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Automatic armature current control system of a motor with a pulsed converter model

Abstract. The paper considers an automatic armature current control system of a braked electric motor using a pulse model of a thyristor rectifier that takes into account the discrete nature of the electric energy conversion process and the influence of the ripple component of the control signal on the dynamic characteristics of the closed-loop system. The relevance of the study is determined by the widespread application of subordinate control systems in DC electric drives and the necessity to improve their response speed, accuracy, and adequacy of the mathematical description of dynamic processes. It is shown that the use of conventional continuous models of thyristor rectifiers does not allow full consideration of the operating features of the power converter associated with its pulse operating mode and incomplete controllability. The aim of the study is the accurate description of dynamic processes in the automatic armature current control system using a pulse model of the thyristor rectifier and the investigation of conditions for ensuring the ultimate response speed of the system. Based on the z-transform, analytical relationships describing the dynamics of the automatic armature current control system were obtained. The conditions for implementing a finite-duration process were determined, and the parameters of the current controller were synthesized to ensure the maximum response speed of the system. To verify the adequacy of the obtained theoretical results, a simulation model was developed in the MATLAB/Simulink environment using the parameters of a 24 kW 2PO200L motor. The novelty of the proposed study in comparison with known approaches based on the use of a continuous thyristor rectifier model lies in taking into account the influence of the incomplete controllability of the thyristor rectifier on the dynamics of the closed-loop automatic control structure. The practical significance of the work consists in the fact that the application of the analytical relationships obtained in the paper during the development of an automatic control system for the output variable of the thyristor rectifier makes it possible to accurately describe the dynamic process of the armature current control loop in a subordinate speed control system and to calculate the system parameters required to achieve the ultimate response speed through the implementation of a finite-duration process.

Keywords: armature current control, motor, thyristor rectifier, pulse model, automatic control system, z-transform.

Relevance of the research topic.

The modern development of DC electric drives and automatic control systems is characterized by increasing requirements for response speed, control accuracy, and energy efficiency of electromechanical systems. Of particular importance is the provision of high-quality dynamic processes in subordinate control systems, where the armature current loop determines the

response speed of the entire electric drive control system. The widespread application of thyristor rectifiers in industrial electric drives necessitates a more accurate consideration of their operating features in the analysis and synthesis of automatic control systems. The use of simplified continuous models of power converters does not always allow an adequate description of the influence of the discreteness of the energy conversion process and the ripple component of signals on the dynamics of a

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closed-loop system. In this regard, the application of pulse models of thyristor rectifiers is of current interest, since they make it possible to improve the accuracy of the mathematical description of dynamic processes and to reasonably perform the synthesis of high-speed automatic control systems. Of particular relevance is the task of ensuring finite-duration processes in the armature current control loop, which makes it possible to achieve the ultimate response speed of the electric drive and improve the quality indicators of transient processes.

In the practice of designing automatic control systems for electric drives, subordinate control systems are widely used due to their high performance characteristics [1, 2]. The construction of a subordinate control system is based on the principle of time separation of transient processes in the inner and outer control loops [3, 4]. In this case, the inner loop has a higher response speed compared to the outer loop. The functional diagram of the subordinate electric drive control system is shown in Fig. 1.

Introduction.

