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Research article

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Behaviour of electric drive of roller-bit drilling rig swivel head with fuzzy control

N.M. Kuznetsov[1] ✉, I.N. Morozov[2]
[1] Kola Scientific Center of the Russian Academy of Sciences, Apatity, Russia
[2] Murmansk Arctic State University, Murmansk, Russia
✉ n.kuznetsov@ksc.ru

Abstract

The efficient consumption of electric power in mining is an important task in power consumption optimization. The use of high-performance drilling rigs requires special attention to the development of energy-saving electric drive for open-cut mining operations. The increase of the efficiency factor and energy performance of a drilling rig is achieved through controlling the electric drive which allows the specific resonance frequency and limiting the current and velocity amplitudes to be regulated. The main idea of the study lies in the application of fuzzy controllers in the systems of automatic control of processes and equipment modes in mining production. The use of fuzzy controllers is aimed at improving the characteristics of PI and PID controllers. The calculations and simulation of transients based on simulation models in the MatLab 7.11 Simulink software package allowed reliable analysis of modes of a swivel head electric drive operation to be carried out. In the course of simulating the transients of swivel head velocity varying with the use of a fuzzy controller, fuzzy variables including mismatch of rotation velocity, mismatch change speed, velocity setting voltage were justified. The analysis allowed for the term-sets of fuzzy variables and the membership functions for each term-set of fuzzy variable to be defined. The simulation results showed that the control time (response) of transients of the swivel head motor torque and current change when using the swivel head velocity control by a fuzzy controller with increasing load depending on the rock hardness decreased by a factor of 2. Implementation of a system of automatic control of swivel head velocity with the application of a fuzzy controller allows drilling rig vibration to be reduced and provided effective protection of the swivel head electric (motor) drive from overload, thus increasing reliability of the equipment, and increasing drilling productivity.

Keywords

minerals, mining, power consumption, energy performance, drilling rig, swivel head, electric drive, automatic control, controllers, transients, fuzzy controller

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Исследование динамики электропривода вращателя бурового станка шарошечного бурения с нечетким управлением

Н.М. Кузнецов[1] ✉, И.Н. Морозов[2]
[1] Кольский научный центр РАН, г. Апатиты, Российская Федерация
[2] Мурманский арктический государственный университет, г. Мурманск, Российская Федерация
✉ n.kuznetsov@ksc.ru

Аннотация

Применение высокопроизводительных буровых станков требует особого внимания к разработке энергосберегающего электропривода при добыче полезных ископаемых открытым способом. Повышение коэффициента полезного действия и энергоэффективности бурового станка достигается при управлении электроприводом, позволяющим регулировать удельную резонансную частоту и ограничивать амплитуды тока и скорости. Основная идея работы заключается в применении нечетких регуляторов в системах автоматического регулирования режимами работы электропривода вращателя бурового станка шарошечного бурения. Использование нечетких регуляторов направлено на улучшение характеристик ПИ- и ПИД-регуляторов. Расчеты и моделирование переходных процессов с применением имитационных моделей в программном комплексе MatLab 7.11 Simulink позволили проводить достоверный анализ режимов работы электропривода вращателя бурового станка. При моделировании переходных процессов изменения скорости вращателя бурового станка с применением нечеткого регулятора обоснованы нечеткие переменные: рассогласование скорости вращения, скорость изменения рассогласования, напряжение задания по скорости. Проведенный анализ позволил установить терм-множества нечетких переменных и функции принадлежности каждому терм-множеству нечеткой переменной. Результаты выполненного моделирования показывают, что время регулирования переходных процессов изменения момента и тока двигателя вращателя при применении регулирования скорости вращателя нечетким регулятором с увеличением нагрузки в зависимости от крепости породы уменьшается в 2 раза. Внедрение системы автоматического регулирования скорости вращателя бурового станка с применением нечеткого регулятора позволяет снизить вибрацию бурового станка, обеспечить эффективную защиту двигателя вращателя от перегрузки, повысить надежность работы оборудования и производительность при бурении.

Ключевые слова

полезные ископаемые, горное дело, электропотребление, энергоэффективность, буровой станок, механизм вращателя, электропривод, автоматическое управление, регуляторы, переходные процессы, нечеткий регулятор

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Introduction

In order to create intelligent systems for predicting electricity consumption at mining enterprises, energy and technological indicators must be monitored and the effect of the indicators on electricity consumption analysed. Modes of process facility operation also need to be simulated

