Control Systems of a Non-stationary Plant Based on MPC and PID Type Fuzzy Logic Controller

Igor S. Nadezhdin, Aleksey G. Goryunov, Flavio Manenti, Anton O. Ochoa Bike

***Abstract*— Typically, processes taking place in modern industrial plants have significant nonlinearity. To control so complex dynamic processes used automatic control system (ACS) based on fuzzy logic controllers (FLC) or on the basis of a predictive model controllers (MPC). In this paper are compared the systems of automatic control with different regulators (fuzzy PID regulator and MPC regulator), if introduced into the system of different disturbing influences.**

***Index Terms*—model predictive control, fuzzy logic controller, PID controller, control system.**

I. Introduction

Currently in the industry, at any stage of processing of the material / substance there is a high level of automation. The use of automatic control systems of production processes is done in order to improve the safety of the technological process, as well as improve the economic performance of plants and production as a whole. As a rule, the majority of technological processes (plants), occurring today in the industry, is a complex dynamic objects. Complex dynamic systems are objects with nonlinear static characteristics, that is, objects that are described by differential equations with time-varying parameters. Experience has shown that control of such plants by means of traditional PID controllers does not provide the required quality control.

In order to improve the efficiency of automatic control system of complex dynamic objects, researchers around the world, doing research, trying to combine the standard PID regulator with fuzzy adaptive controller [1, 2]. Currently, there are different types of fuzzy controllers, but the fuzzy controller based PID regulators are the most common [3, 4]. As a rule, setting a fuzzy controller is made based on the Mamdani controller. In this, the controller Mamdani is located directly in the control channel, as shown in the papers [5, 6]. For this research using fuzzy PID regulator presented in this paper [7], but without the procedure of identification of parameters of the control plant. The distinguishing feature of this fuzzy PID controller is that in him using expert grade determined coefficients PID regulator.

Also, recently, for the control of complex dynamic objects are widely used controllers on the basis of a predictive model [8, 10]. For the synthesis of such a regulator is necessary to make a mathematical model of the control plant. Using a mathematical model of the control plant, regulator is to predict changes in the controlled variable for a certain period of time ahead and calculate the optimal control action, to provide the best trajectory of the controlled variable.

The purpose of this paper is the comparative analysis of automatic control systems with PID regulator based on fuzzy logic and regulator on the basis of a predictive model (MPC-controller). In this case system will be introduced stepwise disturbing influences are not known magnitude and duration.

II. Theoretical Part

A. *Control plant*

Since in the paper discussed automatic control system for a complex dynamic control plant, the parameters of such an plant can be changed during the process.

At the initial time control plant is described by the transfer function of the first order (1). The dynamics of the control plant is described as a linear system with the transfer function $W_p^u(s)$ that represents channel *u* and the transfer function $W_p^f(s)$that stand for channel *f*:

$$W_p^{\,u}(s) = \frac{k_p}{T_p \cdot s + 1} \cdot e^{-\tau_p s},$$
$$W_p^{\,f}(s) = \frac{k_p^f}{T_p^f \cdot s + 1} \cdot e^{-\tau_p^f s} \quad (1)$$

In current of process, when switching plant from one mode to another or when changing characteristics of the

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material (feedstock) may vary the order of the transfer function, which describes the control object on the control channel $W_p^u(s)$. In our case the dynamics of the control plant is described by the following transfer functions:

$$W_p^{\,u}(s)=\frac{k_p}{(T_{p1}\cdot s+1)\cdot(T_{p2}\cdot s+1)\cdot(T_{p3}\cdot s+1)}\cdot e^{-\tau_p s},$$
$$W_p^{\,f}(s)=\frac{k_p^f}{T_p^f\cdot s+1}\cdot e^{-\tau_p^f s} \quad (2)$$

In addition to changing the parameters of the control plant in current of technological process in the system introduced stepwise disturbing influences of unknown magnitude and duration.

B. The automatic control system with adaptive fuzzy PID controller

A proposed automatic control system with fuzzy PID controller is shown in Figure 1.