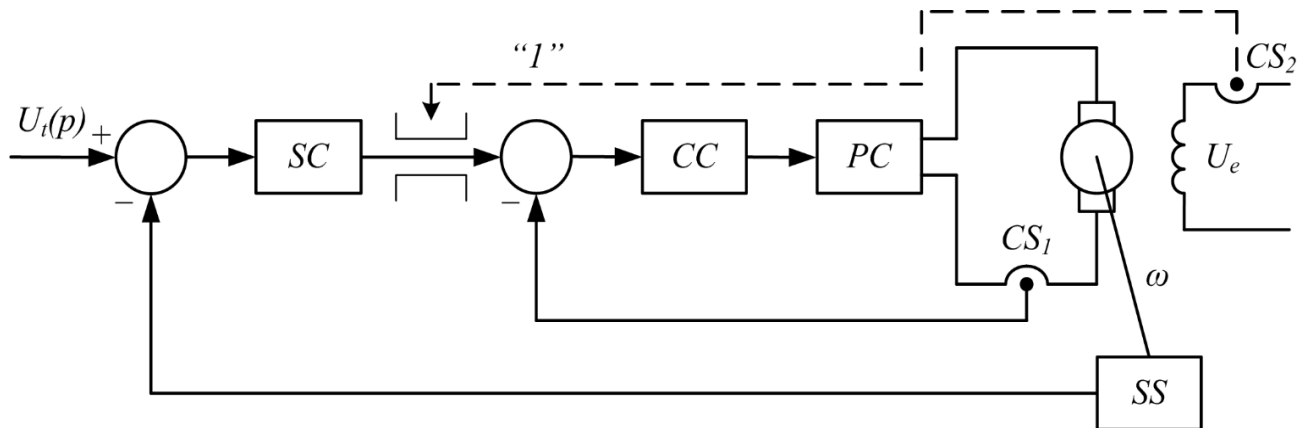


Fig. 1. Functional diagram of the subordinate electric drive control system

The following designations are used in the diagram: *SC* – speed controller; *CC* – armature current controller; *PC* – power converter; *SS* – speed sensor; *CS* – current sensor; «*I*» – dynamic signal limiter («bottleneck»).

The considered system consists of two control loops. The inner loop performs control of the motor armature current. It includes the current controller *CC* and the power converter *PC*. The armature current is measured by the current sensor *CS_i*. The outer loop is intended for speed control. It includes the speed controller *SC*, the dynamic signal limiter «*I*», and the speed sensor *SS*. The output signal of the speed controller serves as the reference signal for the subordinate current controller *CC*. Such a system, based on the principle of time separation of transient processes, is easily subjected to analysis, synthesis, and tuning due to its decomposition into simple controllers, each of which controls its own parameter. This decomposition makes it possible to consider separately the dynamic processes occurring in each control loop.

Analysis of recent research and publications.

Paper [5] presents a detailed description of the dynamic processes of a DC pulse converter with pulse-width modulation of the second kind operating in the continuous load current mode using the theory of generalized functions of one argument for single-sided

and double-sided reference signals. The adequacy of the obtained pulse models of the converter is verified through simulation of a high-speed output current control system in the MATLAB environment. The efficiency of applying the generalized derivative method for obtaining pulse models of a DC pulse converter with pulse-width modulation operating in the continuous current mode is demonstrated. The obtained pulse models make it possible to accurately describe dynamic processes in automatic control systems with a DC pulse converter and to calculate the controller parameters required to achieve the ultimate response speed.

In [6], a method of dual-loop discrete adaptive control (DDAC) for three-phase PWM rectifiers is proposed, which takes into account the mismatch of inductance parameters and constant load disturbance. A discrete model of a three-phase PWM rectifier is created using Euler's direct discretization method, and a double-loop discrete feedback linearization control (DDFLC) is presented. DDAC is developed based on DDFLC. First, an adaptive inductance disturbance observer (AIDO) based on the gradient descent method is proposed in the current control loop. AIDO is used to estimate disturbances caused by inductance parameter mismatches and then to compensate for these disturbances in the current controller, ensuring its high stability to inductance parameters. Second, an adaptive load parameter law (LPAL) based on discrete Lyapunov theory is proposed for the voltage control loop. LPAL evaluates the constant

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load parameter in real time and then adjusts it in the voltage controller, achieving constant load adaptability. Simulation and experimental results show that DDAC demonstrates better steady-state and dynamic performance, lower current harmonic content than DDFLC and dual-loop discrete PI controller (DDPIC), as well as greater immunity to inductance parameters and constant load disturbances.

