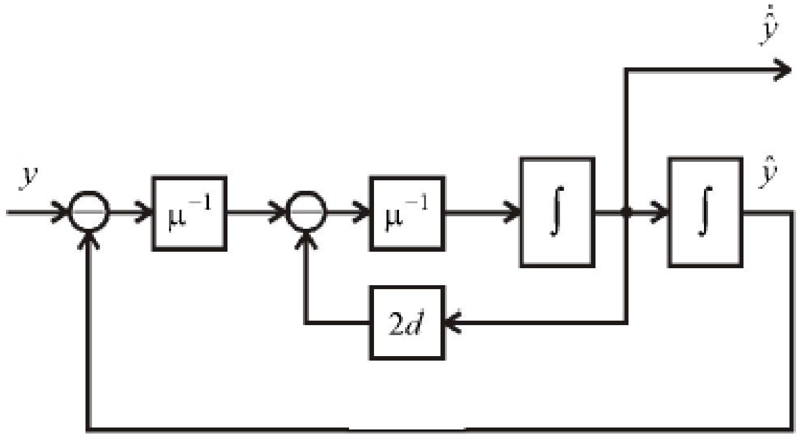

Figure 3.3 – The structure scheme of a second-order differentiating filter

The differentiating filter is a linear structure, its transfer function can be rewritten from differential equation forms (3.18) and (3.19):

$$W_f = \frac{\hat{y}}{y} = \frac{1}{D(\mu p)}, \tag{3.20}$$

where $D(\mu p)$ is the filter characteristic polynomial (it is also called "filtrating polynomial").

The equation for the output variable derivative, with taking to account (3.20), can be written in a following form:

$$\dot{\hat{y}} = \frac{p}{D(\mu p)} y.$$

Due to the fact, that $py = \dot{y}$, this equation can be rewritten to:

$$\dot{\hat{y}} = \frac{1}{D(\mu p)} \dot{y}.$$

If we take limit $\mu \to 0$ in equations (3.18), (3.19), we can consider $\dot{\hat{y}} \to \dot{y}$ – the output derivative evaluation is equal to its real value. Therefore, the filter with a small lag must be chosen in order to realize the actuating equation (3.10). In practice, it is enough to make processes in the filter one order slower, than processes in plant. The differentiating filter implemenation leads to the processes with different speed appearance in the closed loop; besides, faster processes must be stable to keep system operability.

3.4 The different transient processes speeds analysis

As it was noted, processes in main and filtering circuits have the different speed. Therefore, in order to analyze these processes, we must use the process separation method[]. The structure scheme of the closed loop with inserted differentiating has a following form:

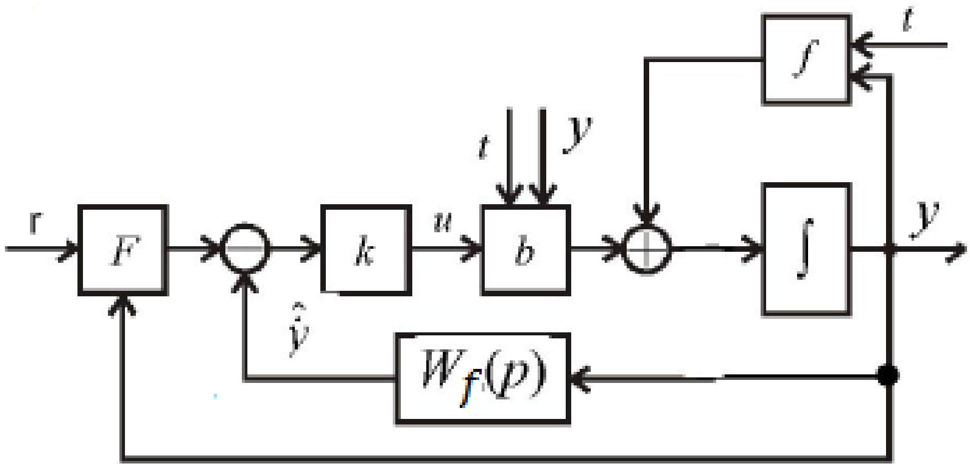

Figure 3.4 – The structure scheme of a closed loop with inserted differentiating filter

In case of a first-order differentiating filter usage the closed loop equations can be written in a following form:

$$\begin{cases} \dot{y} = f(.) + b(.)k\left[F(.) - \dot{\hat{y}}\right], \\ \mu\dot{\hat{y}} = y - \hat{y}. \end{cases} \quad (3.21)$$

As far as there is the derivative in a right-hand side of the first equation, it is necessary to bring this equation to a standard form. Therefore, we define the new variable $z = \mu^{-1}(y - \hat{y})$and transform the equation system (3.21):

$$\begin{cases} \dot{y} = f(.) + b(.)k[F(.) - z], \\ \mu\dot{z} = f(.) + b(.)k[F(.) - z] - z. \end{cases} \quad (3.22)$$

The fast processes subsystem definition:

$$y = const, \qquad \mu\dot{z} = f(.) + b(.)k[F(.) - z] - z.$$

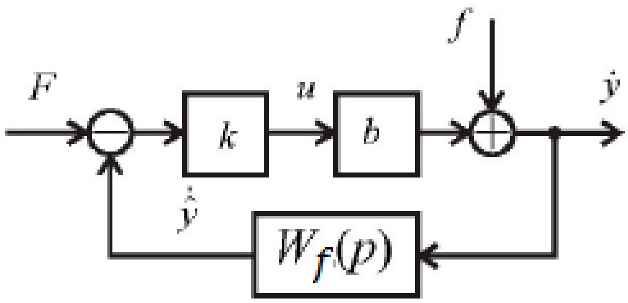

Figure 3.5 – The structure scheme of a fast processes subsystem

The characteristic equation of the fast processes subsystem with a first-order differentiating filter has a following form:

$$\mu p + bk + 1 = 0.$$

In general case:

$$D(\mu p) + bk = 0. \quad (3.23)$$

As far as the fast processes subsystem is linear, general linear system stability criterions are applicable for a stability check. In case of using first- or second-order differentiating filters this subsystem will be stable with any positive values of b(.).

Slow processes subsystem ($\mu = 0$ in (3.22)):

$$\dot{y} = f(.) + b(.)k[F(.) - z], \qquad f(.) + b(.)k[F(.) - z] = z.$$

These equations can be transformed into:

$$\dot{y} = \frac{f(t,y)}{1+b(t,y)k} + \frac{b(t,y)k}{1+b(t,y)k} F(y,r). \quad (3.24)$$

Consequently, the slow processes subsystem description (3.24) is equal to the closed loop with an accurate differentiating (3.11). Therefore, in combination with stable fast processes system behavior is determined by slow processes, which will be close enough to the desired equation (3.9) in case of the correct choice of controller parameters. The design scheme of a closed loop with differentiating filter is presented on the fig.3.6:

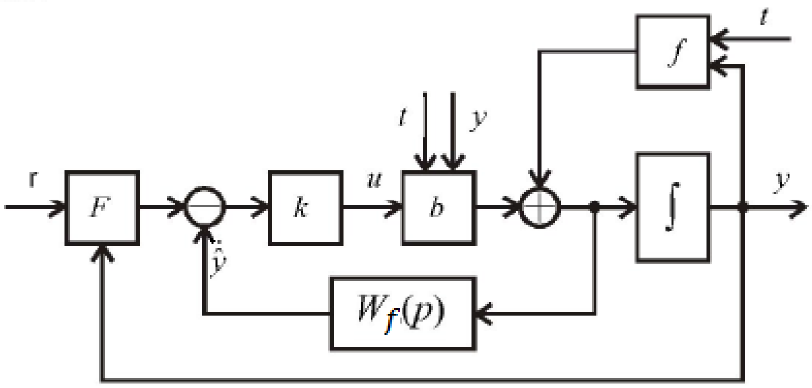

Figure 3.6 – The design scheme of a closed loop with a differentiating filter

In this case the localization circuit is slow processes subsystem, and it is inertial.

3.5 The arbitrary-order system design

Next aim will be the design of localization control system for a plant, described by equation

$$y^{(n)} = f\big(t, y, \dot{y}, \dots, y^{(n-1)}\big) + b\big(t, y, \dot{y}, \dots, y^{(n-1)}\big), \tag{3.25}$$

where $|f(.)| \le f_{max}$, $|b(.)| \le b_{max}$ and $b(t, y) \ne 0$.

The desired dynamic behavior is defined by the desired equation of n-order:

$$y^{(n)} = F(y, \dot{y}, \dots, y^{(n-1)}, r). \tag{3.26}$$

Actuating equation:

$$u = k\big[F(.) - y^{(n)}\big]. \tag{3.27}$$

Placing (3.27) into (3.26), we will obtain the closed loop equation. After resolving to $y^{(n)}$ it takes form:

$$y^{(n)} = \frac{f(.)}{1+b(.)k} + \frac{b(.)k}{1+b(.)k}F(.). \tag{3.28}$$

Increasing gain to the limit $k \to \infty$ gives $y^{(n)} \to F\big(y, \dot{y}, \dots, y^{(n-1)}, r\big)$. Therefore, the correct choice of controller parameters allows realizing desired parameters (3.26) with given accuracy (3.12) for arbitrary-order plant as well. Parameter k choice should be made according to equation (3.13).

The actuating variable value stays finite even if the controller gain is infinite, its maximum is defined by the equation (3.17) and mustn't go through the plant's limitations. In order to realize actuating equation (3.27) we will need the differentiating filter of at least n^{th}-order (which will be able to evaluate $y^{(n)}$). The structure scheme of such an arbitrary-order filter is presented on fig.3.7:

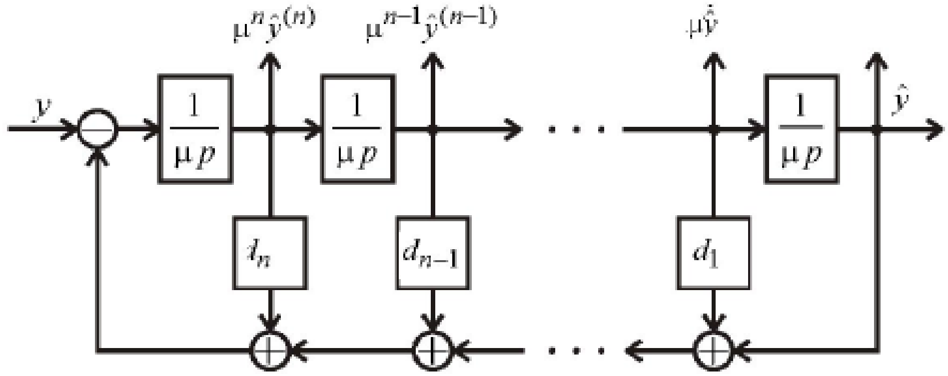

Figure 3.7 – The structure scheme of a n^{th}-order differentiating filter

The transfer function of such a structure:

$$W_f(\mu p) = \frac{1}{D(\mu p)} = \frac{1}{\mu^n p^n + d_{n-1}\mu^{n-1}p^{n-1} + \cdots + d_1 \mu p + 1}, \tag{3.29}$$

where μ – the parameter with small values, which represents filter's lag; $d_i, i = \overline{1, n-1}$ – determines process properties in a filter. The parameters calculation is made by root locus method, the desired locus is chosen according to evaluations:

$$t_f \approx 0.1 t_p;\ \sigma_f \approx 0.1\sigma. \tag{3.30}$$

The design structure scheme of a closed loop is presented on fig.3.8:

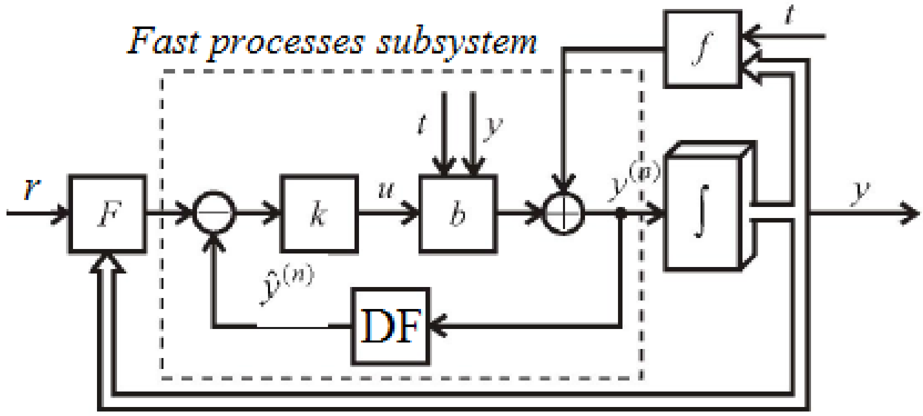

Figure 3.8 – The design structure scheme of a localization closed loop

The transfer function of a fast processes subsystem (marked by a dotted line) is (3.23). Chosen subsystem parameters must maintain its stability.

