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# Optimization of Fuzzy Controller Parameters for the Temperature Control of Superheated Steam

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## Abstract

This paper deals with improvement of superheated steam temperature fuzzy control of high-pressure part in once-through boiler. The improvement of fuzzy control quality is based on optimization of fuzzy controller parameters. The optimization is based on minimization criteria. Optimized fuzzy parameters are function of high pressure steam temperature. More possibilities of optimization are presented in the paper. Fuzzy control properties are verified by simulation experiments within operating mode change, response to disturbance and change of system dynamics. Responses of fuzzy control are compared before and after the optimization.

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*Keywords:* fuzzy; optimization; steam superheating; boiler; temperature control

## 1. Introduction

This paper is concerned with fuzzy control method application of the superheated steam temperature of high pressure part in the once-through boiler in power plant. We require increase of efficiency and suppression of negative ecological thermal power plants impact during their reconstruction. This is an issue of complex system with more inputs and outputs (MIMO). The aim is suppress common disturbances and keep temperature on require tolerance. Currently provided control system uses quasi-adaptive PI(D) controllers in cascade control. Process of adaptation is based on suitable parameter selection from knowledge basis and experience. But the control system cannot meet new requirements to quality control, which brings current situation in energy source area. These

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requirements include fast change of operation modes, which is arising and decreasing to defined load level. There are many applications that deal with control system for steam power plants [1]. One of the options how to achieve better efficiency is a design of new control algorithms for technological unit of superheated steam. Principle of research is quest of other sophisticated control algorithms, e.g. MPC [2] and [3], robust control [4] or fuzzy logic implementation [5] and [6]. This paper deals with option of fuzzy control implementation of superheated steam temperature control of the once-through boiler, further describes the optimization of fuzzy controller parameters for whole load range. The design of fuzzy algorithm uses non-linear characteristics of fuzzy controller.

The aim of optimization task is quest of parameters of all fuzzy PI controllers so that parameters could provide smallest possible change of required steam temperature on the output of superheater II., III. and IV. (see Fig. 3), to all operating modes. Important study for optimization of digital fuzzy controllers is [7]. Published studies [8] and [9] deal with on-line self-tuning mechanism optimization. These studies are based on measurements of many variables. Use of minimization criterion in connection with a net of local linear models is a next logical step for steam reheated temperature optimization if we only have a temperature measurement available.

The nonlinear model of the once-through boiler was developed at our department [10]. Because of high computation demand, the model simulation is relatively slow. Time-consuming sophisticated control algorithms are tested by the non-linear model. Main requirement was to create a model for design and testing of control algorithm, which will be significantly faster. Therefore we found sufficiently accurate substitution of the nonlinear once-through boiler, which has very similar static and dynamic properties. These requirements meet continuously switched set of linearized models [11], which even twenty times allow shorten time of simulation.

## 2. The structure of the controlled process

Fig. 1 shows part of a simplified process of the once-through boiler, where important variables with respect to temperature control are only mentioned. The scheme consists of seven interconnected heat exchangers with predefined heat power Q1...Q6. The HP boiler feed water flows into the boiler. Its parameters (streaming and pressure) are defined by the circulation pump. Regulation of the steam temperature in the superheater is carried out by water injection on valves V1, V2, V3. The heat power of the boiler is given by the flow, pressure and heat power of heat exchangers and water injection amount. Desired temperature on superheater II. output is 460°C, it is 485°C on superheater III. output and 575°C on superheater IV. output. From this output is superheated steam led into turbine.

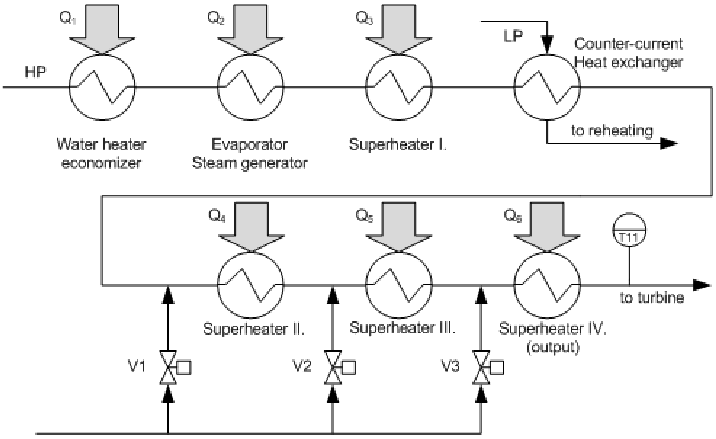

Fig. 1. Scheme of the high-pressure part of the once-through boiler.