When developing mathematical models of power consumption process, methods and approaches of predictive modeling of power consumption must be applied which take into account the specific features of organizing, planning, and conducting mining [1, 2]. Analysis of geological, technological, and organizational factors which influence mining operations in coal mines [3, 4] allows for dynamic and predictive models of power consumption to be developed while taking into account the basic temporal tendencies and additive components within the limits providing stable level of power consumption. The model for determining the processing plant's ball mill power consumption [5] for intelligent predicting system allows the efficiency of electricity consumption by the mill electric drive to be assessed. It also allows for the control system quality indicators to be determined, including controlling the load schedule, predicting production cycles and power consumption peaks, redistributing loads and analyzing changes in the mill operating mode. The implementation of automated systems of monitoring and control of production processes of mining enterprises with the use of frequency-controlled electric drives allows for a significant reduction in power consumption, as well as equipment maintenance and repairing costs [6]. Efficient power consumption in minerals mining and processing sector is an key objective in power consumption optimization [7]. The application of high-performance drilling rigs requires special attention with regard to the development of energy-saving frequency-controlled electric drive for open-cut mining operations. The increase in the efficiency factor, power quality, and energy performance of a drilling rig is achieved through controlling the electric drive. This allows the specific resonance frequency and restricting the current and velocity amplitudes to be regulated using simulation of transients with a PID controller [8, 9]. Frequency-controlled electric drive used for swivel head velocity control provides for high-quality mechanical characteristics in the entire range of electric motor velocity controlling.

Effect of the key process parameters in unstable drill bit rotation mode on the energy performance is shown in [10].

The application of common harmonic filters [11, 12] and resistivity bridge harmonic filters [13] allows the quality of electric power to be improved. The use of fuzzy controllers in automatic process control systems of mining enterprises is expanded [14]. Libraries of fuzzy control in modern programming systems have convenient graphical interface and allows for correction of the type of fuzzy output membership function that greatly simplifies the setting up of fuzzy controllers automatic control systems and improves the characteristics of PI and PID controllers [15]. The computation and simulation of dynamic drilling processes is a complex task which makes it difficult to automate drilling process and requires the use of human resources to control and manage the process. Therefore, the development of drilling process control systems with the use of fuzzy control seems urgent.

Description of swivel head electric drive

The velocity control of swivel head drive (of self-propelled rotary drilling rigs (BSSh-1M, BSSh-2M, 2SBSH-200) was achieved by changing the generator excitation in the generator-motor system with the use of generator voltage feedback and rotating magnetic amplifier [16]. The swivel head electric drive of BASh-320 self-propelled roller-bit drilling rig was powered by a three-phase power magnetic amplifier. The swivel head electric motor drive of SBSh-250 MN self-propelled roller-bit drilling rig is provided by the thyristor converter, a direct current motor system with automatic bit velocity control, when changing drilling parameters. A voltage and velocity sensor is used in the swivel head motor control and excitation circuit. After applying voltage to the control and excitation circuit of the swivel head motor drive, the velocity and feed force are set depending on rock hardness. The required axial force applied to the bottom hole is set with the control knob of the pressure controller.

Model parameters

Parameters of the main drive links of the swivel head electric motor drive control system were determined pursuant to the traditional method and are shown in Table 1.

Table 1

Parameters of swivel head electric motor drive control system with different types of standard controllers

Parameter, model element	Function	Value
	Current elements	
Transfer function $W(p)$	$W(p)=\frac{\beta}{1+T_e p}$	$\frac{42.07}{1+0.066p}$
Modulus of rigidity of linearized mechanical characteristic of electric motor, β	$\beta=\frac{2M_k}{\omega_{0_{nom}}}s_{cr}$	42.07
Breakdown torque M_c, Nm	–	309
Critical slip, s_{cr}	–	0.144
Angular rated motor velocity $\omega_{0_{nom}}$, c^{-1}	$\omega_{0_{nom}}=\frac{2\pi n_n}{60}$	102
Equivalent electromagnetic time constant of motor stator and rotor circuits T_e, c	$T_e=\frac{1}{\omega_{0_{el.nom}} s_{cr}}$	0.066
Angular velocity of electric motor electromagnetic field $\omega_{0_{el.nom}}$, rad/s	$\omega_{0_{el.nom}}=\frac{2\pi f}{p}$	104.7
Supply frequency f, Hz	–	50
Number of pole pairs, p	–	3
	Mechanics	
Transfer function $W(p)$	$W(p)=\frac{1}{\beta T_m p}$	$\frac{1}{0.13p}$
Electromechanical time constant of motor, T_m	$T_m=\frac{J}{\beta}$	0.003
Mass moment of inertia reduced to motor shaft, J, $kg \cdot m^2$	0.126	