The overall design algorithm for the localization method:

1) The construction of a desired equation of n^{th}-order (3.26) according to requirements (3.4) and (3.5).

2) The controller gain k calculation according to (3.13).

3) The differentiating filter (3.29) choice. Chosen filter must have small lag.

4) The check of a fast processes subsystem stability; the correction elements implemenation, if it is necessary.

5) The structure realization of a closed loop.

3.6 The method's capabilities demonstration

As it was mentioned before, the main idea of the localization design method is using of the output variable derivatives in an actuating equation. Difference between real derivative value and its desired behavior (defined by desired equation $F(.)$) must be reduced to zero by the controller. In previous chapters we considered only the proportional actuating equation (gain k). In practice, any suitable actuating equation can be defined to meet plant's requirements – of course, changes in actuating equation lead to changes in fast processes subsystem. Therefore, in combination with the actuating equation complementation one must also recheck stability of fast processes subsystem.

In this chapter we will demonstrate localization method's capabilities, considering only proportional actuating rules, applied to linear and nonlinear plants of second-order.

All process simulations were made in *MATLAB Simulink*.

3.6.1 Linear second-order plant

The proposed plant is described by a transfer function:

$$F_p(p) = \frac{y}{r} = \frac{b}{p^2+a_2p+a_1}, \tag{3.31}$$

where $b = 10, a_2 = 3, a_1 = 5$. The output curve with $r = 1$ is presented on fig.3.9:

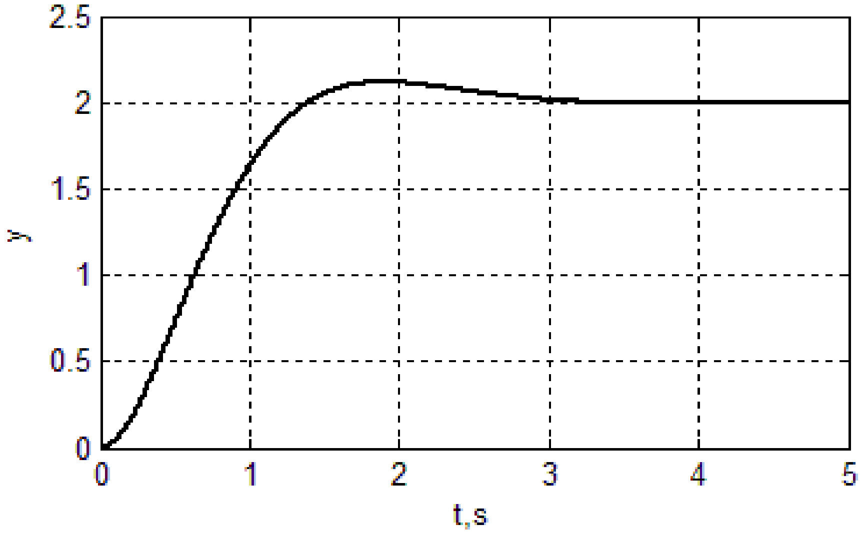

Figure 3.9 – Output variable changes in the plant (2.31)

Processes quality requirements:

$$\Delta \leq 0.05r;\ t_p \leq 4s;\ \sigma = 0. \tag{3.32}$$

The proportional actuating equation will be used:

$$u = k(F(y, \dot{y}, r) - \ddot{y}). \tag{3.33}$$

According to the design algorithm, firstly the desired equation of a second order must be defined. There must be no overshoot in a closed loop, so the imaginary part of chosen roots must be equal to zero. Taking into account speed requirement from (3.32), we will choose desired roots $p_1 = -2, p_2 = -3$. The desired equation takes form:

$$\ddot{y} = F(y, \dot{y}, r) = -5\dot{y} - 6y + 6r. \tag{3.34}$$

The controller gain k is calculated according to (3.13). The upper limit of an acceptable steady state error is 5%, so it will be enough to make $bk = 20$. Therefore, we can choose $k = 2$.

The processes speed in a differentiating filter must be significantly lower (at least by one order), than the speed of plant's processes. According to requirements (3.32), the processes setting time in plant should be lower, then 3 seconds. Therefore, processes in filter should end in approximately 0.3 seconds. For general case, filter parameters can be chosen by root locus method (similar to the desired equation parameters choice). In case of second-order differential filter implementation, it is possible to use much more faster and suitable evaluation:

$$\begin{cases} \mu \approx 0.1T_p^*, \\ d \approx (0.5 \dots 0.7), \end{cases} \tag{3.35}$$

where T_p^* is the desired time constant, $T_p^* \approx 3t_p$. Therefore, we can choose

$$\mu = 0.1; d = 0.5. \tag{3.36}$$

Placing calculated parameters (3.36) into the differential equation of a second-order filter (3.20) we will acquire the filtrating polynomial:

$$D(\mu p) = 0.01p^2 + 0.1p + 1.$$

The characteristic equation of the fast processes subsystem:

$$0.01p^2 + 0.1p + 21 = 0.$$

This subsystem is stable.

Structure realization of the closed loop is presented on fig.3.10:

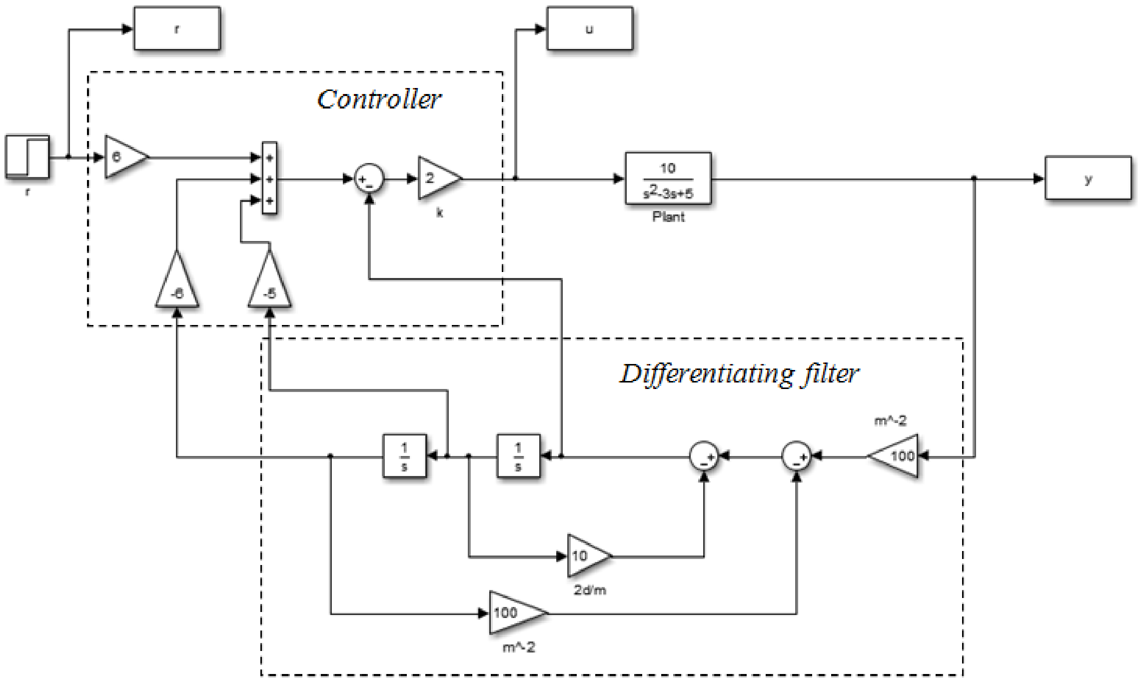

Figure 3.10– The simulation scheme of a closed loop

Output and actuating variables changes are presented on fig.3.11 ($r = 1$):

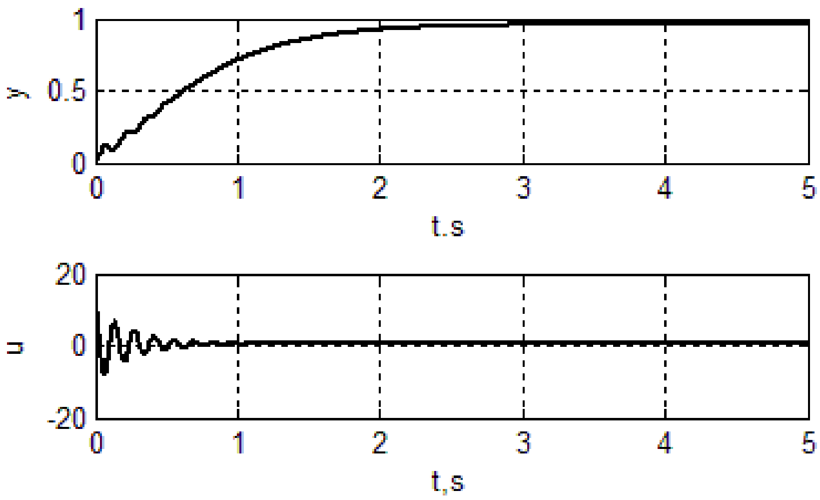

Figure 3.11 – Output and actuating variable changes in a closed loop

The desired quality of processes is obtained: setting time is 3 seconds, no overshoot, steady state error doesn't go beyond 5%. One of proportional actuating rule problems can be seen on the actuating variable curve – there are big "peaks" of the actuating value, arising in the beginning of processes. Using of more complicated rules can decrease these peaks.