The aim is replacement of existing control using quasi-adaptive PI controllers with variable parameters by fuzzy PI controllers (F-PI) with fixed parameters. Existing cascade structure is maintained [12]. The technology of superheated steam with cascade F-PI control system is shown on Fig. 2. Each of the six F-PI controllers has form according to Fig. 3. Main part of fuzzy PI controller is Fuzzy Logic Controller (FLC), in which a fuzzification, inference and defuzzification is made.

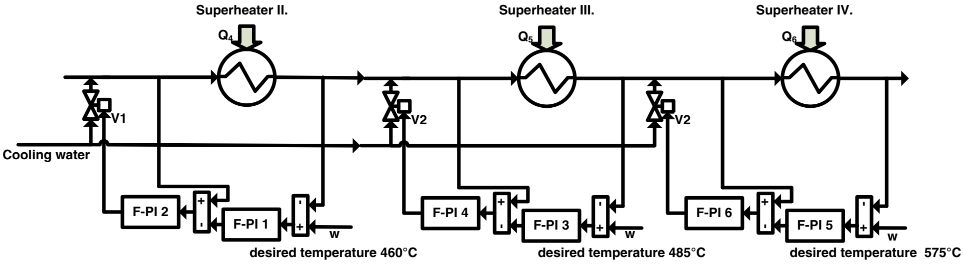

Fig. 2. Structure of the HP part with the fuzzy PI cascade control system.

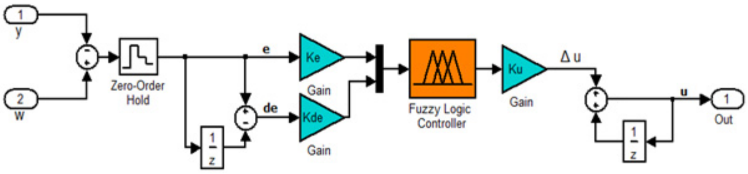

Fig. 3. Structure of the fuzzy PI controller.

Control error *e(k)* and its increment *Δe(k)* is input to F-PI. Output from F-PI is increment of actuating variable *Δu(k)*, which is transferred to actuating variable by integrating block. One of the most important points is factor research which affects the fuzzy control. Selection of scale factor *Ke, Kde, Ku* (see Fig. 3) was evaluated as one of the key point of fuzzy control design. Principle of the selection is multiplication (scaling) by constant of input and output fuzzy controller variables. Universe on the input of fuzzy controller is changed by the gain *Ke, Kde*, while universe on the output is changed by the gain *Ku*. Each fuzzy PI controller contains three parameters. Through the parameters is possible to change gains. Quality of fuzzy controller affects two gains *Ke, Kde* and gain *Ku*. It is possible to affect fuzzy algorithm by eighteen parameters. Quest of appropriate set of gains is a topic of the next chapter. Fuzzy controllers are defined by the following parameters which are default state for optimization task:

- Linguistic variables (control deviation and its increment) have nine terms in final form.
- Membership functions are triangular type with concentration to the middle.
- Eighty-one rules in form IF-THEN are generated.
- Defuzzification method is “Centre of Area”.
- Universe is set in range <-1,1>.

## 3. The optimization strategy

### *3.1. The optimization based on the maximum utilization of input intervals*

We start by selecting of suitable strategies out of the simplest procedures. One version of possible optimization is described in the publication [13]. The version is based on principle quest of scale factor values which transferred variables on input to FLC that the whole range of universe is used on maximum. At first we are looking for six parameters of superheater II. controller and then proceed to next superheaters in series. Parameters are searched heuristically. Step change of load (i. e. power level) from 100% to 50% with trend of 50% per 90 seconds is tested experiment. It is a real operation mode in the power plant. It is important change which covers whole load range. Therefore the change is one of the most difficult tasks for steam temperature control. Step change requirement invokes superheater II. input temperature increase of about 35°C, see Fig. 4 (a). The change can be understood as disturbance on the superheater II. input. Steam temperature in tolerance 2°C is required on the output of Superheater IV.