End of Table 1

Parameter, model element	Function	Value
Frequency transformer (pole zone $f_1 \le f_{1_{nom}} = 50$ Hz)		
Transfer function $W_{pr}(p)$	$W_{pr}(p) = \frac{k_{pr}}{1 + T_{pr}p}$	$\frac{0.3}{1 + 0.001p}$
Transfer factor k_{pr}	$k_{pr} = \frac{\Delta\omega_0}{\Delta U_{pc}} = \frac{2\pi\Delta f_1}{p\Delta U_{pc}}$	0.3
Integration constant T_m, s	$T_m = T_{02} + T_{pr}$	0.021
PI controller of velocity		
Transfer function $W_{pc}(p)$	$W_{pc}(p) = \frac{\Delta U_{pc}}{\Delta U_y} = k_{pc} + \frac{1}{T_{pc}p}$	$\frac{0.008p + 1}{0.09p}$
Integration constant T_{pc}, c	$T_{pc} = k_{f.c}k_{pm}k_{pr}a_mT_m$	0.09
Transfer factor k_{pc}	$k_{pc} = \frac{T_{01}}{T_{pc}}$	0.09
PI controller of current		
Transfer function $W_{pm}(p)$	$W_{pm}(p) = \frac{\Delta U_{pm}}{\Delta U_y} = k_{pm} + \frac{1}{T_{pm}p}$	$\frac{0.06p + 1}{0.03p}$
Integration constant T_{pm}, c	$T_{pm} = k_{o.t}k_{pr}a_mT_m$	0.3
Transfer factor k_{pm}	$k_{pm} = \frac{T_{01}}{T_{pm}}$	0.2
Feedback circuit		
Transfer function $W_{f.c}(p)$	$W_{f.c}(p) = \frac{\Delta U_{f.c}}{\Delta\omega} = k_{f.c}$	
Velocity feedback factor k_y	$k_y = \frac{u_{f.c_{nom}}}{\omega_{nom}}$	3.7
Current feedback factor k_c	$k_c = \frac{u_{f.c_{nom}}}{I_{nom}}$	0.03
Rated control signal $u_{f.c_{nom}}$, V	–	380
Rated velocity ω_{nom}, rad/s	–	102
Asynchronous motor		
Transfer function $W_d(p)$	$W_d(p) = \frac{\Delta\omega}{\Delta\omega_0} = \frac{1}{T_eT_mp^2 + T_mp + 1}$	
at $T_m \ge 4T_e$	$W_d(p) = \frac{1}{(T_{01}p + 1)(T_{02}p + 1)}$	$\frac{1}{(0.008p + 1)(0.02p + 1)}$
Small uncompensated constant T_{01}, s	$\frac{1}{T_{01}} = \frac{1}{2T_e}\left(1 + \sqrt{1 - \frac{4T_e}{T_m}}\right)$	0.008
Small uncompensated constant T_{02}, s	$\frac{1}{T_{02}} = \frac{1}{2T_e}\left(1 - \sqrt{1 - \frac{4T_e}{T_m}}\right)$	0.02

Simulation of transients with PI controller

Transient design and calculation was carried out using MatLab 7.11 software by means of simulating the system in Simulink program (Fig. 1).

The simulation was performed for the following modes of the swivel head velocity change: start-up; velocity change according to the setpoint at the 5th second; velocity change at the 10th second, introducing variable load at the 15th second. The load application mode is a sharp change in static torque on the motor shaft. The simulation results are shown in Fig. 2.

Simulation of transients with PID controller

When performing the system control with a PID-controller. In MatLab 7.11, it is possible to automatically determine PID controller parameters for a given system using the tune (tune, adjust) button available in the PID controller parameters. Entering the tune block allows for the parameters to be adjusted manually. By comparing the characteristics obtained by automatic tuning and manual tuning, we select the most favorable PID controller control for the given system. The control of the PID controller parameters is shown in Fig. 3.