The study [7] compares PI controller designs in s-domains and z-domains in the context of controlling a three-phase rectifier with pulse width modulation. Using the double closed-loop control method with a pole-zero compensation approach, the parameters of the PI controller for controlling the current and voltage in the circuit are calculated. The Euler direct method is used to convert the PI controller from the s-domain to the z-domain.

In [8], a controller with an adaptive and stable structure based on a proportional-derivative fuzzy neural network of type 2 (PD-T2FNN) is proposed for controlling the voltage of the DC link of a PWM rectifier. The dynamic characteristics of the PWM rectifier using the proposed controller are evaluated using an experimental setup based on dSPACE under various operating conditions: setpoint change, step change in load on the DC side of the rectifier, setpoint change under load, and capacitive mode of operation. Experimental results are presented for traditional PD controllers, proportional-integral and T2FNN controllers to evaluate the reliability of the proposed controller. It is noted that the PWM rectifier with a PD-T2FNN DC voltage controller has better performance characteristics under all operating conditions according to the performance criteria compared to other controllers.

Article [9] proposes a method for controlling the speed of a DC motor using a three-phase thyristor converter and a module control approach. The control methodology is implemented using MATLAB/Simulink. The developed power converter is based on a thyristor. The speed of the DC motor was controlled by changing the voltage across the armature circuit.

In [10], basic diagrams of the power section were developed to ensure stable braking of a variable speed electric drive with a series excitation motor. Requirements have been developed and zones of stable operation of the dynamic braking mode have been determined. A special place in the research is given to the development of two models of an electric motor with subsequent excitation, taking into account the saturation of the magnetic circuit – mathematical and simulation.

The materials [11] discusses the principle of constructing an automatic control system for a multi-motor controlled electric drive with an electrical connection via a rotary circuit of asynchronous electric motors with phase rotors and a common inverter

controlled by a network for controlling the technological process of water supply to pump units in a water-lifting pump installation. The feasibility of constructing an automatic control system for the rotation speed of the drive motors of the pumping unit in the form of a digital electric drive implemented through a subordinate control system is revealed.

The study [12] examines the automatic control system of an electric drive and the importance of considering elastic connections. The proposed adaptive system uses an RBF neural network. The use of the proposed controller ensures resistance to disturbing influences and allows load fluctuations to be compensated. The adaptability of the system is ensured by changing parameters (load, speed of movement of mechanisms, rigidity, positioning accuracy, etc.) to match the operating conditions of the bridge crane. Thanks to this, the system is able to work effectively even under variable loads and external influences.

Article [13] presents a study of an electric drive with a frequency-controlled synchronous motor. It shows that two-link frequency converters are the most widely used for wide-range frequency control of synchronous motors. They convert the electrical energy of the power supply into electrical energy with the required voltage, current, and frequency values in two stages. This conversion is performed by special devices called autonomous inverters. It has been established that the efficiency of a two-link frequency converter is quite high – 96.5...98.5 %, which is due to the efficiency of power semiconductor devices used in the key mode of operation. It has been shown that the use of new semiconductor devices has made it possible to fundamentally change the topology of the power circuit and the principles of inverter control.

The conducted analysis of scientific publications indicates a considerable interest of researchers in the problems of improving the accuracy, response speed, and stability of automatic control systems for electric drives and power semiconductor converters. A significant part of the studies is devoted to the development of adaptive, discrete, and intelligent control methods, as well as to the improvement of current and voltage controller structures for PWM and thyristor converters. At the same time, most known approaches are based on the use of continuous models of power converters or simplified discretization methods that do not fully take into account the influence of the pulse nature of the energy conversion process on the dynamics of closed-loop control systems. The issues of analytical description of dynamic processes in automatic armature current control systems, taking into account the incomplete controllability of the thyristor rectifier and the ripple component of the control signal, remain insufficiently investigated. Of particular relevance is the task of ensuring the ultimate response speed of the system while maintaining control accuracy and stability of transient processes. This determines the necessity for

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developing mathematical models and synthesis methods for automatic control systems that would more adequately describe the dynamics of an electric drive with a pulse converter. In this regard, the investigation of an automatic armature current control system using a pulse model of a thyristor rectifier is considered appropriate.