Comparison of superheated steam temperature response on the superheater IV. for initial and optimized setting is shown on Fig. 4 (b). The graph shows that this setting provides improvement of temperature output process compare to original setting. Overshoot amplitude is significantly lower, settling time is faster and process is not so oscillatory. However, this manual setting is considered as sub-optimal and we will try to improve it by using some optimization method with minimization criteria.

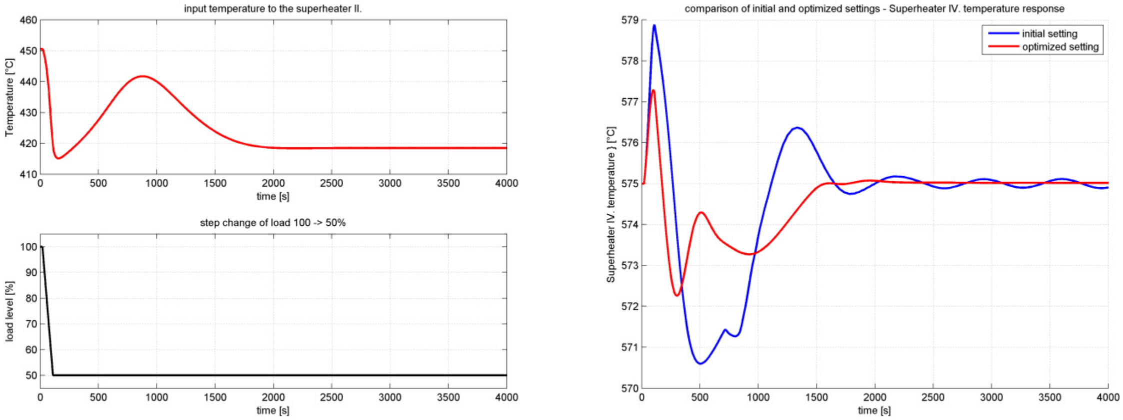

Fig. 4. (a) Response of the input temperature on the superheater II. and (b) comparison of the superheater IV. output temperature response.

### *3.2. The optimization based on the minimization criterion*

Let us try to optimize temperature process on the output of superheater IV., which is marked in red on Fig. 4 (b). In general the minimization criterion has a form:

$$J(X) \cong \sum_{i=0}^{N} e(i,X)^2 = \sum_{i=0}^{N} \left[ w(i) - y_M(i,X) \right]^2 \to \min \tag{1}$$

The criterion looks for minimum deviation between required temperature output process and simulated response with fixed parameters in each step of iterative process. Where $X$ is searched parameters vector, $w(i)$ is a value of required temperature in superheater output $i$, $y_M(i,X)$ is simulated response of superheated steam temperature behind superheater output and $N$ corresponds to simulation time.

The aim is to obtain a set of parameters appropriate for the regulation not only of this specific step change experiment from 100% to 50% but also for other common operation modes. Therefore we will continue to work with trend change of load level from 50% to 100% with a trend rate of 10 MWt per 60 seconds, which is an opposite extreme to operating mode of load step change.

Based on the significance parameters analysis [14] was observed that regulation quality is mostly affected by *Ku* parameter in fuzzy PI controllers output. Furthermore was found that the last one of three superheaters (superheater IV) is the most sensitive to parameter changes. Based on these facts we would decrease number of optimized parameters as bellow:

- The searched parameter vector of fuzzy controllers will contain the output parameters of fuzzy PI controllers for inner and outer loop of superheater II., III. and IV.
- Input parameters of fuzzy PI controllers for inner and outer loop of superheater VP will be used for possible tuning.

For iteration calculation of optimization task is used a net of linear models. Computational time-consuming of one of the task (one hundred iteration steps) is in hours. In criteria is searched minimum deviation between required temperature output process and simulated response. Vector of searched parameters of fuzzy controllers is adapted in each iteration step. We would discuss two variants of optimization.