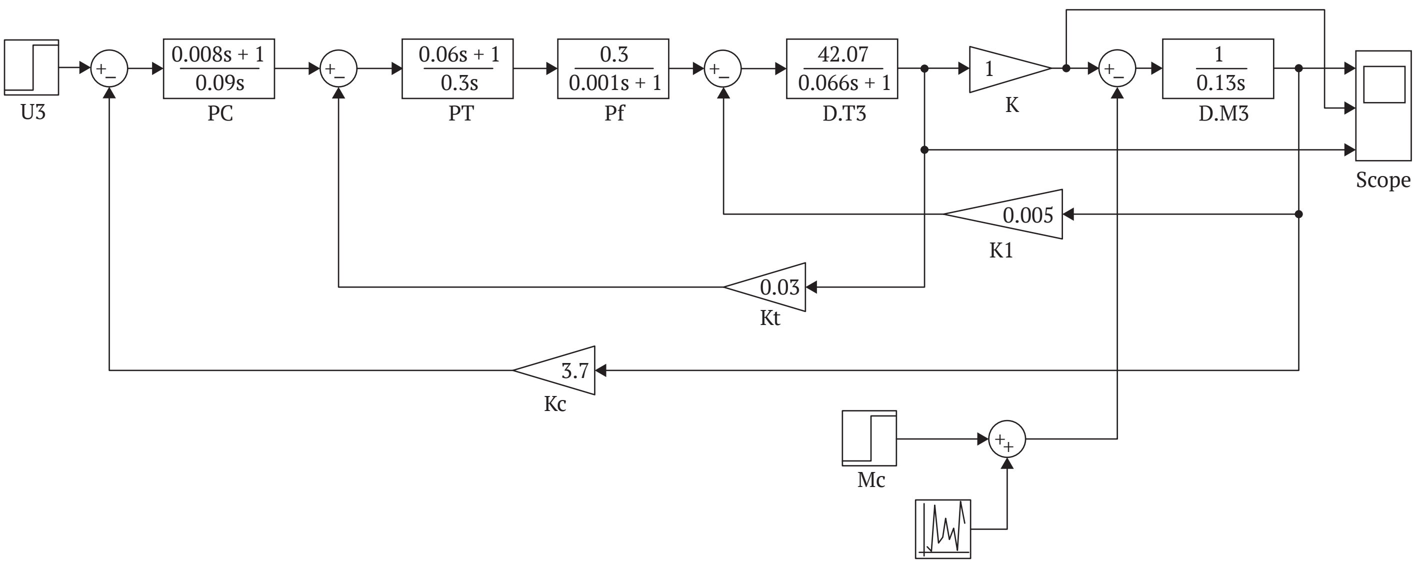

Fig. 1. The system model in the MatLab environment

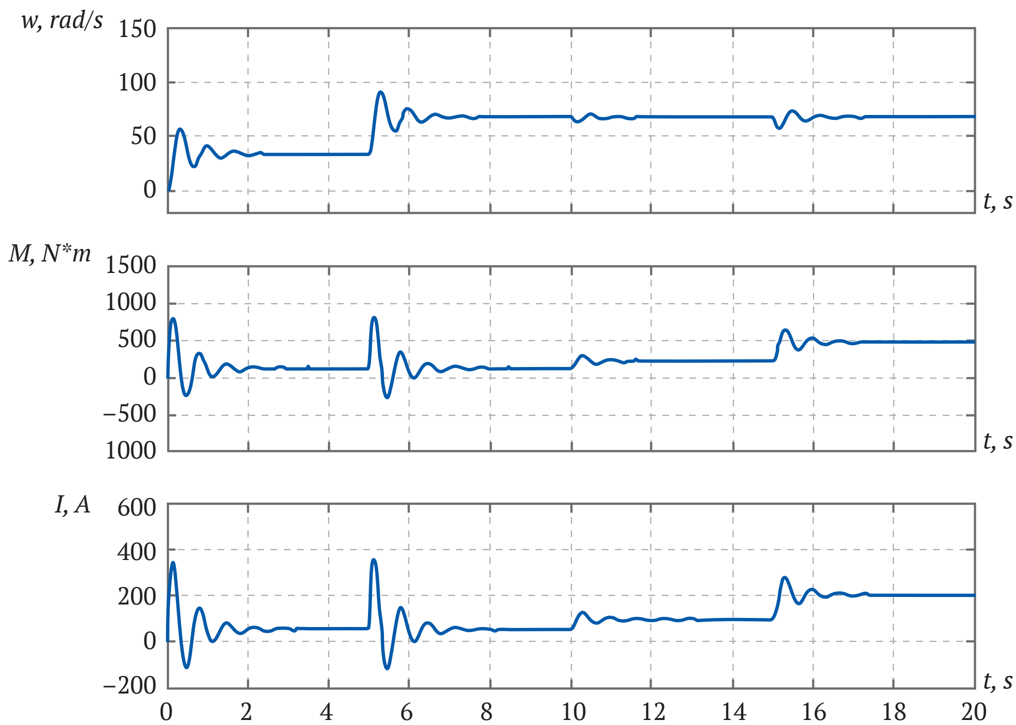

Fig. 2. Plots of transients with PI controller

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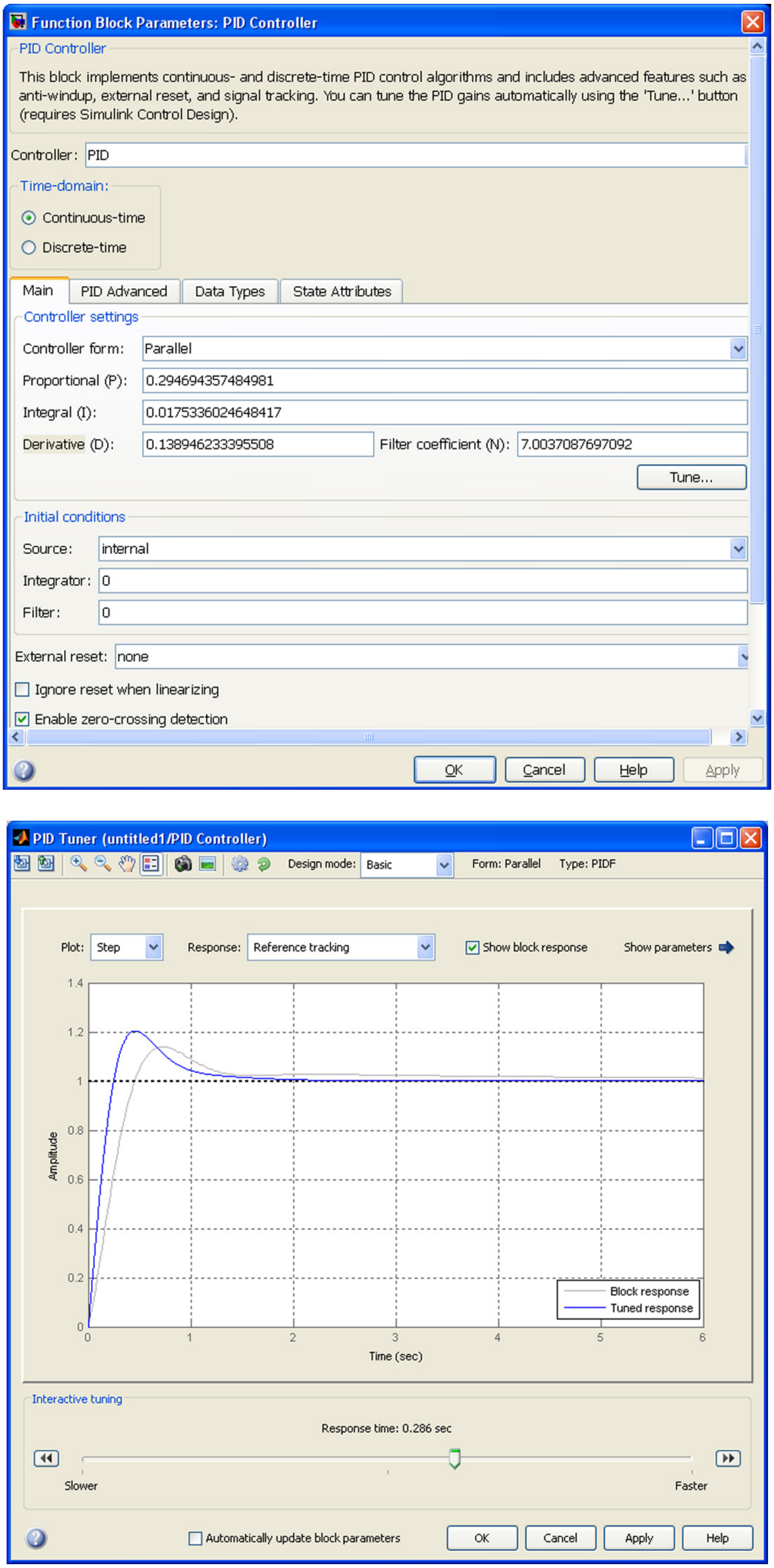

Fig. 3. PID controller parameters control

The simulation was performed for the following modes of the swivel head velocity change: startup, velocity change according to the setpoint at the 5th second, load change at the 10th second, introducing variable load at the 15^{th} second (Fig. 4).

The load application mode is represented by a sharp change in static torque on the motor shaft. The simulation results are presented in Fig. 5.

The graphs of transients when using PID controller show the change in swivel head velocity, change in torque, change in current at the preset values. The graphs show that the use of a PID velocity controller has a much better effect on the change in velocity, torque, and current characteristics. The control time (response or transient period) decreases. The use of such a controller is most advantageous for this system.

Synthesis of fuzzy controller for automatic control of swivel head velocity

In order to simulate the transients of a swivel head velocity varying with the use of a fuzzy controller, the fuzzy variables were set, including mismatch of rotation velocity, mismatch change rate, velocity setting voltage. The term-sets of fuzzy variables were determined, and the membership functions were set for each term-set of fuzzy variable. All these membership functions were implemented in the MatLab function editor (Fig. 6).