Defining the purpose and objectives of the research.

The purpose of the article is to accurately describe the dynamic processes in the automatic regulation system of the armature current of a braked electric motor using a pulse model of a thyristor rectifier, which takes into account its discreteness and influence on the dynamics of the pulsation component of the control signal. To achieve this goal, the following tasks were set:

– in accordance with the proposed structural diagram of the pulse system for automatic regulation of the armature current of a braked motor, describe the dynamic processes using a pulse model of a thyristor rectifier;

– develop a simulation model and conduct experimental studies of the dynamics of the synthesized armature current control system of a braked motor.

The main part of the research.

The block diagram of the automatic regulation system of the motor armature current loop with a pulse model of a thyristor rectifier for continuous current mode in its load circuit is shown in Fig. 2.

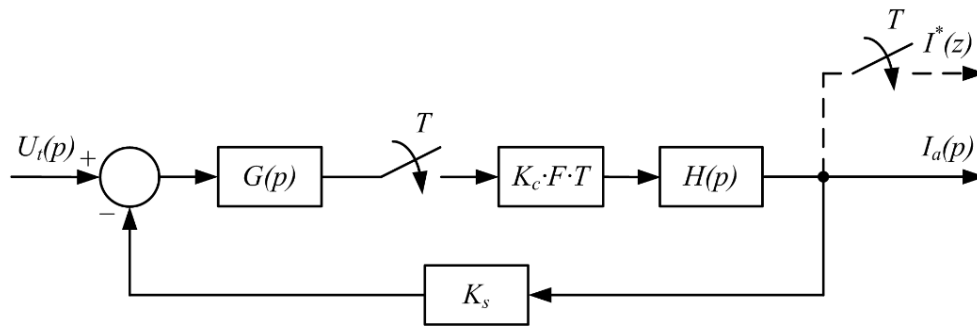


Fig. 2. Block diagram of the automatic regulation system for the motor armature current circuit

Fig. 2 shows the following symbols: $G(p)$ is the current controller transfer function, $G(p) = \frac{T_2 \cdot p + 1}{T_1 \cdot p}$; $H(p)$ is the motor armature circuit transfer function with active resistance R_a ; K_s is the current sensor transfer coefficient.

The pulse model of the converter consists of an ideal pulse element with a discrete period T and a reduced continuous part, which includes: the static transfer coefficient of the converter K_c , the discrete period T , and the ripple factor F .

Modern current sensors have a significantly higher bandwidth compared to the bandwidth of the reduced continuous part of the control system [14, 15], which makes it possible to consider it as an inertia-free link with a transfer coefficient K_s .

The relationship between the input and output signals of the automatic armature current control system, recorded in the form of a z -transform, is determined by the expression

$$I_a^*(z) = \frac{U_t G^*(z) \cdot K_c \cdot T \cdot F \cdot H^*(z)}{1 + K_c \cdot K_s \cdot T \cdot F \cdot GH^*(z)}. \quad (1)$$

The transfer function of the reduced continuous part is defined as

$$W(p) = \frac{K_c \cdot K_s \cdot T \cdot F \cdot (T_2 \cdot p + 1)}{T_1 \cdot p \cdot (T_a \cdot p + 1)}. \quad (2)$$

From expression (2) it follows that the difference between the orders of the denominator and numerator polynomials is equal to one, which indicates that the output signal of the controller $G(p)$ has a finite gap. To fix the left-sided values of the input signal with a pulse element, we represent the characteristic polynomial of expression (1) as:

$$1 + z^{-1} \cdot K_c \cdot K_s \cdot F \cdot T \cdot GH^*(z, 1) = 0, \quad (3)$$

where $GH^*(z, 1)$ is the modified z -transform of the transfer function of the reduced part $W(p)$ for $\varepsilon = 1$.