### *3.2.1. Variant I. – The sequential optimization by structure technology*

First variant uses serial technological connection. Initial estimation of parameters corresponds to the best setting from the previous chapter 3.2. In the first step we would make optimization of temperature $T_{SII\text{-}OUT}$ on the Superheater II. output. The criterion has following form (2). We are looking for two of output gain parameters of fuzzy PI controllers F-PI-1 and F-PI-2 (Fig. 2). $T_{SII\text{-}OUT}$ is function of searched parameters (3).

$$J(X) \cong \sum_{i=0}^{N} e(i,X)^2 = \sum_{i=0}^{4000} \left[460 - T_{SII-OUT}\right]^2 \rightarrow \min \tag{2}$$

$$T_{SII-OUT} = f(K_{u-SII-IN}, K_{u-SII-OUT}) \tag{3}$$

In the second step the temperature $T_{SIII\text{-}OUT}$, which is a function of parameters (5), is optimized on Superheater III. output (4):

$$J(X) \cong \sum_{i=0}^{N} e(i,X)^2 = \sum_{i=0}^{4000} \left[485 - T_{SIII-OUT}\right]^2 \rightarrow \min \tag{4}$$

$$T_{SIII-OUT} = f(K_{u-SIII-IN}, K_{u-SIII-OUT}) \tag{5}$$

And finally in the third step the temperature $T_{SIV\text{-}OUT}$, which is a function of parameters (7), is optimized on Superheater IV. output (6):

$$J(X) \cong \sum_{i=0}^{N} e(i,X)^2 = \sum_{i=0}^{4000} \left[575 - T_{SIV-OUT}\right]^2 \rightarrow \min \tag{6}$$

$$T_{SIV-OUT} = f(K_{u-SIV-IN}, K_{u-SIV-OUT}) \tag{7}$$

On the Fig. 5 (a) are temperature responses $T_{SII\text{-}OUT}$ on the SII. output after optimization of fifty iteration steps. Initial optimization state is marked green and final optimization state is marked purple. Each iteration step is marked blue. By optimization of two parameters we have achieved a significant improvement of output temperature process on linear model. Whereas the superheater SII. is preceded by superheater III. and IV., optimization has positive effect of both output temperature $T_{SIII\text{-}OUT}$ of SIII., see Fig. 5 (b) and the most important temperature $T_{SIV\text{-}OUT}$ on output of superheater IV., see Fig. 6, too. In the second step we use optimization parameters as initial estimation and move to optimization of controller output parameters F-PI-3 and F-PI-4 to superheater III. see Fig. 5 (b). Further optimization of temperature output is marked green. Final state of optimization task in the second step is marked purple. Improvement is still evident on temperature response $T_{SIII\text{-}OUT}$, however on temperature response $T_{SIV\text{-}OUT}$ is not so evident, see Fig. 6. The third step of optimization is made and the final state of whole optimization task is marked purple. It is evident that parameters of fuzzy controller on superheater II. and III. have the most important weight during the output temperature $T_{SIV\text{-}OUT}$ of output superheater optimization process.

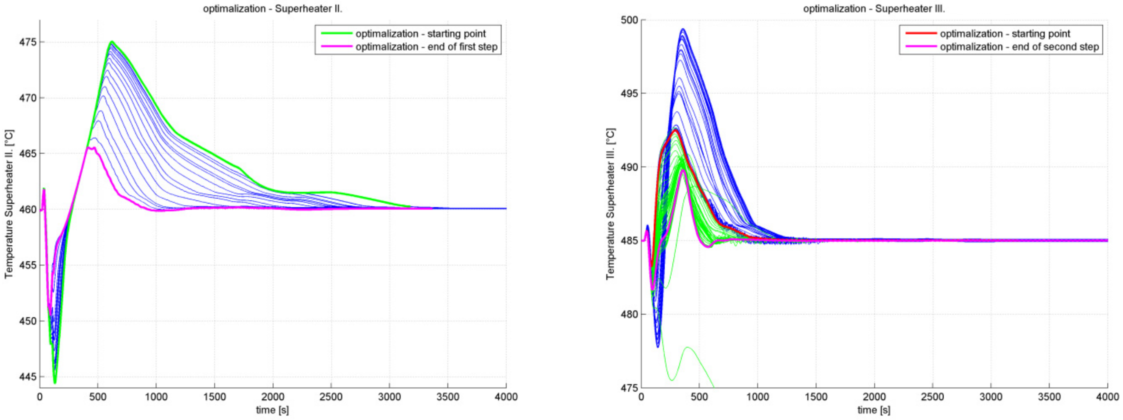

Fig. 5. (a) Optimization of the superheater II. temperature and (b) Optimization of the superheater III. Temperature.