3.6.2 Nonlinear second-order plant

The proposed nonlinear plant is described by an differential equation:

$$\ddot{y} + a_2\dot{y} + a_1 y^2 = bu, \tag{3.37}$$

where $b = 2, a_2 = 1, a_1 = 1$. Output variable changes are presented on fig.3.12:

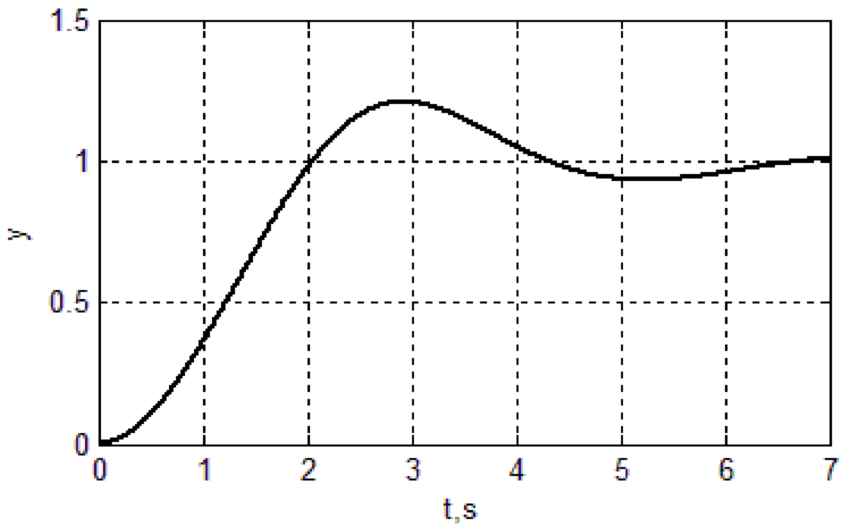

Figure 3.12 – Output variable changes in the plant (3.37)

Process quality requirements are represented by expressions (3.32); we will use the actuating equation (3.33) for the closed loop design. Due to the similarity of requirements, we can also use the same desired equation (3.34).

According to (3.13), in order to obtain $bk = 20$ we choose $k = 10$.

The fast processes subsystem will be also the same, as it was in previous chapter.

Structure realization of the closed loop is presented on fig.3.13:

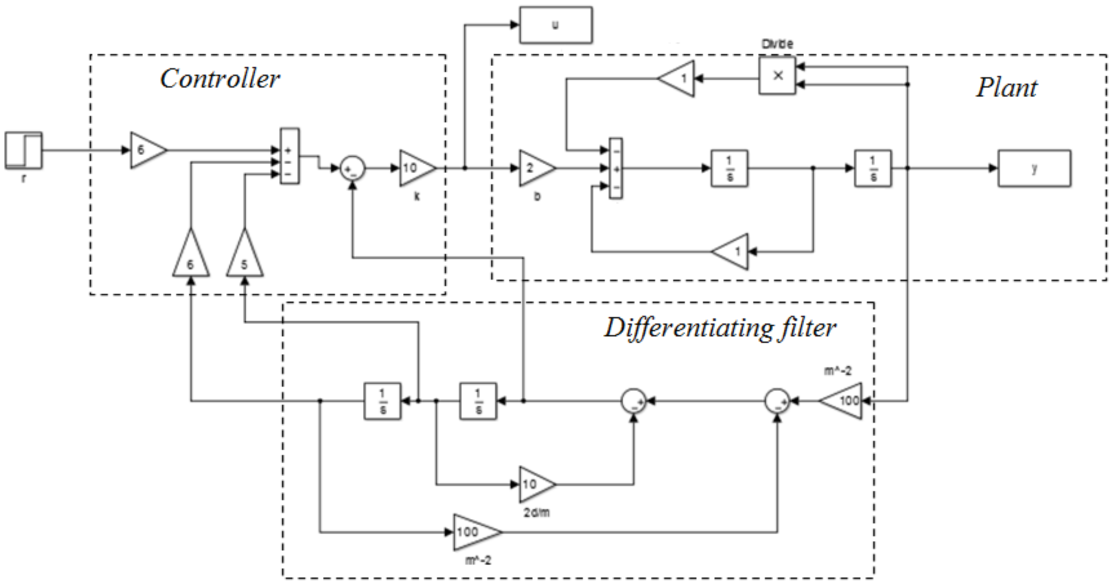

Figure 3.13 – The simulation scheme of a closed loop

Output and actuating variables changes are presented on fig.3.14 ($r = 1$):

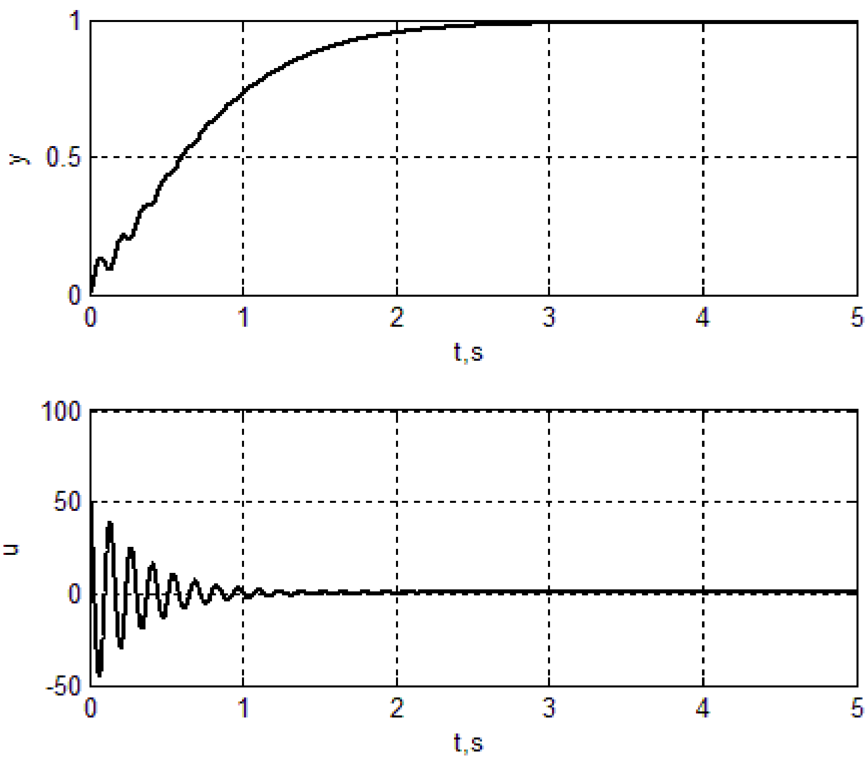

Figure 3.14 – Output and actuating variable changes in a closed loop

The desired quality of processes is obtained: setting time is 3 seconds, no overshoot, steady state error doesn't go beyond 5%. The added plant's nonlinearity brings further increase of actuating variable peaks in the beginning of the transient processes. Also, oscillations can be seen in the beginning of transient processes. They are caused by the derivative evaluating process in the differentiating filter – it takes some time to make outputs of plant and differentiating filter equal.

4 Localization control system design

4.1 The control task analysis

The control system synthesis for the set of linearized models is presented in this chapter. Summarizing transfer functions (2.1) and (2.2), we will obtain transfer function for the whole system

$$G(p) = G_{Tin}(p)G_{Tout}(p) = \\ = \frac{k_{Tin}}{(T_{Tin1}p + 1)(T_{Tin2}p + 1)(T_{Tin3}p + 1)} * \\ * \frac{k_{Tout}}{(T_{Tout1}p + 1)(T_{Tout2}p + 1)(T_{Tout3}p + 1)}. \tag{4.1}$$

Due to classical approach to localization synthesis method, differentiating filter for such plant will be 6^{th} order. The design and the calculation of parameters for such filter are quite complicated; also, high-order differentiating filter brings additional oscillations into the closed loop. As it was mentioned in the plant description, there is a possibility to measure the temperature on the input of the heat exchanger. Therefore, we can use output of the $G_{Tin}(p)$-block in the control circuit. Moreover, according to the numerical values of plant's parameters, presented in Table 1, transient processes in $G_{Tin}(p)$- and $G_{Tout}(p)$-blocks have significantly different speeds. Time constants of $G_{Tin}(p)$ are 1-2 orders lesser, then time constants of $G_{Tout}(p)$. Due to these factors, it is possible and reasonable to use cascade control principle. Each of presented plant's transfer functions will be controlled in its own circuit by the localization controller and the 3^{rd} order differentiating filter. Structure scheme of the closed loop is shown on fig. 4.1.

Thus, in closed loop with two cascades transient processes have four stages, separated by processes speed criterion. From the fastest to the slowest:

- Processes in the differentiating filter of the inner circuit (~ milliseconds);
- Processes in the inner circuit (~ seconds);
- Processes in the differentiating filter of the outer circuit (~ tens of seconds);
- Processes in the outer circuit (~ hundreds of seconds).

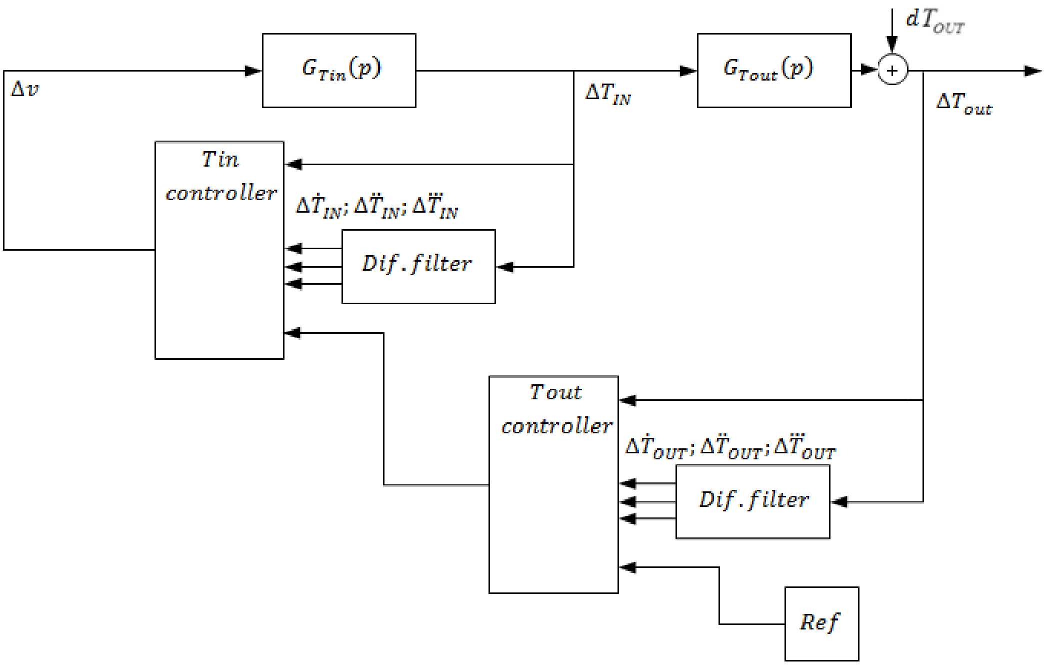

Figure 4.1. – The structure scheme of the closed control loop

In order to choose controllers gain values k_{in}, k_{out}, transfer functions (2.1) and (2.2) must be rewritten in form

$$G_{Tout}(p) = \frac{b_{Tout}}{p^3 + a_{Tout2}p^2 + a_{Tout1}p + a_{Tout0}}; \tag{4.2}$$

$$G_{Tin}(p) = \frac{b_{Tin}}{p^3 + a_{Tin2}p^2 + a_{Tin1}p + a_{Tin0}}. \tag{4.3}$$

In these equations:

$$b_{Tout} = \frac{k_{Tout}}{T_{Tout1}T_{Tout2}T_{Tout3}}; \; b_{Tin} = \frac{k_{Tin}}{T_{Tin1}T_{Tin2}T_{Tin3}};$$

$$a_{Tout0} = \frac{1}{T_{Tout1}T_{Tout2}T_{Tout3}}; \; a_{Tin0} = \frac{1}{T_{Tin1}T_{Tin2}T_{Tin3}};$$

$$a_{Tout2} = \frac{(T_{Tout1} + T_{Tout2})(T_{Tout1} + T_{Tout3})(T_{Tout2} + T_{Tout3})}{T_{Tout1}T_{Tout2}T_{Tout3}};$$

$$a_{Tin2} = \frac{(T_{Tin1} + T_{Tin2})(T_{Tin1} + T_{Tin3})(T_{Tin2} + T_{Tin3})}{T_{Tin1}T_{Tin2}T_{Tin3}};$$

$$a_{Tout1} = \frac{T_{Tout1} + T_{Tout2} + T_{Tout3}}{T_{Tout1}T_{Tout2}T_{Tout3}}; \; a_{Tin1} = \frac{T_{Tin1} + T_{Tin2} + T_{Tin3}}{T_{Tin1}T_{Tin2}T_{Tin3}}.$$

In case of power load level changes, plant parameters b_{Tout} and b_{Tin} are also changed. Controller gain, found for one of linearized models, can be unacceptable for model with another power load level. Firstly, controller gain must satisfy fast processes subsystem stability condition (characteristic equation (3.23)). On the other hand, the requirement for the steady state error (3.13) must be also met. Therefore, after searching controller gain value for the model with one power load level, we should tune this gain in order to make the controller capable of working with whole set of models. The initial calculation of the controller parameters will be made for the plant with 50% power load level.