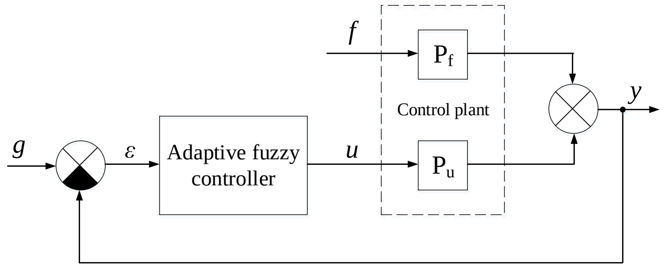

Fig. 1. Adaptive fuzzy automatic control system

Depicted in Figure 1 the variables have the following meanings: g – set point; f – measurable disturbance; u – control action; P_u – plant control channel; P_f – plant disturbance channel; y – controlled variable; ε – control error is defined as $\varepsilon = g - y$.

Let us consider in more detail the adaptive fuzzy regulator, presented in Figure 1. Scheme adaptive fuzzy controller is shown in Figure 2.

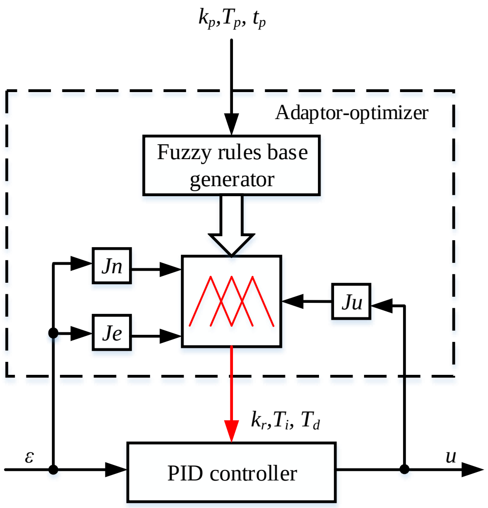

Fig. 2. Adaptive fuzzy controller

Adaptive fuzzy regulator consists of the following blocks: a fuzzy rules base generator, a Mamdani fuzzy output controller and *Jn*, *Je* and *Ju* terms calculation engines.

The optimization problem consists of maximizing or minimizing a functional which plays the key role from the viewpoint of the design of adaptive and optimal control systems. It is addressed here in the following form:

$$\min\left(Je_k + Ju_k + Jn_k\right) \quad (3)$$

where

$$Je_k = \sqrt{\frac{\sum_{j=k}^{k+he}(\varepsilon_j)^2}{he-1}} \quad (4)$$

$$Ju_k = \sqrt{\frac{\sum_{j=k}^{k+hu}(u_j-u_k)^2}{hu-1}} \quad (5)$$

Jn_k – the number of control error oscillations in the interval *he*, (4).

where $k = 1,2,\ldots\infty$, ε_j – the control error, u_j – the control action, *he* – the control error interval, *hu* – the control interval, *j* – the index of time sampling.

For the calculation of parameters of the PID regulator is used controller Mamdani with fuzzy rules, obtained by minimizing the functional (3).

C. The automatic control system with MPC controller

The automatic control system with MPC controller is similar automatic control system with adaptive fuzzy controller (Figure 3).

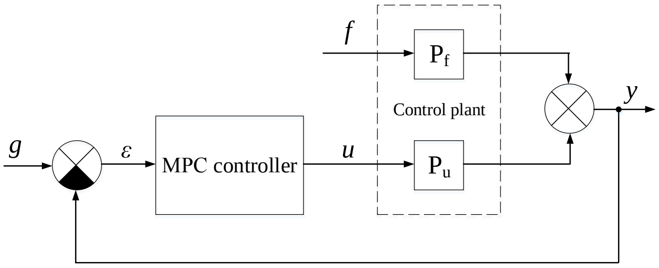

Fig. 3. The automatic control system with MPC controller

Structural sheme of MPC controller is shown in Figure 4. The structure of the regulator includes: a predictive model and power optimization.