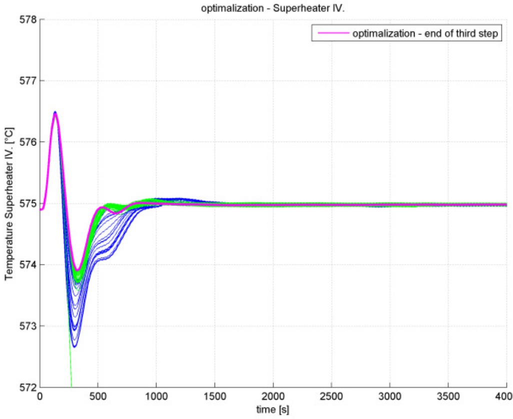

Fig. 6. Optimization of the superheater IV. Temperature.

### *3.2.2. Variant II. – Parameters optimization by superheater IV. output temperature*

In this part we would try an access, where criteria stay same in all steps and output temperature $T_{SIV\text{-}OUT}$ is occur, thus the temperature, which is the most important. The criterion for optimization task has form (8):

$$J(X) \cong \sum_{i=0}^{N} e(i,X)^2 = \sum_{i=0}^{4000} \left[575 - T_{SIV-OUT}\right]^2 \rightarrow \min \tag{8}$$

In the first step the temperature $T_{SIV\text{-}OUT}$ is function of output parameters of fuzzy PI controller on superheater II. (9), in the second step the temperature $T_{SIV\text{-}OUT}$ is function of parameters according to (10) and in the final step the temperature is function of fuzzy PI controller parameters on superheater IV. (11).

$$T_{SIV-OUT} = f(K_{u-SII-IN}, K_{u-SII-OUT}) \tag{9}$$

$$T_{SIV-OUT} = f(K_{u-SIII-IN}, K_{u-SIII-OUT}) \tag{10}$$

$$T_{SIV-OUT} = f(K_{u-SIV-IN}, K_{u-SIV-OUT}) \tag{11}$$

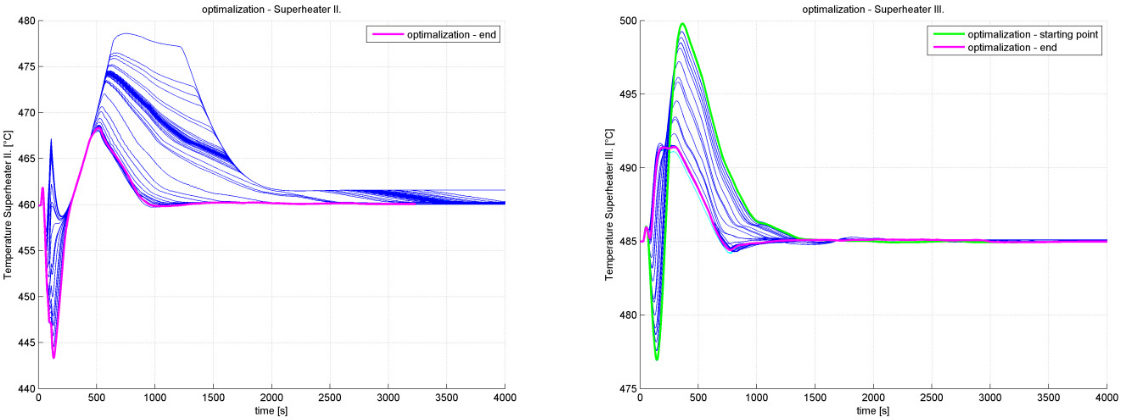

Fig. 7. (a) Optimization of the superheater II. temperature and (b) Optimization of the superheater III. Temperature.

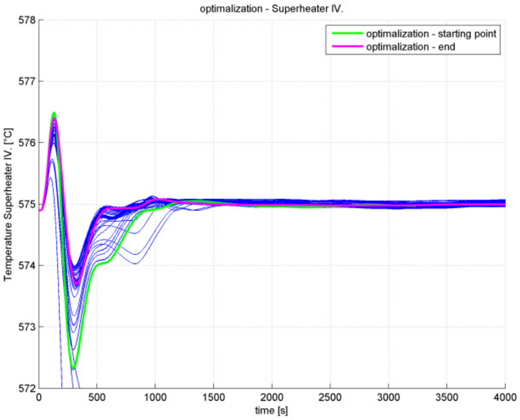

Fig. 8. Optimization of the superheater IV. Temperature.