4.2 The inner circuit controller design

4.2.1 The controller parameters choice

According to the synthesis algorithm, presented in chapter 3, first step of the control system design is desired equation choice. Dynamic requirements (2.5) must be fulfilled on the output of the outer circuit. The processes setting time in the inner circuit must be at least one order lesser than in the outer circuit, in order to maintain system's operability. Due to the processes speed division in whole system, it would be better to make the inner circuit processes two orders faster, than the outer ones. Therefore, desired dynamic properties of the inner circuit are

$$t_p \approx 10s;\ \sigma \leq 10\% \tag{4.4}$$

Inner circuit transfer function is 3rd order, therefore desired equation also should be 3rd order. In order to obtain desired dynamics (4.4), chosen root locus of the desired equation will be $p_1 = p_2 = p_3 = -1$. Desired equation has form

$$\Delta\dddot{T}_{in} = F_{in}\left(r, \Delta T_{in}, \Delta\dot{T}_{in}, \Delta\ddot{T}_{in}\right) = -3\Delta\ddot{T}_{in} - 3\Delta\dot{T}_{in} - \Delta T_{in} + r. \tag{4.5}$$

In this chapter we will use the proportional actuating equation. 3rd order variant of (3.27) has form

$$u = k_{in}(F_{in}\left(r, \Delta T_{in}, \Delta\dot{T}_{in}, \Delta\ddot{T}_{in}\right) - \Delta\dddot{T}_{in}). \tag{4.6}$$

The controller gain is chosen according to equation (3.13). Using Table 1 values and transformation (4.3), for $Q_{level} = 50\%$ we obtain $b_{Tin} \approx -10{,}16$. Therefore, chosen controller gain is $k_{in} = -2$. The increase of Q_{level} leads to the decrease of $|b_{Tin}|$ $-$ possibly, it will be necessary to tune the controller gain during simulation of models with another Q_{level}.

4.2.2 The differentiating filter design

The processes setting time in the differentiating filter must be one order lesser, than processes in the circuit. Taking into account (4.4), requirement for the inner circuit filter's setting time is $t_p \approx 1s$. The fast processes subsystem characteristic equation while using the 3rd order differentiating filter has form

$$p^3 + \frac{d_{2in}}{\mu_{in}} p^2 + \frac{d_{1in}}{\mu_{in}^2} p + \frac{1 + b_{Tin} k_{in}}{\mu_{in}^3} = 0.$$

Fast processes subsystem must be stable. According to the Hurwitz stability criterion [5], the sequence of determinants of Hurwitz matrix H principal submatrices must all be positive. Therefore, stability conditions for the 3rd order differentiating filter are:

$$\frac{d_{2in}}{\mu_{in}} > 0;\ d_{1in} d_{2in} > 1 + b_{Tin} k_{in};\ \frac{1 + b_{Tin} k_{in}}{\mu_{in}^3} > 0. \quad (4.7)$$

Chosen filter parameters are

$$\mu_{in} = 0.05;\ d_{2in} = 8;\ d_{1in} = 20. \quad (4.8)$$

Therefore, the characteristic equation of the inner circuit's fast processes subsystem takes form

$$0.000125 p^3 + 0.02 p^2 + p + 21 = 0.$$

This subsystem is stable.

4.3 The outer circuit controller design

4.3.1 The controller parameters choice

Desired dynamic properties of the outer circuit are presented in equations (2.5):

$$t_p \leq 1000s;\ \sigma \leq 10\%.$$

Outer circuit transfer function is 3rd order, therefore desired equation also should be 3rd order. In order to obtain desired dynamics (2.5), chosen root locus of the desired equation will be $p_1 = p_2 = p_3 = -0.05$. Desired equation has form

$$\Delta\dddot{T}_{out} = F_{out}(r, \Delta T_{out}, \Delta\dot{T}_{out}, \Delta\ddot{T}_{out}) =$$
$$-0.15\Delta\ddot{T}_{out} - 0.0075\Delta\dot{T}_{out} - 0.000125\Delta T_{out} + 0.000125r. \quad (4.9)$$

The actuating equation for the outer circuit is similar to the inner circuit's one

$$u = k_{out}(F_{out}(r, \Delta T_{out}, \Delta\dot{T}_{out}, \Delta\ddot{T}_{out}) - \Delta\dddot{T}_{out}). \quad (4.10)$$

The controller gain is chosen according to equation (3.13). Using Table 1 values and transformation (4.2), for $Q_{level} = 50\%$ we obtain $b_{Tout} \approx 7.56 * 10^{-6}$. Therefore, chosen controller gain should be $k_{out} = 2{,}64 * 10^6$. Such big gain value will lead to big oscillations of actuating value in the beginning of processes (limit actuating value can be evaluated by equation (3.17)). Also, the increase of Q_{level} leads to the significant increase of $|b_{Tout}|$, and such gain value can lead to the instability of the fast processes subsystem. Therefore, much more acceptable way is to decrease gain value, in order to meet all models stability requirements. In the worst case $-$ $Q_{level} = 50\%$ $-$ the steady state error can arise in the system. Through the experiments, gain value $k_{out} = 4 * 10^5$ has shown acceptable result by both criterions $-$ the stability and the steady state error. For $Q_{level} = 50\%$: $b_{Tout}k_{out} \approx 3{,}024$.

4.3.2 The differentiating filter design

The parameter calculation process for the outer circuit differentiating filter is the same, as for the inner one. Taking into account (2.5), requirement for the outer circuit filter's setting time is $t_p \approx 100s$. Chosen filter parameters are

$$\mu_{out} = 1;\ d_{2out} = 8;\ d_{1out} = 20; \quad (4.11)$$

these parameters satisfy requirements (4.7). The characteristic equation of the fast processes subsystem:

$$p^3 + 8p^2 + 20p + 4 = 0.$$

This subsystem is stable.

4.4 Simulation results

4.4.1 The inner circuit processes simulation

Plant's transfer function is described by equation (2.1), numerical values of parameters are taken from Table 1. The simulation scheme for circuit with $Q_{level} = 50\%$ is presented on fig. 4.2.

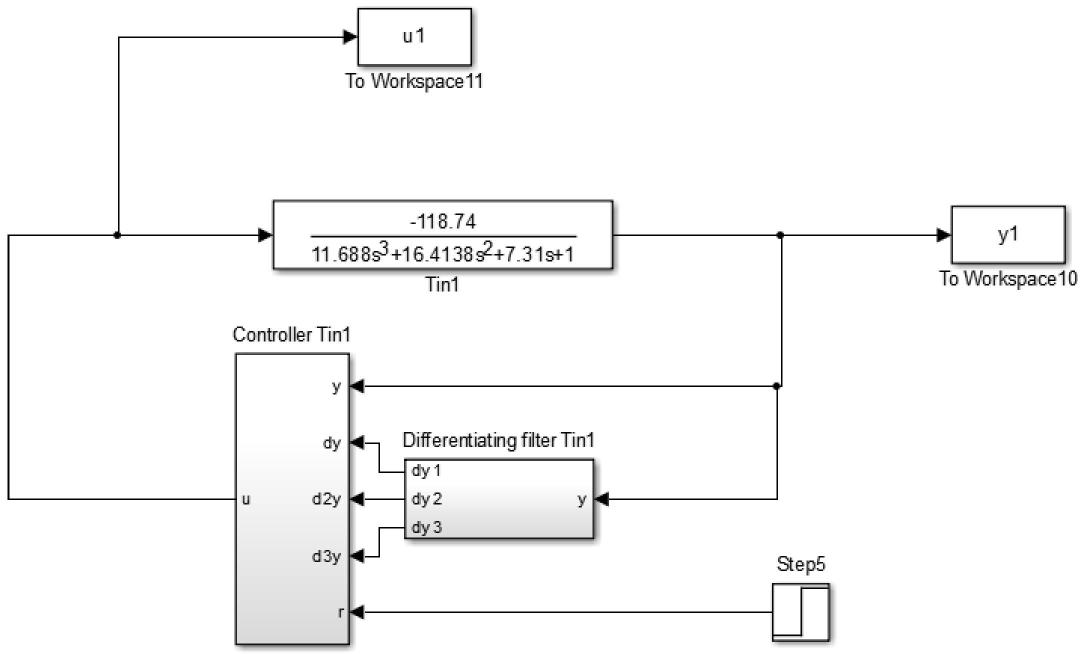

Figure 4.2 – The simulation scheme of the inner circuit

The controller block realizes the actuating equation according to (4.5) and (4.6). The simulation scheme of this block is presented on fig. 4.3.

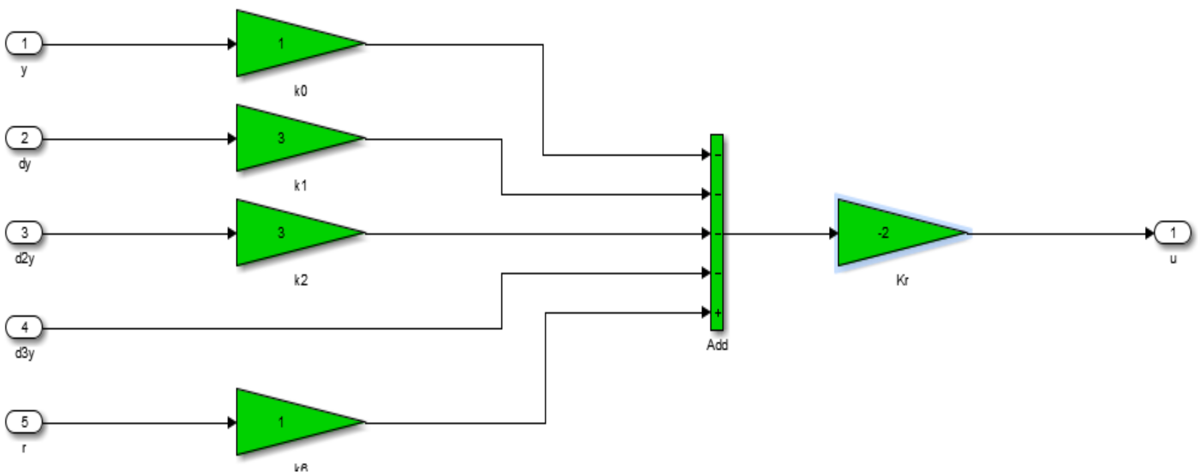

Figure 4.3 – The simulation scheme of the inner circuit controller

The differentiating filter block realizes output derivatives evaluation. Numerical values are equal to (4.8). The simulation scheme of this block is presented on fig. 4.4.