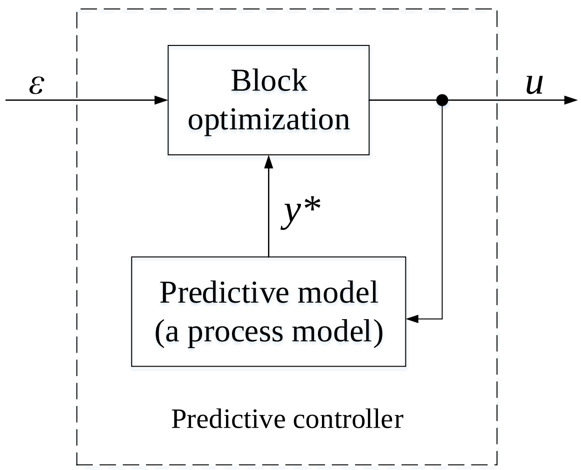

Fig. 4. Structural scheme of MPC controller

Main idea of model predictive control can be represented

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following manner: there are control action *u(t)* and *y(t)* controlled variable, *g(t)* is the desired value (dependence) changes in the controlled variable. Consider a system in discrete time, it is only in moments of time $t=k\cdot\Delta T$, where ΔT – some sampling period, and k – some integer. For convenience the graphical representation we will consider $\Delta T=1$.

The main feature of model predictive control is a mathematical model of the control plant, which accurately describes its behavior. Availability of an adequate mathematical model of control plant allows to predict the value of the controlled variable to a certain number of steps forward (Figure 5).

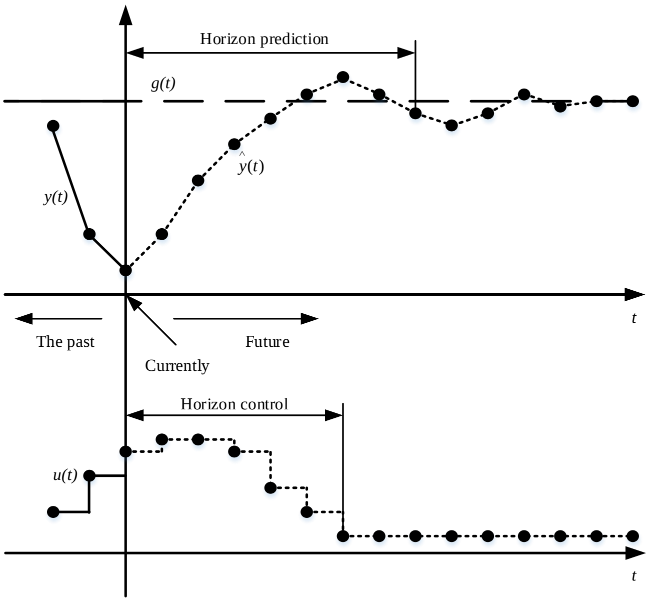

Fig. 5. A graphical representation of the idea of model predictive control

The values of the controlled variable *y(t)*, predicted at some time *t*, in Figure 5 are designated following manner $\hat{y}(t)$. Horizon prediction is built on a certain number of clock cycles. The projected trajectory of the controlled variable will depend on the future values of the control action *u(t)*.

Essence of method consists in finding a sequence of values of the control action *u(t)*, which will provide the best projected trajectories for the controlled variable *y(t)*. The sequence length of the calculated control actions *u(t)* is a fixed quantity and is called the *horizon control*. The sequence of values of the control action is determined by solving a problem of optimization. Choosing the best trajectory the controlled variable is determined by indicators of quality control.

The paper is used the quality indicators, which contains the square error between the predicted controlled variable control plant *y(t)* and the desired trajectory (set point) *g(t)*. When choosing the optimal values of the control action *u(t)*, regulator seeks to minimize the functional submitted by expression of the form:

$$J = Q\cdot\sum_{i=1}^{p}\left(y(k+i)-r(k+i)\right)^2 + R\cdot\sum_{i=0}^{m-1}u^2(k+i) \qquad (6)$$

where: Q and R – weighting coefficients, p – the number of cycles on which build the prediction of the behavior of the controlled variable *y(t)* (prediction horizon), m – the length of the sequence of future values of the control action *u(t)* (horizon control).

After feeding by at control plant of the first element calculated the optimal sequence the control action *u(t)*, at the next clock cycle the whole procedure is repeated again, taking into account the the newly received information.

So is functioning regulator with a predictive model.

III. Results of Experimental Research

Described before automatic control system with different controllers have been implemented in MATLAB/Simulink.

To configure fuzzy PID regulator in automatic control systems (Figure 1) have been defined parameters control plant described by the transfer function of the first order (1).

For the synthesis of regulator with model predictive is used the transfer function of the first order (1), with the same parameters as for setting fuzzy PID regulator.

In both automatic control systems impose restrictions on the control action.