There are two optimization tasks from which were obtained two set of parameters. These parameters were verified on non-linear model for same load level step change from 100 % to 50 %. Response of temperature output $T_{SIV-OUT}$ corresponds to results of linear model and response is within the tolerance. However the process shows small oscillations around required value. It is necessary to tune four parameters of fuzzy PI controllers in superheater IV. output. Second logical step is verification set of parameters to other than step changes and verification whether the fuzzy algorithm is able to cover these requirements. For this experiment was choose trend change of load level from 50 % to 100 %, which covers whole load range and is extreme opposite to step change of operating modes. Optimization task was performed here as well, see Fig. 9. Initial setting is marked green, each optimization process is marked blue and appropriate setting is marked purple.

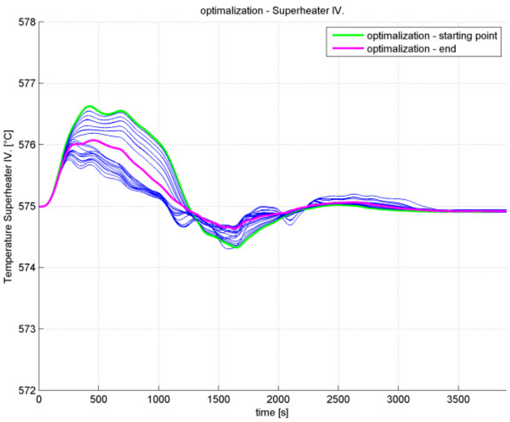

Fig. 9. Optimization of the superheater IV. temperature for trend change of load.

To find compromise solution between two types of operating modes and avoid unwanted oscillations, we use the outcome parameters, which correspond to purple process in the middle of optimization and which are closest to parameters obtained from optimization tasks for step changes. Tuning of remaining four parameters of superheater IV. output is made out of the optimization task. The compromised solution obtained in this way is verified by simulation experiments of both step change Fig. 10 (a) and trend change of load on non-linear model Fig. 10 (b).

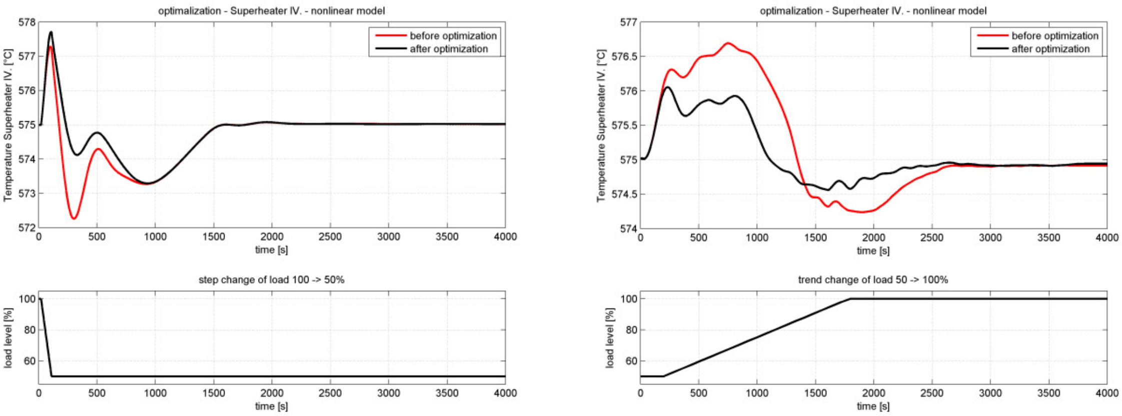

Fig. 10. Comparison of the superheater IV. output temperature response for (a) step change and (b) trend change of load.

## Conclusion

It can be said, based on two presented graphs, that improvement of controlled system responses was achieved by implementation of minimization criteria of fuzzy PI controller parameters. Appropriate selection of fuzzy PI controller parameters significantly facilitates the optimization task. Optimization process for both step and trend load change is demonstrated on Fig. 10. As you can see on pictures, the optimization effect is evident. Fuzzy algorithm was tested on current operating modes represented by step changes and trend changes over whole range of monitored load level changes. Properties of designed fuzzy algorithm like that were tested on both responses of disturbances and dynamics process changes, which were compared with original PI control system results. Fuzzy control system brings improvement of the controlled process.

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