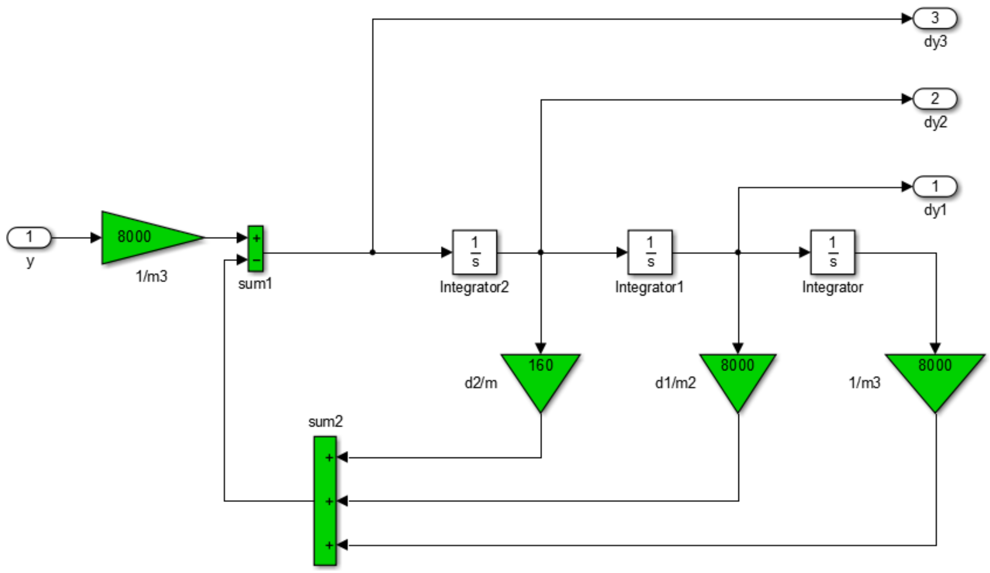

Figure 4.4 – The simulation scheme of the inner circuit differentiating filter

Configuration parameters for the presented simulation:

- Simulation time – 20 seconds;
- Reference point change – 1°C.

Simulation results for output and actuating variables are presented on fig. 4.5.

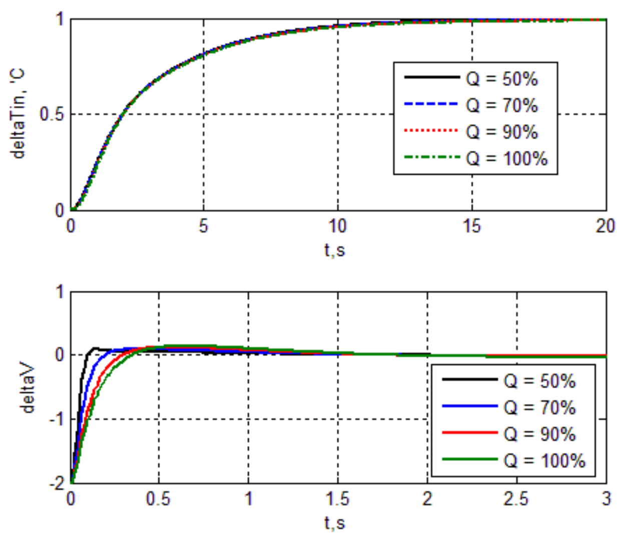

Figure 4.5 – Output and actuating variable curves of the inner circuit processes

According to presented graphs, control task for the inner circuit is accomplished. Setting time for all linearized models is about 10 seconds, there is no overshoot, changes of power load level have almost no influence on the output variable curve. In the beginning of processes the actuating value doesn't satisfy limitation (2.4) – it is caused by the inner circuit simulation excluding outer circuit processes, reference point at the input of the inner circuit controller will have another value while simulating whole control system.

4.4.2 The closed loop processes simulation

Results of closed loop (whole system) processes simulation are presented in this subchapter. Plant's transfer function is described by equation (4.1), numerical values of parameters are taken from Table 1. The simulation scheme is presented on fig. 4.6.

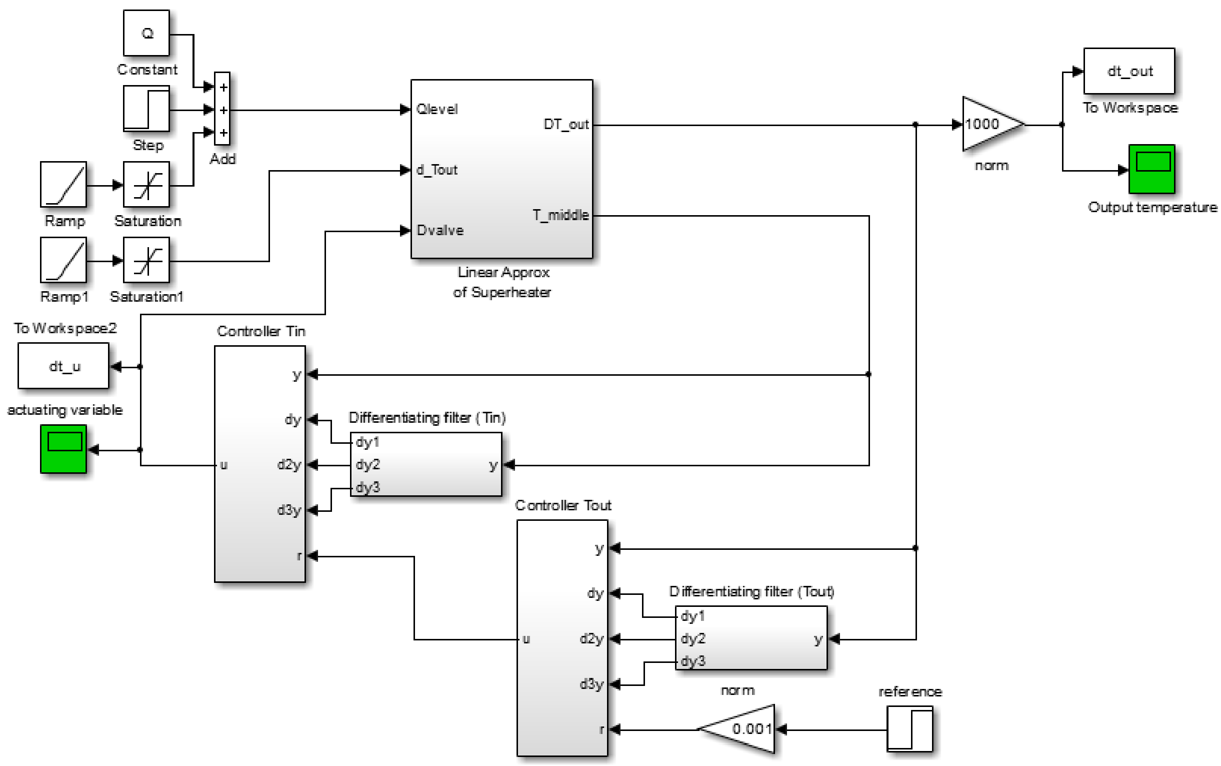

Figure 4.6 – The simulation scheme of the closed loop

Outer controller and differentiating filter blocks have the same structure, as inner ones. Numerical values of controller parameters are set according to (4.9),(4.10); numerical values of differentiating filter parameters are set according to (4.11). The closed loop with such parameters doesn't meet actuating variable limitation (2.4) – oscillations amplitude in the beginning of processes exceeds this limitation by three orders. Without changes in the control loop, the normalization of input and output signals was supposed as possible solution. Therefore, normalizing gains were added into the simulation scheme.

Results of the processes simulation for different power load levels and without disturbances are presented on fig. 4.7.

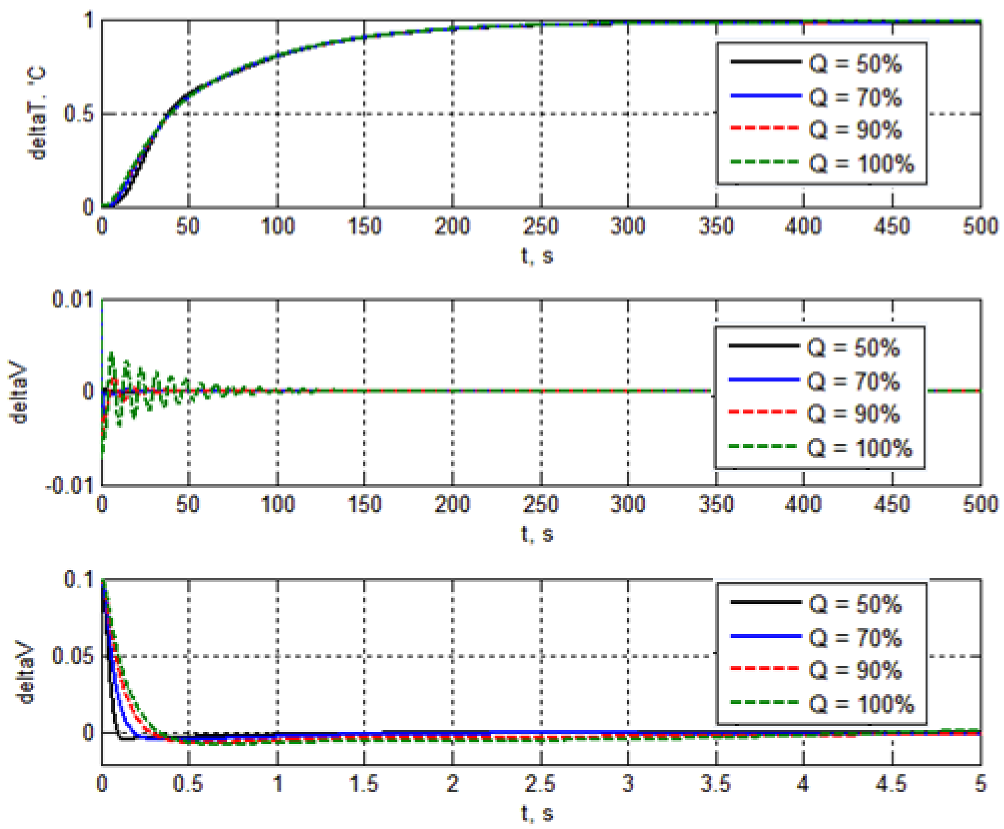

Figure 4.7 – Output and actuating variable curves of the closed loop processes

The first graph represents normalized output variable changes. It can be seen, that different power load level values have almost no influence on the output curve. The steady state error value is acceptable. Changes in Q_{level} lead to changes in the actuating oscillations amplitude values, it can be seen on the second graph. As it was mentioned, the increase of Q_{level} brings the increase of plant's outer circuit gain value. The controller gain, at the same time, remains constant. Therefore, the overall system's gain is also increasing – which leads to actuating oscillations increase. The third graph represents actuating variable changes in first 5 seconds.

The actuating limitation (2.4) brings two big problems into the design of the control system with the actuating equation (4.10). This proportional actuating rule supposes, firstly, relatively big actuating oscillations amplitude in the beginning of transient processes, and, secondly, these actuating oscillations often make the actuating variable switching its sign – both of these features contradict with (2.4). The first problem during the simulation can be solved as it was suggested – by entering normalization gains. During the real system application this problem will arise again – as far as output variable is not electric signal, there will be problems with the realization of the normalization (need for special converters, special tuning, etc.). The only second problem solution using actuating equation (4.10) is decreasing of the outer circuit processes speed, in order to make the actuating variable not to cross the zero limitation. On the other hand, the decreasing of the outer circuit processes speed brings problems with the dynamic requirements (2.4) satisfaction.