According to [16] and taking into account (2), we obtain:

$$GH^*(z, 1) = \frac{z}{T_1} \cdot \left[\frac{1}{z - 1} - \frac{T_a - T_2 \cdot e^{-\frac{T}{T_a}}}{T_a \cdot (z - e^{-\frac{T}{T_a}})} \right]. \quad (4)$$

Substituting expression (4) into (3) and performing the transformation, we obtain the canonical formula of the characteristic equation:

$$z^2 + a_1 \cdot z + a_2 = 0, \quad (5)$$

where

$$a_1 = \frac{T}{T_1} \cdot K_c \cdot K_s \cdot F - 1 - e^{-\frac{T}{T_a}} - \frac{T}{T_1} \cdot \frac{K_c \cdot K_s \cdot F \cdot (T_a - T_2)}{T_a} \cdot e^{-\frac{T}{T_a}};$$

$$a_2 = 1 - \frac{T}{T_1} \cdot K_c \cdot K_s \cdot F + \frac{T}{T_1} \cdot \frac{K_c \cdot K_s \cdot F \cdot (T_a - T_2)}{T_a}. \quad (7)$$

To achieve maximum speed, we will configure the armature current control loop for the final duration process [17, 18]. The conditions for configuring the system for the final duration process are determined by the system of equations [19]

$$\begin{cases} a_1 = 0; \\ a_2 = 0. \end{cases} \quad (8)$$

As a result of solving system (8), we obtain expressions for calculating the time constants of the current controller transfer function:

$$T_1 = T \cdot K_c \cdot K_s \cdot F \cdot \left(1 - e^{-\frac{T}{T_a}} \right); \quad (9)$$

$$T_2 = T_a \cdot \left(1 - e^{-\frac{T}{T_a}} \right). \quad (10)$$

According to the method for determining the ripple factor of multi-loop automatic control systems [20, 21], the expression for the ripple factor in a system with a reduced continuous part can be obtained, which is determined by (2):

$$F^{-1} = 1 + K_c \cdot K_s \cdot \left[\frac{T \cdot T_2}{2 \cdot T_1 \cdot T_a} + \frac{T_2 - T_a}{T_1} \cdot \frac{\omega_o \cdot T_a \cdot \text{ctg} \alpha_o - 1}{1 + (\omega_o \cdot T_a)^2} \times \right. \\ \left. \times \left(\frac{T}{2 \cdot T_a} \text{ctg} \frac{T}{2 \cdot T_a} - \frac{\pi}{m} \cdot \text{ctg} \frac{\pi}{m} \right) + \frac{\text{ctg} \alpha_o}{\omega_o \cdot T_1} \cdot \left(1 - \frac{\pi}{m} \cdot \text{ctg} \frac{\pi}{m} \right) \right], \quad (11)$$

where ω_o is the circular frequency of the supply network, $\omega_o = 2 \cdot \pi \cdot f_o$; m is the pulse width of the thyristor rectifier; α_o is the control angle of the thyristor rectifier.

From the analysis of expressions (9)...(11), it follows that the physical implementation of the finite duration process in the synthesized automatic control system.

Fig. 3 shows a simulation model of the armature current control system of a braked motor, built in MATLAB/Simulink. The simulation processes use the parameters of a 2PO200L motor with a power of 24 kW and a supply voltage of 220 V. The current controller parameters are calculated in accordance with conditions (9) and (10). The graphs of transient processes obtained as a result of simulation modeling are shown in Fig. 4.