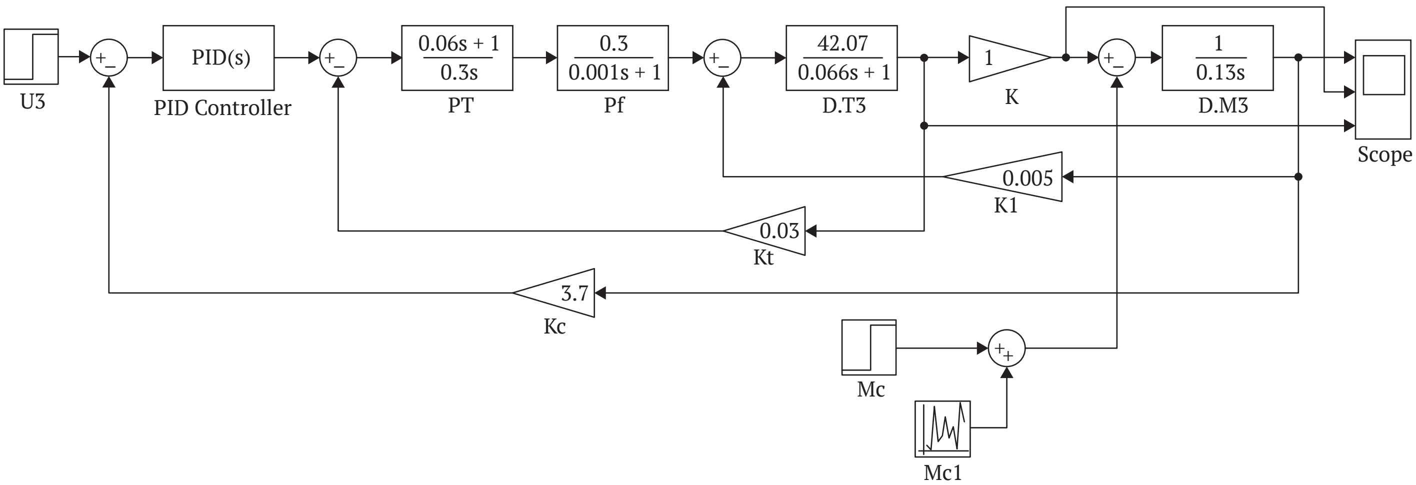

Fig. 4. System model in MatLab

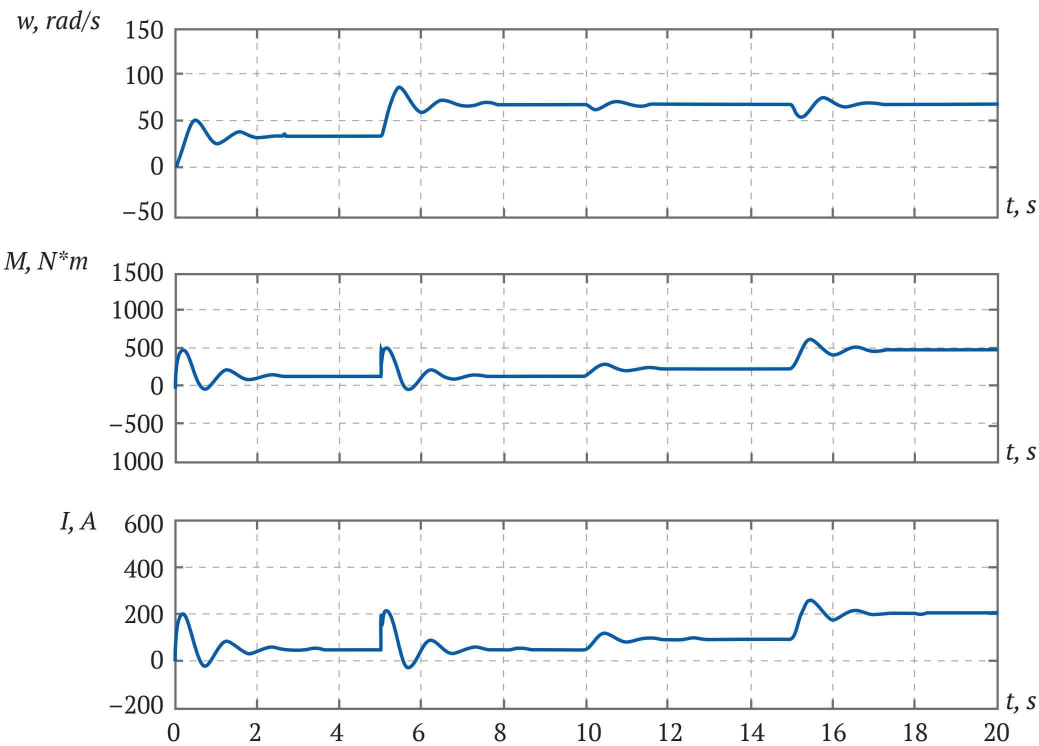

Fig. 5. Graphs of transients with PID controller

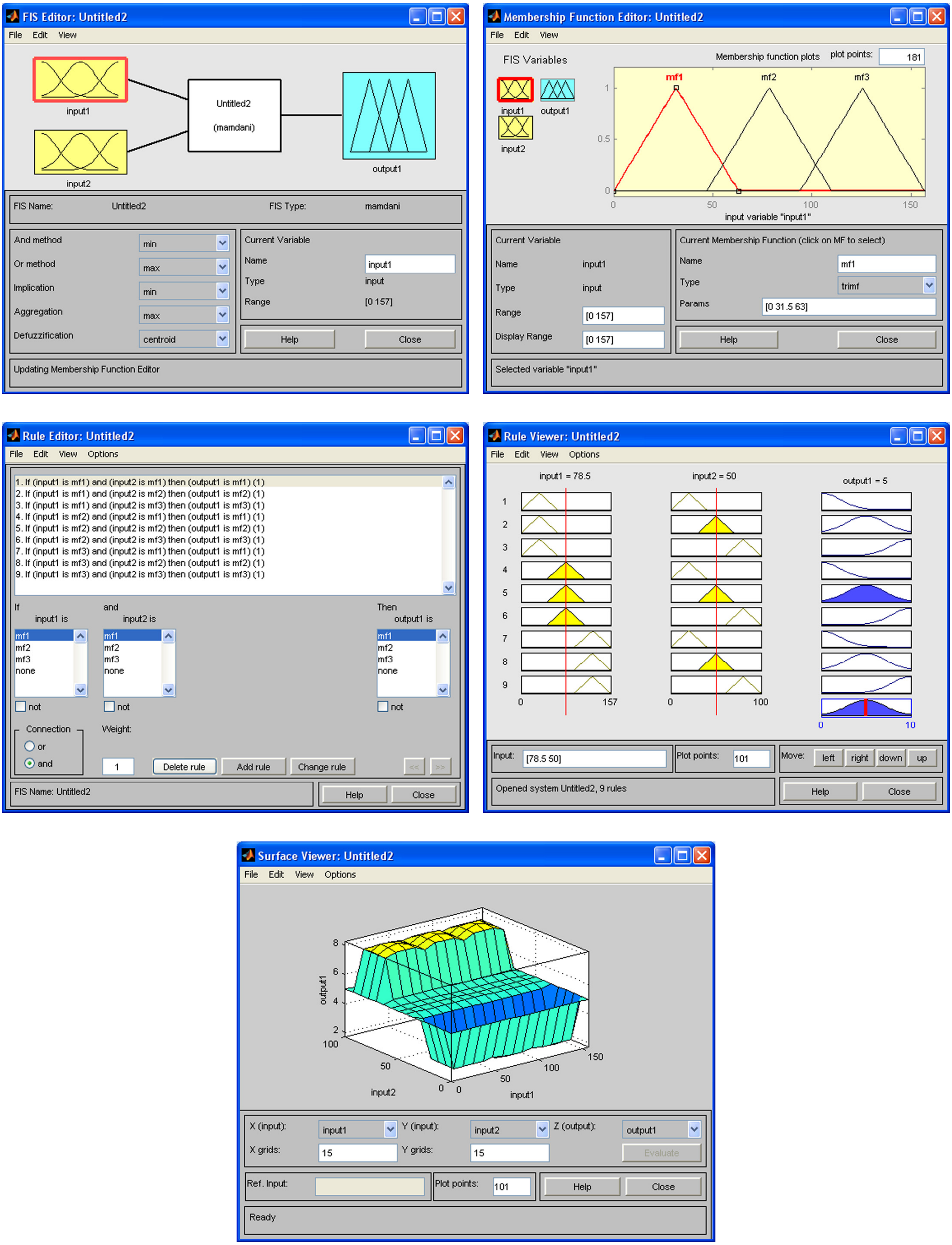

Fig. 6. Logical rule editor

The signals of mismatch of rotation velocity and speed of the mismatch change were set at the input of fuzzy controller, and attained the velocity setting voltage signal at the output.

Designing transients with fuzzy controller

Transient design and calculation was carried out using MatLab 7.11 software through simulating the system in Simulink program (Fig. 7).

Transients modes for simulating swivel head's velocity automatic control system with fuzzy controller were set as the same for the simulation with PI and PID controllers. The results of transients with fuzzy controller simulation under the given modes are shown in Fig. 8.

The results of the transients simulation for the set modes with different controllers are shown in Table 2.

Mode 1: Transient at startup under load (t = 0 s).

Mode 2: Transient at increasing setting signal (t = 5 s).

Mode 3: Transient at increasing load (t = 10 s).

Mode 4: Transient at uneven load (t = 15 s).

A comparative analysis of the transients quality indicator based on the results of simulating the drilling rig automatic control systems at the set modes showed that using swivel head's velocity control system with fuzzy controller significantly reduces the current change of transient response (time).