4.4.3 The closed loop reaction on the disturbance

Results of the processes simulation for different power load levels and with the ramp dT_{out} (fig. 2.4) disturbance addition (start time 500s, slope 0.01°C/s) in the steady state are presented on fig. 4.8.

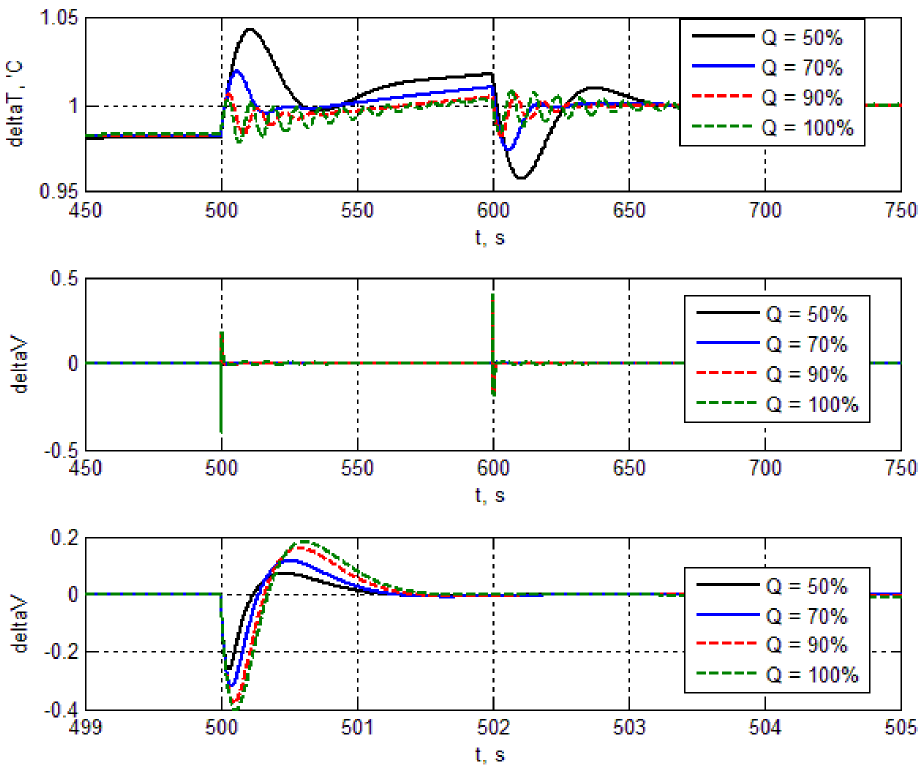

Figure 4.8 – Output and actuating variable curves of processes with added ramp disturbance

Output variable curves for all power load levels are acceptable. Disturbance feed forward on the outer circuit differentiating filter also causes "peaks" of the actuating variable. The same problems, as for the reference point reaction, also arise for the disturbance reaction. Actuating limitation (2.4) is again not satisfied.

4.4.4 The closed loop reaction on the power load level changes

Results of the processes simulation for the step change of Q_{level} from 50% to 70% in the steady state (step time = 500s) are presented on fig. 4.9.

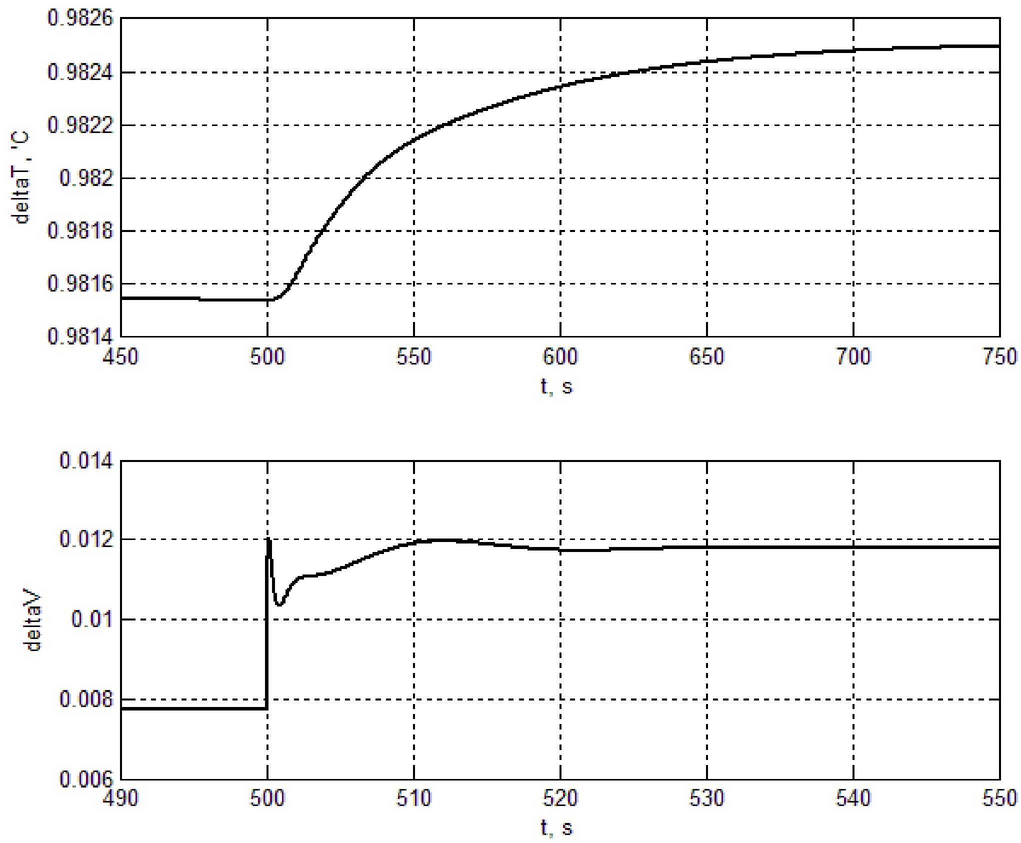

Figure 4.9 – Output and actuating variable curves of processes with the step change of Q_{level} in the steady state

Output and actuating variables curves are acceptable. In the real system switching process can have bigger setting time because of the valve opening speed (the step rise of the actuating value is impossible).

Results of the processes simulation for the ramp change of Q_{level} from 50% to 100% (start time = 500s, slope 0.5%/s) in the steady state is presented on fig. 4.10.

Output and actuating variables curves are acceptable. Overall, different changes of plant parameters in the steady state are worked out by localization circuit successfully.

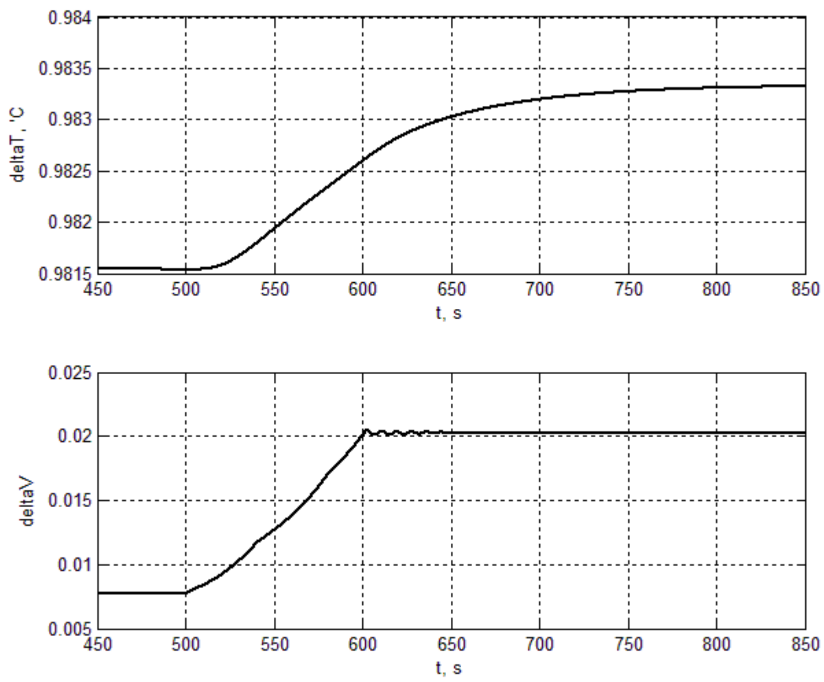

Figure 4.10 − Output and actuating variable curves of processes with the ramp change of Q_{level} in the steady state

To summarize, the two-circuit localization control loop with actuating rules (3.27) is not able to satisfy all requirements, which are given for discussed plant. Big values of outer circuit controller gain k_{out}, needed to compensate outer circuit own gain, make the satisfaction of the actuating value limitation (2.4) almost impossible. The normalization of signals is possible, but it significantly complicates the control system application and rises it cost. On the other hand, the localization circuit almost perfectly deals with changes of plant's dynamic due to the power load level changes. Also, all mentioned problems are located in outer circuit, processes in the inner one are acceptable.

The possible solution for arisen problems is changing of the outer circuit actuating equation (4.10). As it was told in Chapter 3, main idea of the localization method is the output derivative usage. The proportional actuating equation (3.27) is the simplest variant of possible localization rules. In the next chapter we will consider another actuating rule − with the integrator addition to the control circuit.

5 Localization control loop improvement by integrator implementation

5.1 Outer circuit control loop recalculation

5.1.1 Controller parameters choice

As it was told in the previous chapter, using of the actuating equation (3.27) doesn't allow getting required processes qualities in the outer circuit. Therefore, in this chapter we will consider more complicated actuating algorithm. The inner circuit's structure and parameters remain the same, as before.

The standard option for making system astatic in the control theory is the integrator addition into the control loop. This element allows to obtain zero steady state error without using the big valued gain. Therefore, in order to decrease actuating value oscillation amplitudes and to fully neglect steady state error, we will use the direct connection of gain and integrator in the outer circuit control loop. The general case actuating equation takes form

$$u = \frac{k}{p}\left[F(.) - y^{(n)}\right];$$

or, in our case

$$u = \frac{k_{out}}{p}\left(F_{out}\left(r, \Delta T_{out}, \Delta\dot{T}_{out}, \Delta\ddot{T}_{out}\right) - \Delta\dddot{T}_{out}\right). \tag{5.1}$$

The outer circuit desired equation stays the same. The controller gain k_{out} now can be significantly decreased in order to satisfy the actuating limitation (2.4). During processes simulation there was used $k_{out} = 40$.

5.1.2 The differentiating filter design

The outer circuit differentiating filter's structure remains the same. Numerical values of filter's parameters (4.11) also can be used without changes, but it is necessary to recheck fast processes subsystem stability. After applying actuating equation (5.1), the outer circuit fast processes subsystem can be described by characteristic equation

$$D_{fout}(\mu_{out}p)p + b_{Tout}k_{out} = 0,$$

or, in expanded form,

$$p^4 + \frac{d_{2out}}{\mu_{out}} p^3 + \frac{d_{1out}}{\mu_{out}^2} p^2 + \frac{p + b_{Tout} k_{out}}{\mu_{out}^3} = 0.$$

According to Hurwitz criterion, stability conditions for such fast processes subsystem are

$$d_{2out} d_{1out} > 1;\ d_{2out} d_{1out} - b_{Tout} k_{out} d_{2out}^2 \mu - 1 > 0.$$

Chosen differentiating filter parameters (4.11) satisfy this conditions. The fast processes subsystem is stable. Also, influence on the stability of the controller gain k_{out} can be seen from the second condition.