At a certain moment in time has been set a desired value for the controlled variable (setpoint). The resulting setpoint the transient processes shown in Figure 6.

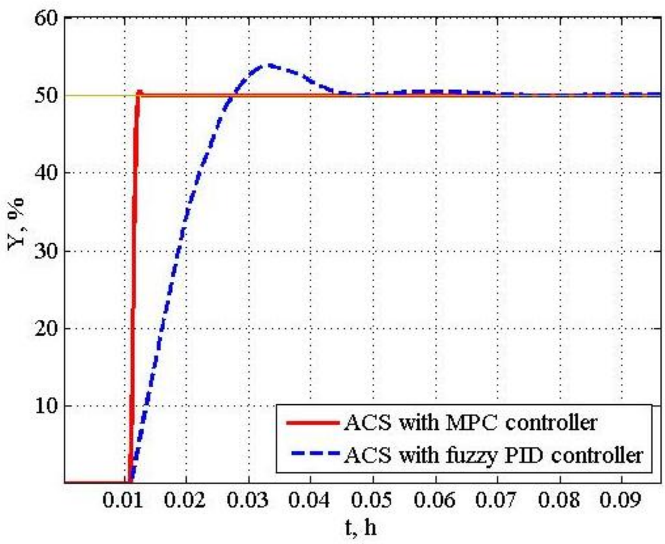

Fig. 6. The transient processes for set point

As can be seen from of transient processes (Figure 6), both the automatic control systems derive controlled variable to a predetermined level. Time control of the automatic control system with fuzzy PID controller totaled 0,036 hours (128.9 seconds), but with the MPC-controller 0.0094 hour (34 seconds). Overshoot automatic control system with fuzzy PID was 7.8 %, and the control system with MPC-controller came out on a predetermined level without overshoot. Also for of transient processes presented in Figure 6 it was calculated quadratic integral criterion (QIC) from the following expression:

$$QIC = \int_{t_1}^{t_2}\left(g(t)-y(t)\right)^2 dt \qquad (7)$$

Calculation results are shown in Table 1.

TABLE I
INTEGRAL QUALITY INDICATORS

Regulator	Quadratic integral criterion
Fuzzy PID controller	$1{,}14 \cdot 10^5$
MPC controller	$7{,}78 \cdot 10^4$

After analyzing the quality indicators can be seen that best the transition process for set point system automatic control with MPC controller provides.

Then, at time 0.14 hours, the system been introduced 30% stepwise disturbance. The obtained the transient processes are presented in Figure 7.

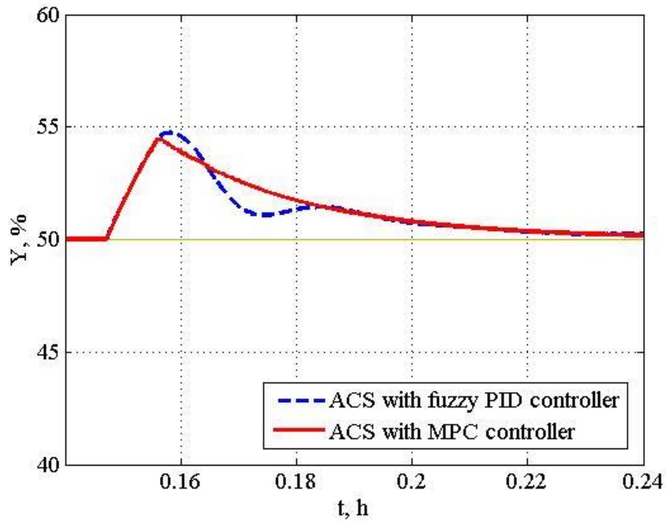

Fig. 7. The transient processes for 30% of a step disturbance

For of transient processes (Figure 7) were identified quality indicators of transient processes automatic control system for the disturbing influence.

Time control of automatic control system with fuzzy PID controller was 0.0275 hours (99 seconds), and with MPC regulator 0.0318 hour (114.48 seconds). To estimate the maximum deviation of the controlled variable from the steady-state value calculated relative maximum deviation using the following expression:

$$\sigma = \frac{y_{max}}{g} \cdot 100[\%] \quad (8)$$

where y_{max} – the maximum deviation of the controlled variable, g – setpoint for the controlled variable.