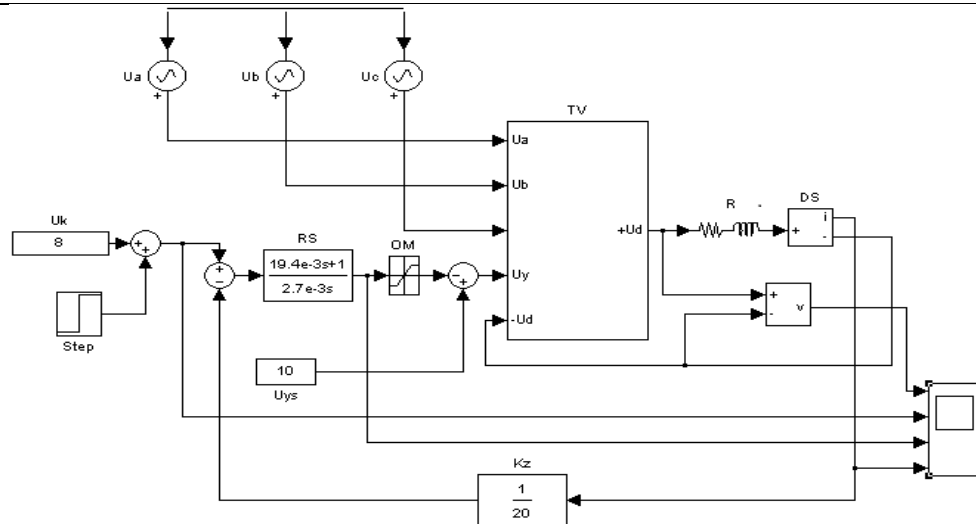


Fig. 3. Simulation model of the armature current control system of a braked motor:

RS – current controller; *OM* – control signal limiter of the *TV* thyristor rectifier;

R – active-inductive circuit of the motor armature; *DS* – sensor for measuring the armature current

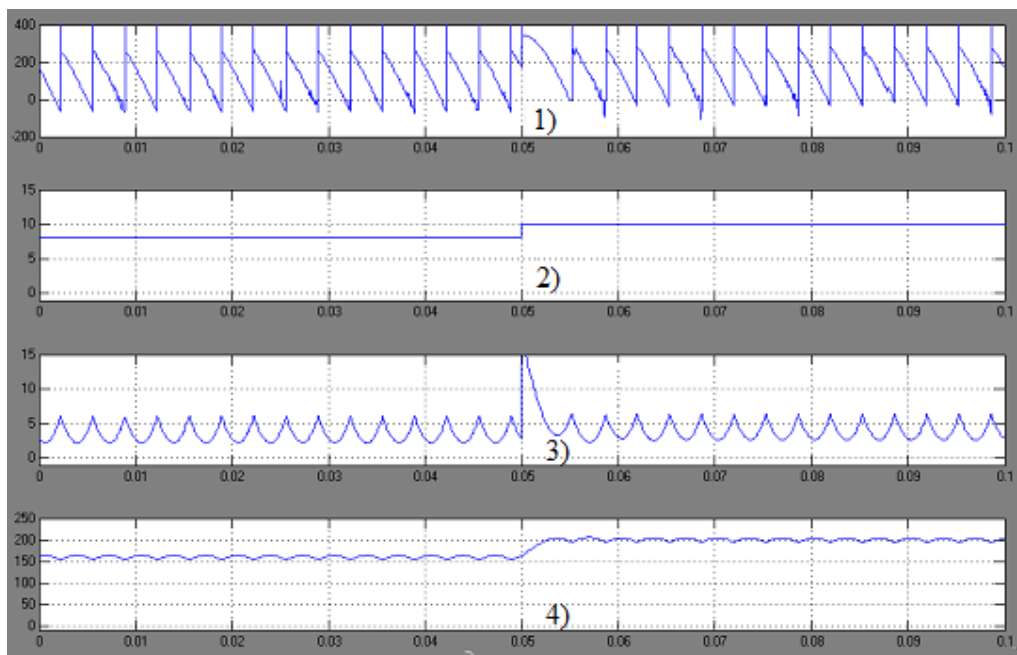


Fig. 4. Oscillograms of transient processes:

1 – output voltage of the thyristor rectifier; 2 – control signal of the thyristor rectifier *TV*; 3 – output signal of the current controller *RS*; 4 – motor armature current

From the obtained oscillograms it follows that the transient process ends in two clock intervals of the thyristor rectifier, which corresponds to the order of the control system.