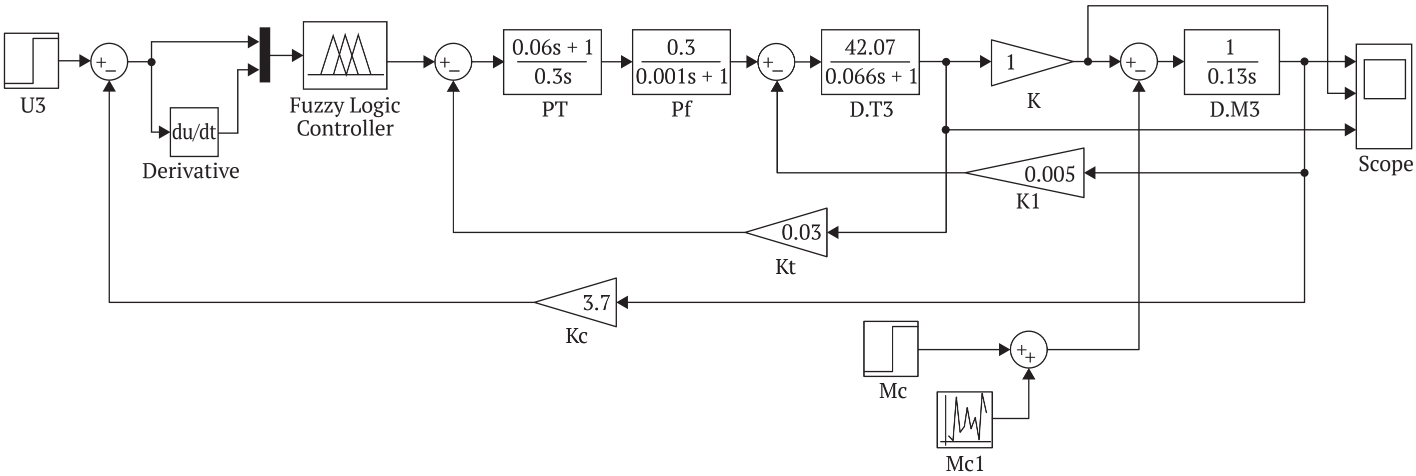

Fig. 7. Model of the system with fuzzy logic controller in MatLab

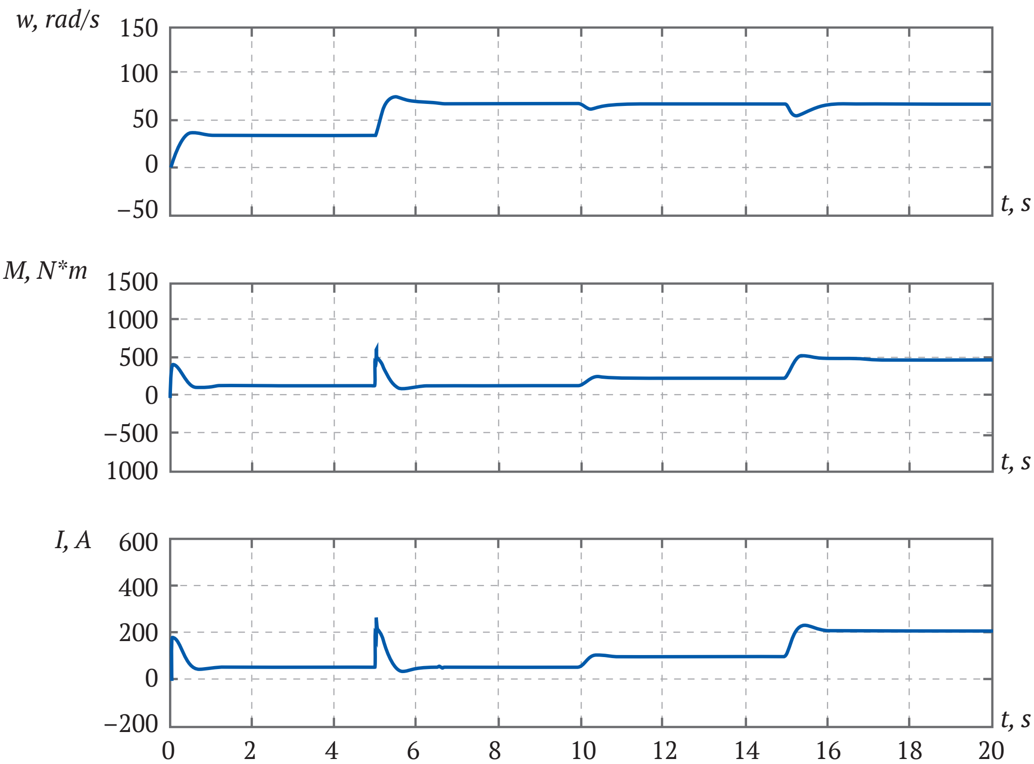

Fig. 8. Graphs of transients with fuzzy controller

Table 2

Transients control time

Operation modes	Controller type	Control (response) time, s		
		swivel head velocity	torque	current
Mode 1	PI controller	2.3	2.5	2.4
	PID controller (three-term controller)	2.3	2.8	2.5
	Fuzzy controller	2.3	1	1
Mode 2	PI controller	2.8	2.4	2.5
	PID controller (three-term controller)	2.4	3	3
	Fuzzy controller	1.4	1.1	1.4
Mode 3	PI controller	1.4	1.7	1.9
	PID controller (three-term controller)	1.8	1	2
	Fuzzy controller	1.1	0.7	0.7
Mode 4	PI controller	1.9	2.1	1.8
	PID controller (three-term controller)	2	2	2.2
	Fuzzy controller	1.3	2	1.3

Conclusions

The study substantiated the feasibility of successful applying simulation modeling for investigating the operation of swivel head electric drive, using the MatLab software environment. The results of the swivel head operation modes simulation with the standard controllers and the fuzzy controller showed that transients response (time) for the set modes of the automatic control system with the fuzzy controller decreased. The simulation results showed that the transient control time of the swivel head motor torque, and current change when using the swivel head velocity control with a fuzzy controller with increasing load depending on the rock hardness, decreased about two times. Implementation of the system of automatic control of the swivel head velocity of the drilling rig with application of the fuzzy controller will allow drilling rig vibration to be reduced. It will also provide effective protection of the swivel head electric (motor) drive from overload, increase the reliability of the equipment and productivity while drilling.

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Information about the authors

Nikolai M. Kuznetsov – Cand. Sci. (Eng.), Leading Researcher, Kola Science Centre of the Russian Academy of Science, Apatity, Russian Federation; ORCID 0000-0002-9440-8677, Scopus ID 56252352900, ResearcherID G-3754-2017; e-mail n.kuznetsov@ksc.ru

Ivan N. Morozov – Cand. Sci. (Eng.), Associate Professor, Murmansk Arctic State University, Murmansk, Russian Federation; ORCID 0000-0003-3488-8186, Scopus ID 57210912468, ResearcherID W-4918-2018

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