Calculation results are shown in Table 2. Also for of transient processes presented in Figure 6 it was calculated quadratic integral criterion (QIC) using the expression (7).

TABLE II
QUALITY INDICATORS TRANSIENT PROCESSES

Regulator	The relative maximum deviation, σ (%)	Quadratic integral criterion
Fuzzy PID controller	9,48	$1{,}09 \cdot 10^3$
MPC controller	8,92	$1{,}16 \cdot 10^3$

Analyzing the obtained values of the indicators quality of transient processes can be concluded that the fuzzy PID controller is a little better compensate the disturbance.

Then at time 0.28 hours been introduced 50 % stepwise disturbance, and changed the order of the transfer function describing the object on the control channel from the first to the third order (2). At moment in time 0.38 hours, been introduced one more 50% of the step wise disturbance, while controlled variable is not yet stabilized. The obtained in result this extremal disturbance the transient processes are presented in Figure 8.

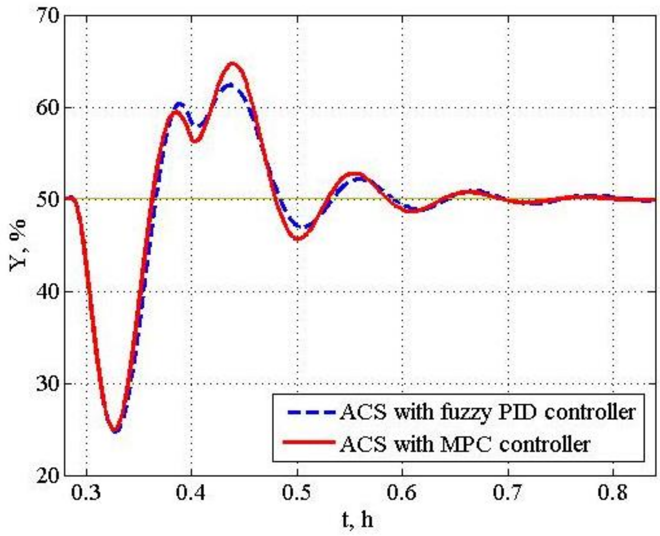

Fig. 8. The transient processes for 50% of a step disturbance and changing the parameters of the control plant

For obtained transient processes (Figure 8) were also identified quality indicators transient processes.

Time control of automatic control system with fuzzy PID controller was 0.2384 hour (858 seconds) and with the MPC-controller 0.2836 hour (1021 seconds).

Calculated relative maximum deviation of the controlled variable from the setpoint according to the expression (8), as well as to determine the quadratic integral criterion (QIC) of transient processes using the expression (7). Calculation results are shown in Table 3.

TABLE III
QUALITY INDICATORS TRANSIENT PROCESSES

Regulator	The relative maximum deviation, σ (%)	Quadratic integral criterion
Fuzzy PID controller	50,68	$1{,}1543 \cdot 10^5$
MPC controller	50,22	$1{,}1571 \cdot 10^5$

From the obtained indicators of quality of transient processes it is obvious that better compensate for disturbing influences automatic control system with fuzzy PID controller.

At moment in time 0.83 hours in the system been introduced 30 % of the disturbance, while plant on the control channel described transfer function by the third order. Because both controllers have been configured to the control plant of the first order, the quality of control deteriorated somewhat compared with the experience shown in Figure 6. The obtained the transient processes are shown

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in Figure 9.

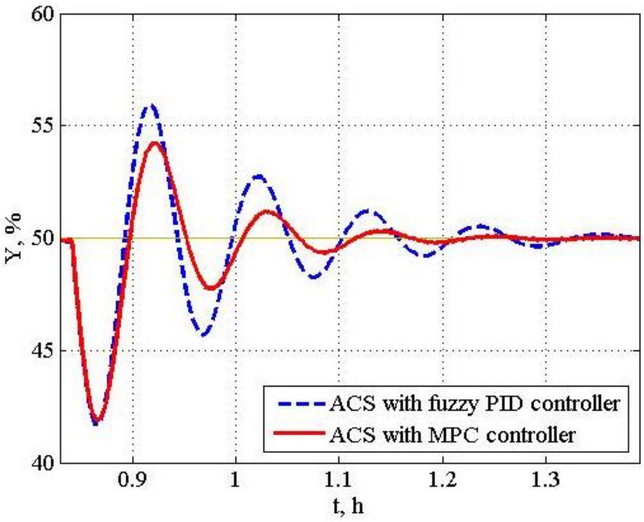

Fig. 9. The transient processes for 30% of a step disturbance and the new parameters of control plant

As seen in Figure 9, obtained the transient processes characterized by the presence of oscillations of the controlled variable. For represented of the transient processes determine the direct indicators of quality.