5.2 The closed loop processes simulation

Results of closed loop with the changed outer circuit processes simulation are presented in this subchapter. Plant's transfer function is described by equation (4.1), numerical values of parameters are taken from Table 1. The simulation scheme structure remains the same (fig. 4.6), the only change is normalization gains deletion (the small controller gain makes them unnecessary). The structure and the numerical values of the differentiating filter blocks also remains the same (fig. 4.4; (4.11)). The structure scheme of the outer circuit controller is presented on fig. 5.1.

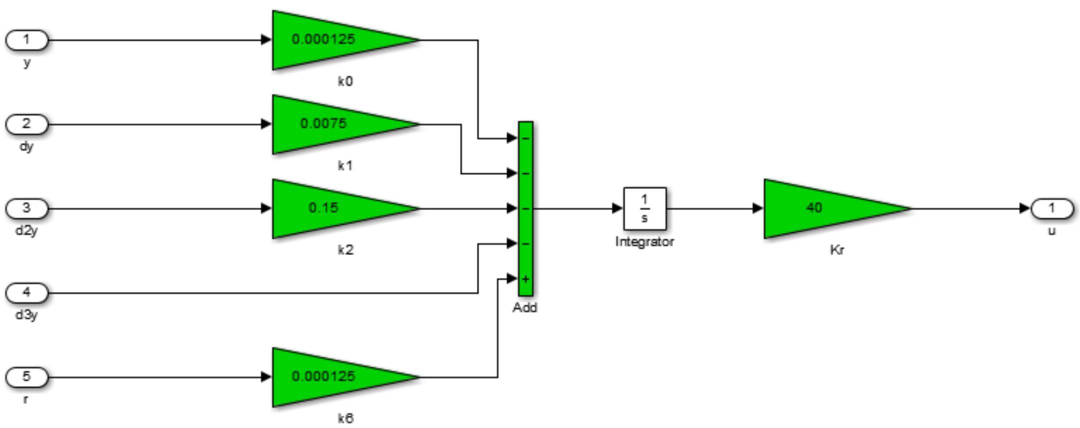

Figure 5.1 — The simulation scheme of the outer circuit controller

Results of the processes simulation for different power load levels and without disturbances are presented on fig. 5.2.

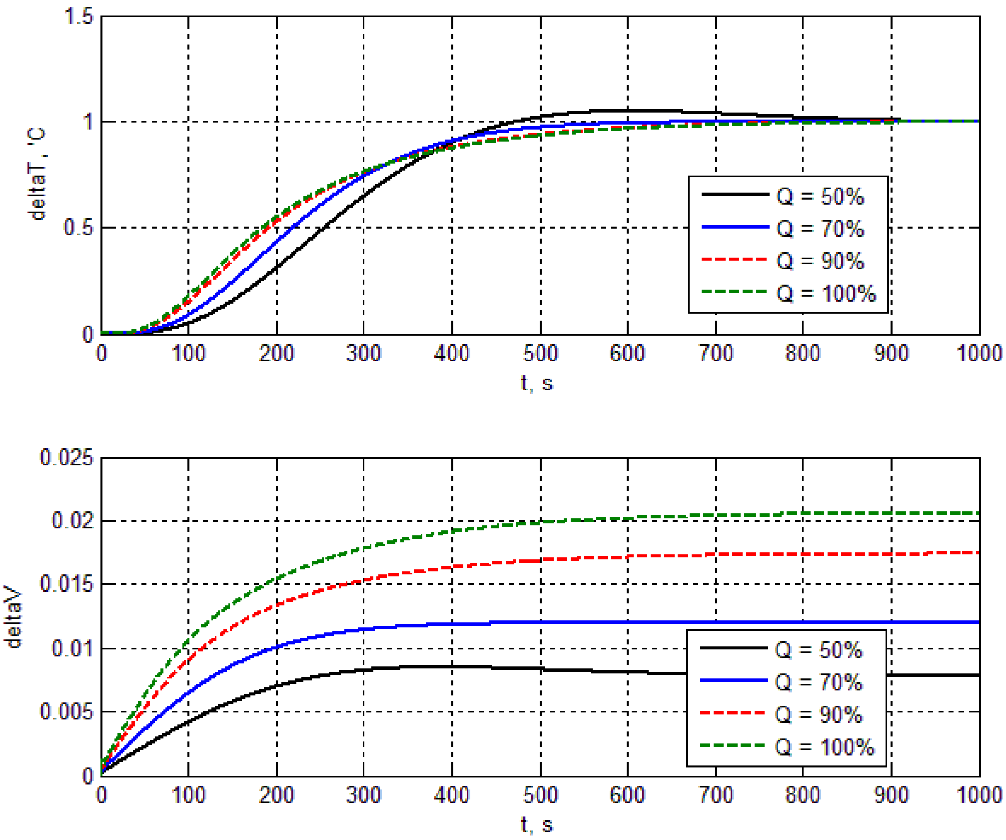

Figure 5.2 – Output and actuating variable curves of the closed loop processes

These graphs show, that the integrator implemenation with decreasing of the controller gain in the outer circuit allow to satisfy the actuating limitation (2.4). Now, there are no oscillations of the actuating values in the beginning of the processes. On the other hand, such changes in the outer circuit decrease the localization circuit ability to neglect plant's dynamic changes due to the different power load levels, output variable curves for different Q_{level} values are different, but all of them are acceptable. Also, setting time has been increased in comparison to actuating equation (4.10). However, all dynamic and steady state requirements (2.5) are satisfied, the output and actuating variables behavior is acceptable.

5.2.1 The closed loop reaction on the disturbance

Results of the processes simulation for different power load levels and with the ramp disturbance addition (start time 1000s, slope 0,05°C/s) in the steady state are presented on fig. 5.3.

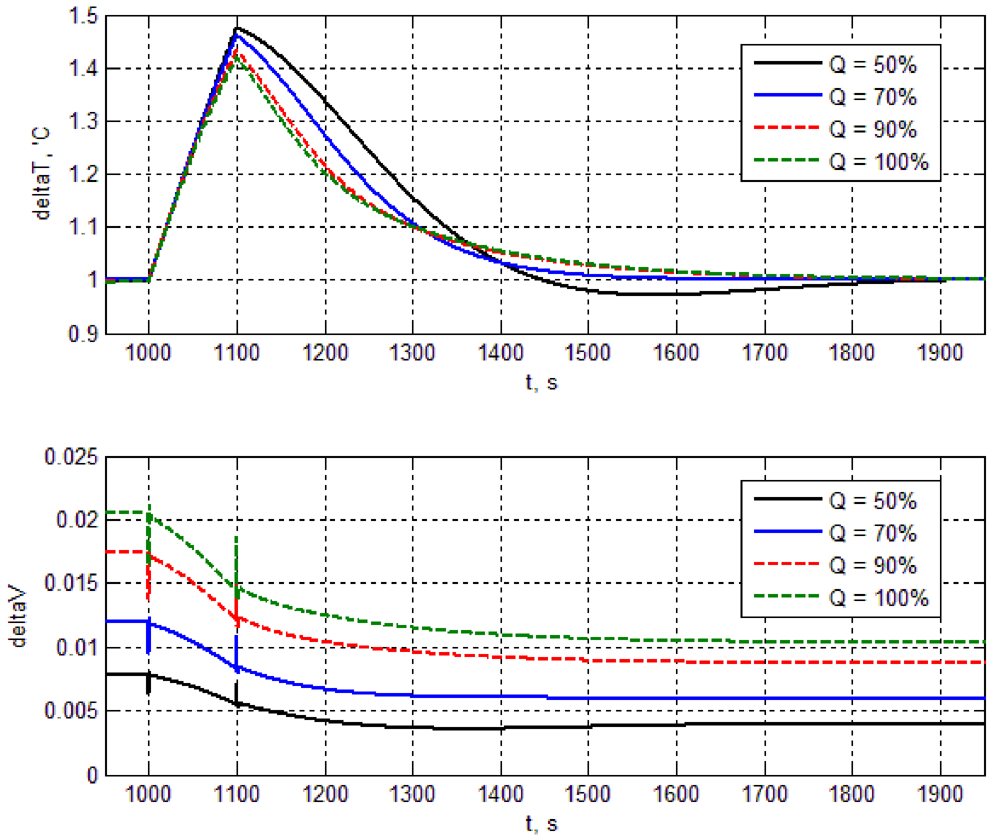

Figure 5.3 – Output and actuating variable curves of processes with added ramp disturbance

The reaction on the disturbance with the changed outer circuit actuating equation (5.1) is slower, than for (4.10). On the other hand, oscillations of the actuating variable are now much smaller and don't overcome actuating limitation (2.4). Moreover, in real system application small "peaks" of the actuating value in the beginning and ending of disturbance value changes can be not processed by the valve (because of its opening speed, it won't be able to realize such fast changes). Overall, control loop is able to work out disturbance addition for all values of the power load level.

5.2.2 The closed loop reaction on the power load level changes

Results of the processes simulation for the step change of Q_{level} from 50% to 70% in the steady state (step time = 1000s) are presented on fig. 5.4.

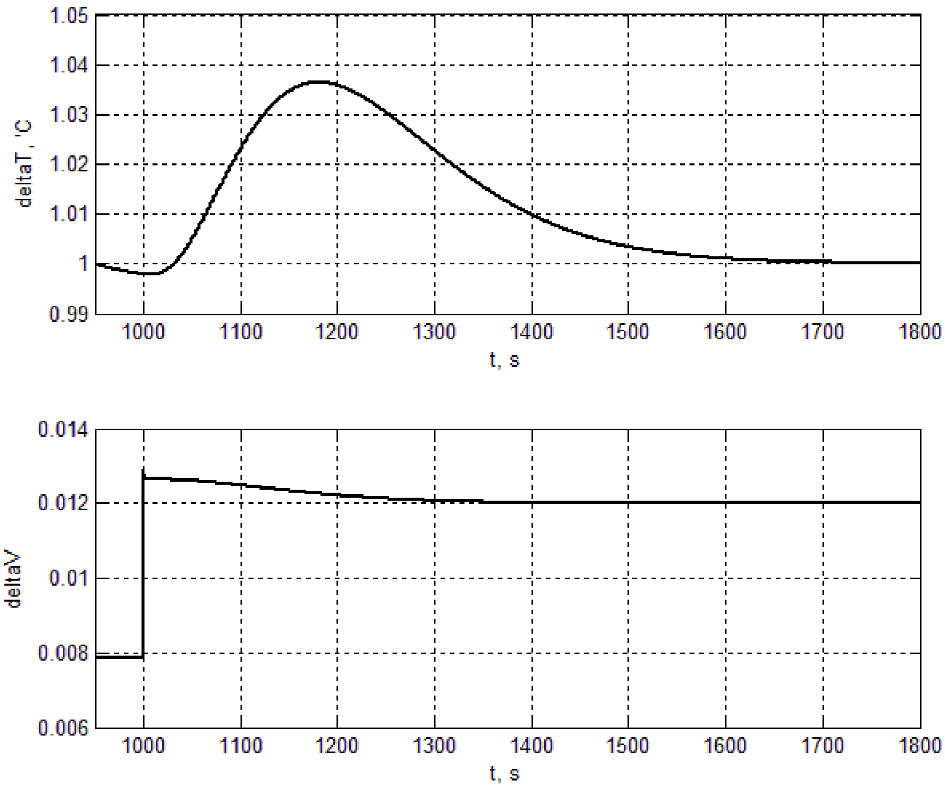

Figure 5.4 − Output and actuating variable curves of processes with the step change of Q_{level} in the steady state

Output and actuating variables curves are acceptable. In the real system switching process can have bigger setting time because of the valve opening speed (the step rise of the actuating value is impossible).