Conclusions. The study investigates an automatic armature current control system of a braked

electric motor using a pulse model of a thyristor rectifier. It is shown that the use of the pulse model makes it possible to describe the dynamic processes in the closed-loop control system more accurately in comparison with traditional continuous models, since the discrete operating nature of the thyristor converter and the influence of the ripple component of the control signal are taken into

account. Based on the z-transform, analytical relationships describing the dynamics of the motor armature current control loop were obtained, and the conditions for implementing a finite-duration process were determined. It was established that tuning the automatic control system to a finite-duration process ensures the ultimate response speed of the system and contributes to improving the quality of transient processes in the subordinate electric drive speed control system. The simulation model developed in the MATLAB/Simulink environment confirmed the adequacy of the obtained theoretical results. According to the simulation results, it was found that the transient process is completed within two sampling intervals of the thyristor rectifier, which corresponds to the order of the synthesized control system. The obtained results can be used in the synthesis of high-speed automatic control systems for DC electric drives with thyristor converters, as well as in further studies of the dynamics of pulse electromechanical systems.

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Щербак Я. В., Івакіна К. Я., Нерубацький В. П. Система автоматичного регулювання струму якоря двигуна з імпульсною моделлю перетворювача

Анотація. У статті розглянуто систему автоматичного регулювання струму якоря загальмованого електродвигуна із застосуванням імпульсної моделі тиристорного випрямляча, яка враховує дискретний характер процесу перетворення електричної енергії та вплив пульсаційної складової сигналу керування на динамічні характеристики замкнутої системи. Актуальність дослідження обумовлена широким застосуванням підлеглих систем керування в електроприводах постійного струму та необхідністю підвищення їхньої швидкодії, точності й адекватності математичного опису динамічних процесів. Показано, що використання традиційних безперервних моделей тиристорного випрямляча не дає змогу повною мірою врахувати особливості роботи силового перетворювача, пов'язані з його імпульсним режимом функціонування та неповною керованістю. Метою роботи є точний опис динамічних процесів у системі автоматичного регулювання струму якоря із застосуванням імпульсної моделі тиристорного випрямляча та дослідження умов забезпечення граничної швидкодії системи. На основі з-перетворення отримано аналітичні залежності, які описують динаміку системи автоматичного регулювання струму якоря. Визначено умови реалізації процесу кінцевої тривалості та синтезовано параметри регулятора струму для забезпечення максимальної швидкодії системи. Для перевірки адекватності отриманих теоретичних результатів розроблено імітаційну модель у середовищі MATLAB/Simulink із використанням параметрів двигуна 2ПО200L потужністю 24 кВт. Новизна запропонованої роботи порівняно з відомими, що базовані на застосуванні безперервної моделі тиристорного випрямляча, полягає в урахуванні впливу на динаміку замкнутої структури автоматичного регулювання неповної керованості тиристорного випрямляча. Практична цінність роботи полягає в тому, що застосування отриманих у статті аналітичних залежностей для розроблення системи автоматичного регулювання вихідної координати тиристорного випрямляча дає змогу точно описати динамічний процес контуру регулювання струму якоря в системі підлеглого регулювання швидкості та розрахувати параметри системи для отримання граничної швидкодії за рахунок реалізації процесу кінцевої тривалості.

Ключові слова: регулювання струму якоря, двигун, тиристорний випрямляч, імпульсна модель,

система автоматичного регулювання, з-перетворення.

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