Time control of automatic control system with fuzzy PID controller was 0.1957 hour (704 seconds) and with the MPC controller was 0.1053 hour (379 seconds).

Similar to previous experiments, calculated relative to the maximum deviation of the controlled variable from the set point using the expression (8), as well as to determine the quadratic integral criterion (QIC) of transient processes using the following expression (7).

Furthermore, in order to evaluate the oscillatory transient processes was calculated degree of damping vibrations according to the following expression:

$$\psi = \frac{A_1 - A_2}{A_1} \tag{9}$$

where: A_1 and A_2 – amplitude two adjacent vibrations directed in the same direction.

Calculation results are shown in Table 4.

TABLE IV
QUALITY INDICATORS TRANSIENT PROCESSES

Regulator	Fuzzy PID controller	MPC controller
The relative maximum deviation, σ (%)	16,62	16,26
Quadratic integral criterion	$1{,}2569 \cdot 10^4$	$9{,}4949 \cdot 10^3$
The extent of damping, ψ	0,48	0,72

The calculated quality indicators of transient processes (Figure 9) numerically confirm that the automatic control system with the MPC controller has a much better quality control.

IV. Discussion of the Results

Comparing the transient processes shown in Figures 5-8 and analyzing quality indicators calculated for these of transient processes define the controller that provides the best quality control.

In the derivation of the controlled variable to a predetermined level the best indicators quality of transient processes provides the control system with MPC controller. When using the MPC controller is no overshoot of the controlled variable (Figure 5), and the time regulation is 3.8 times less than using fuzzy PID controller.

However, when in a system occurs 30% of stepwise disturbance the transient processes were obtained (Figure 7) which show that time regulation of fuzzy PID regulator in 1.15 times less than using the MPC controller, as well as the quadratic integral criterion is 1.1 times less. But a relative maximum deviation when using the fuzzy PID regulator more is 1.1 times. As can be seen, the control system with the fuzzy PID controller provides the transient processes with the best quality indicators.

Then, in the system been introduced 50% of the disturbance, and change the parameters of the control plant and the order of the transfer function, which describes the plant on the control channel with first order for a third (2). According to the obtained the transition process (Figure 8) determined that the control system with the fuzzy PID controller provides is 1.2 times less time regulation, but has by 0.5 % more relative maximum deviation. Quadratic integral criteria calculated for of transient processes (Figure 8) are presented in Table 3, and they do not differ significantly. In this case, the control system with fuzzy PID controller slightly better fulfills disturbing influences.

Then for control plant with new parameters of been introduced 30% of the disturbance. From the presented in Figure 9 of transient processes determined that the control system with the MPC controller provides the best quality indicators (Table 4). Time regulation control system with MPC controller is 1.86 times less than that the control system with the fuzzy PID controller. As well as a relative maximum deviation is 1.02 times less and quadratic integral criterion is 1.37 times less. In addition, the MPC controller provides is 1.5 times higher degree of damping of oscillations controlled variable than the fuzzy PID controller.

Thus, by comparing and analyzing the results obtained when modeling of automatic control system with two different controllers (fuzzy PID controller and MPC controller), can not be selected any single.

Separately, let us note advantages and disadvantages of the used controllers.

The advantages of the considered fuzzy PID regulator is the possibility its realization using standard industrial components. For this requires a PID controller and industrial controller, in which DLL library will be implemented adapter optimizer.

The need to in accurate and adequate mathematical models of the control plant is possible to carry to the disadvantages of the MPC controller. The first is not always possible to make an adequate mathematical model of the control plant and secondly, than more complex mathematical model of control plant, the more computing power is required to implement the MPC controller.

V. Conclusion

This paper devoted to the synthesis and comparison of automatic control systems with fuzzy PID controller with MPC controller. When comparing the quality indicators obtained transient processes, failed to make an unambiguous choice in favor of one of the comparable regulators. Noted advantages and disadvantages the considered regulators.

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