Results of the processes simulation for the ramp change of Q_{level} from 50% to 100% (start time = 1000s, slope 0.5%/s) in the steady state is presented on fig. 5.5.

Output and actuating variables curves are acceptable. Overall, different changes of plant parameters in the steady state are successfully worked out by the localization controllers with the integrator addition into the outer circuit.

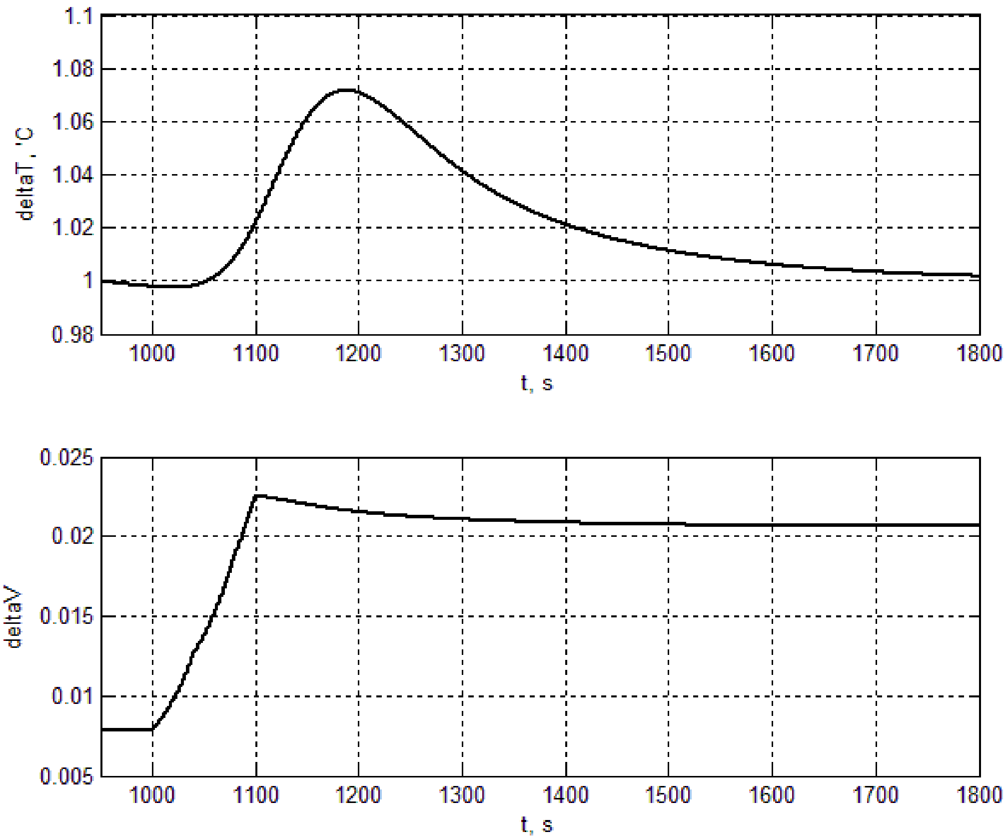

Figure 5.5 − Output and actuating variable curves of processes with the ramp change of Q_{level} in the steady state

To summarize, in contrast with localization control loop, discussed in chapter 4, system with the integrator addition to the outer circuit is able to satisfy all requirements for dynamic, steady state (2.5) and actuating values (2.4). The integrator allows to remove oscillations of the actuating variable in the beginning of the processes, and makes steady state error equal to zero even with the small controller gain value. In comparison to the proportional actuating rule, disadvantages of this control loop configuration are the bigger setting time and the plant parameters influence increase. However, these disadvantages are not significant, and don't break the system's operability.

In the next subchapter there are presented processes simulation results for the localization control loop (with the integrator in the outer circuit) in the nonlinear model of the output superheater.

5.3 The nonlinear model processes simulation

The simulation scheme of the nonlinear output superheater is shown on fig. 5.6.

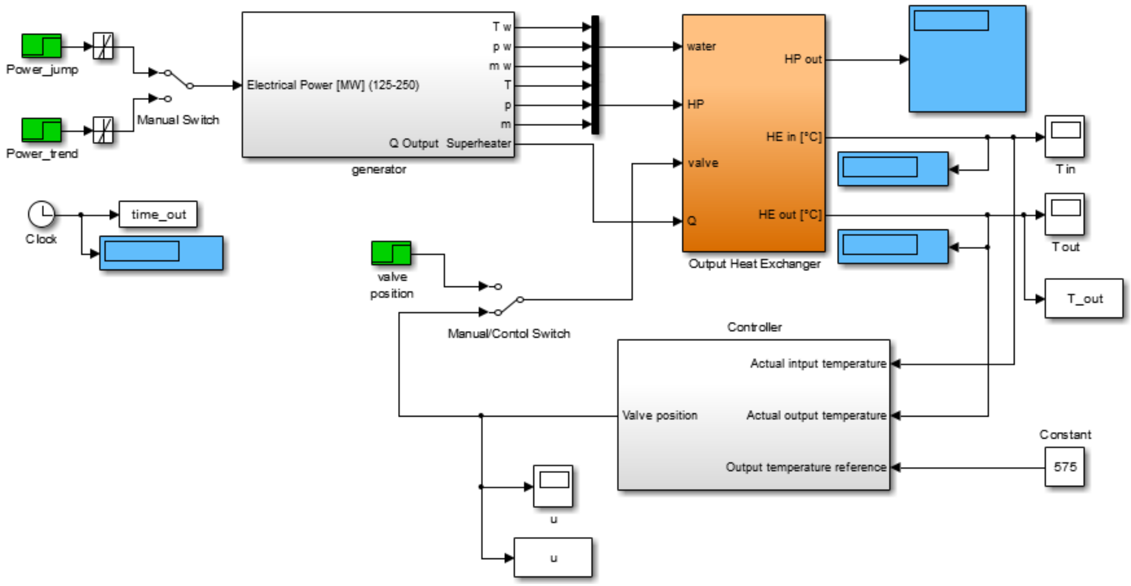

Figure 5.6 – The simulation scheme of the output superheater

The controller structure consists of two circuits:

- The inner circuit – the controller, which realizes the actuating equation (4.6) with numerical parameters, equal to the desired equation (4.5); differentiating filter parameters are equal to (4.8).
- The outer circuit – the controller, which realizes the actuating equation (5.1) with numerical parameters, equal to the desired equation (4.9); differentiating filter parameters are equal to (4.11).

The nonlinear works with nominal values of the steam temperature. The nominal reference point for the output superheater is $r = 575°C$. As it was mentioned it the control task, the only aim for the nonlinear model simulation is to show the suppression of operating point changes influence in the steady state and with zero disturbances. Therefore, following graphs are representing system behavior in the steady state with different changes of Q_{level}.

Results of the processes simulation for the step change of Q_{level} from 50% to 70% in the steady state (step time = 2000s) are presented on fig. 5.7.

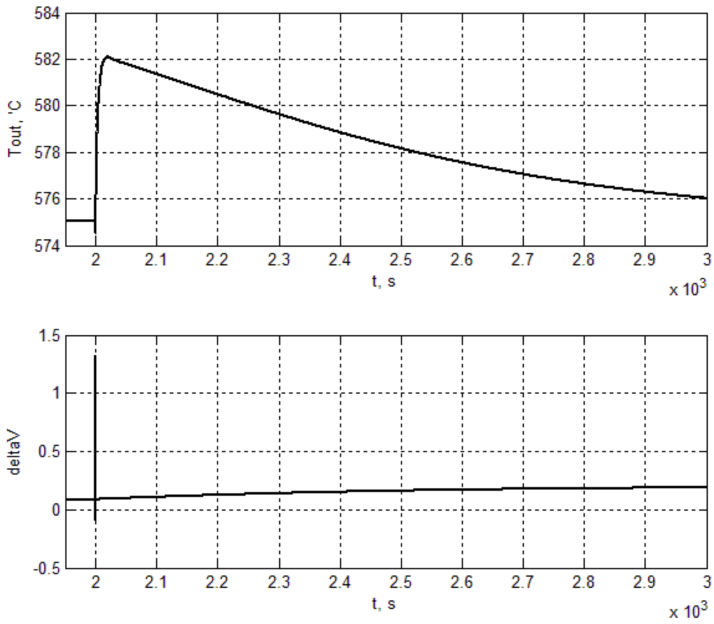

Figure 5.7 − Output and actuating variable curves of processes with the step change of Q_{level} in the steady state

The step change of the power load level leads to actuating "peak" on the controller's output, but the "peak" isn't being processed by the valve. The nonlinear system reaction is slower, than the linearized one's, but it keeps stability and suppresses the Q_{level} influence, making output steam temperature equal to the reference point. Results of the processes simulation for the ramp change of Q_{level} from 50% to 100% in the steady state (start time = 2000s, slope 0,01%/s) are presented on fig. 5.8.

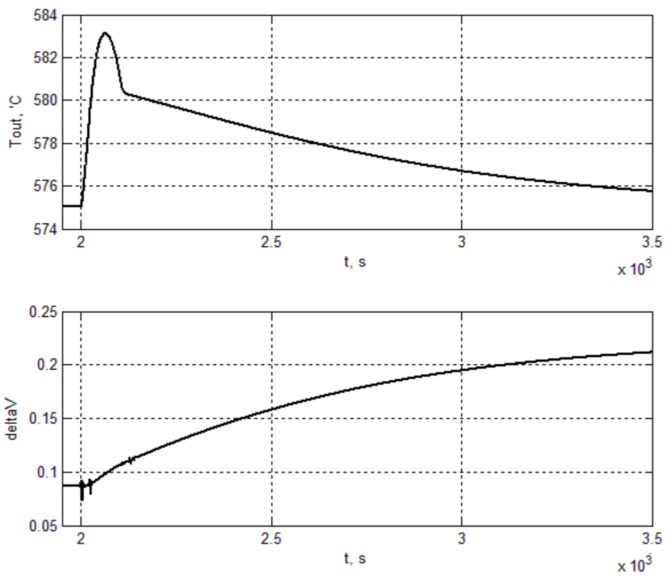

Figure 5.8 − Output and actuating variable curves of processes with the ramp change of Q_{level} in the steady state

Similar to step change of the power load level, processes in case of its ramp rise are also much slower, than in linearized models. The control loop is capable of suppressing the power load level changes.

The localization method also gives possibilities for further improvement of processes performance. Deeper nonlinear model analysis will give some options:

- Numerical control parameters tuning. Control loops of the outer and inner circuits can be done faster (it should be remembered, that after any changes it is necessary to recheck control loops stability and plant's requirement satisfaction).
- Increasing of controllers and differentiating filters order. It significantly increases the design procedure complexity, but allows to obtain better results.

6 Conclusion

The localization method of the control system is presented in this thesis. The method was successfully applied for the linearized and nonlinear models of the once-through boiler's output superheater. Presented results show, that such control system design algorithm has potential for further development.

Different variants of localization control loop are presented. The results analysis shows, that the main idea (nonlinearities and disturbances localization) is working, but the most simple control equations are often insufficient for obtaining desired processes quality and satisfying all limitations. Therefore, the control equation complication is needed for the correct system's functioning. Also, calculated controllers parameters often should be tuned during the simulation experiments; it also can increase the processes performance.

During any alterations in calculated controller parameters values there always must be a recheck of stability conditions for the localization circuits. Are some cases alterations of one parameters can cause undesired changes of another or even make system inoperable.

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