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Development and study of a microprocessor automatic control system for a mono-switch tie type with a linear inductive electric motor and a discrete speed controller

Introduction. *The article is devoted to the development of the microprocessor automatic control system for a gearless controlled electric drive of a mono-switch tie based on a linear inductor electric motor. This solution provides control the position of the switch point, to carry out the transfer process with a smooth drive of shanks to the frame rail, to protect electric motor elements from overloads.* ***Goal.*** *Development and study of the behavior of microprocessor automatic control system for mono-switch tie type with linear inductive electric motor and discrete PID speed controller which coefficients are adjusted according to Chien-Hrones-Reswick method to meet modern traffic safety requirements and improve operational reliability factors.* ***Methodology.*** *On the basis of electric drive theory, a kinematic line of a mono-switch tie type with nonlinear friction characteristic is presented. Using differential equation theory and Laplace transformation, a mathematic description of a linear inductor electric motor has been made. Using the z-transform method, a difference equation for describing a discrete PID speed controller is obtained, the coefficients of which are derived using the Chien-Hrones-Reswick method. A simulation mathematical model of the electric drive mono-switch tie type as the microprocessor automatic control system with linear inductive electric motor and discrete PID speed controller and nonlinear friction characteristic was built in MATLAB.* ***Results.*** *Simulation modelling of a mathematical model of the microprocessor automatic control system of the electric drive mono-switch tie type with the linear inductive electric motor and discrete PID speed controller and nonlinear friction characteristic have been developed and performed. Studies of dynamics of switch point movement have shown that, a drive time of less than 0.7 s at a constant speed motor armature of 0.2 and 0.3 m/s provides to meet modern requirements for railway switch points. The application of discrete PID speed controller has shown improved dynamics of switch point.* ***Originality.*** *First for the electric drive of the mono-switch tie type with linear inductive electric motor a mathematical model of the discrete PID speed controller and nonlinear friction characteristic as an object of speed control of switch point movement, has been developed.* ***Practical value.*** *Mathematical model of a railway track switch of the mono-switch tie type with linear inductive electric motor and discrete PID speed controller has been developed to carry out the control of the position of the switch point, process with a smooth drive them to the frame rail, to protect electric motor elements from overloads.* References 25, tables 2, figures 12.

Key words: **electric drive with linear inductive electric motor, electromechanical system, control system, discrete PID speed controller.**

Робота присвячена розробці мікропроцесорної системи автоматичного керування безредукторним регульованим електроприводом стрілочного переводу моношпального типу на базі лінійного індукторного двигуна. Таке рішення дозволяє контролювати положення гостряків, здійснювати процес переводу з плавним доводом гостряків до рамної рейки, захистити елементи електродвигуна від перевантажень. Запропоновано структурну схему дискретного ПІД-регулятора швидкості, синтезованого в z-зображенні та отримано діаграми розподілу його коефіцієнтів за методом Чина-Хронса-Ресвіка. Наведені результати комп'ютерного моделювання показали, що час переводу гостряків менший ніж 0,7 с при сталому рівні задавання швидкості якоря 0,2 і 0,3 м/с, що дозволяє реалізувати сучасні вимоги до стрілочних переводів залізничного транспорту. Бібл. 25, табл. 2, рис. 12.

Ключові слова: **електропривод з лінійним індукторним двигуном, електромеханічна система, система керування, дискретний ПІД-регулятор швидкості.**

Introduction. The transport system is an important component of the economic growth of the national economies of the world economy. The development of railway international transport networks contributes to the integration of trade between the European Union (EU) and Ukraine. Therefore, the renewal of the transport infrastructure of Ukraine is one of the main directions of the implementation of the National Transport Strategy of Ukraine for the period until 2030 [1], which lays the foundation for changes in the transport sector for the next 8 years, namely the development of new high-speed interregional connections, connections with EU countries and the renewal urban transport infrastructure [2].

Turnouts are an integral part of the railway infrastructure. The development of their automation systems and the improvement of service technologies contribute to a large extent to the increase of traffic safety and the improvement of economic indicators of railway activity [3–5].

Global companies are working on the creation of new types of turnouts [6, 7], namely, their mono-switch tie implementation. Their general concept, both for normal and high-speed traffic, comes down to ensuring maximum reliability and safety, with minimal ongoing maintenance costs. Modern turnouts are equipped with new electric motors [7–10] and control systems [4, 11].

In Ukraine, the lack of adjustable electric drives for turnouts requires the creation of specialized electric drives. To increase their efficiency, there is a need to create new types of electric drives [12–14]. In [15], the questions of the development of the functionality of the railway turnout by introducing an electric drive with a valve-inductor motor were considered, which is justified by the simplification of the mechanical part of the turnout by replacing the gearbox with a ball-screw pair and placing the entire kinematic line of the turnout on one sleeper.

The replacement of rotary electric motors with linear ones provides even more simplification of the design, which ensures an increase in efficiency, a decrease in maintenance costs, and an increase in the reliability of the operation of turnouts. A distinctive feature of such motors is their ability to convert electrical energy into mechanical translational movements of the executive mechanisms of the turnouts – points and movable cores of the crossbars, directly, without intermediate mechanical converters. The electric drive taking into account linear electric motors of the electromagnetic type (LMEMT) was considered in [16]. The rationality of such a technical solution consists in the reserve of excess energy, which takes place at the end of the cycle of the electric drive of the turnout, in order to use it later at the beginning of the movement of the turnout. This article is devoted to the improvement of the microprocessor system of automatic control of the gearless adjustable electric drive of the mono-switch tie type based on the linear motor of the inductor type to obtain a given law of control of the movement of the sharps and reduce the time of the switch transfer.

The peculiarity of turnouts of this type is that, thanks to the unique properties of the structures and the capabilities of the control systems, they ensure high accuracy of the positioning of the spikes and the necessary controllability of the traction force, taking into account the increase in speed and cargo flow of transportation.

Thus, the way proposed in the article to create a new control system for the electric drive of the turnout is relevant from the point of view of the need to transition to a new modern element base of automation systems and new design solutions.

The purpose of the article is the development of a microprocessor-based system for automatic control of a mono-switch tie type turnout with a linear inductive electric motor (LIEM) and a discrete proportional-integral-differential (PID) speed controller with adjusted coefficients according to the Chien-Hrones-Reswick method to ensure modern traffic safety requirements.

To achieve the intended goal, the following tasks are set:

- development of a system of automatic control of a mono-switch tie type turnout with LIEM, which allows the transfer process to be carried out with a smooth approach of the spikes to the frame rail, protection of the motor from overloads and control of the position of the spikes for high-speed and ultra-high-speed electric transport railways;
- synthesis of a discrete PID speed controller for an electric drive with an inductive motor, as an element of improvement of the microprocessor system of automatic control of the turnout transfer to improve its operation both in regular and non-stationary modes.

Research material. The functional diagram of the electric drive of the turnout is shown in Fig. 1, which includes three units: a LIEM, a speed regulator with a power converter as part of the control unit, and a sensor for the position of the spikes, which monitors the movement of the spikes and their close fit to the frame rail.

Figure 2,*a* shows the cross-section of the LIEM, which is placed in the sleeper as shown in Fig. 2,*b*.

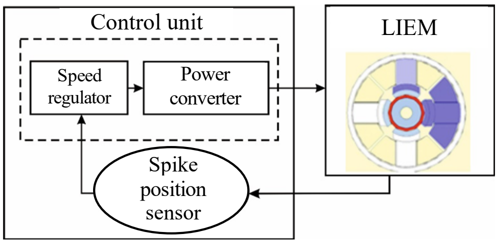
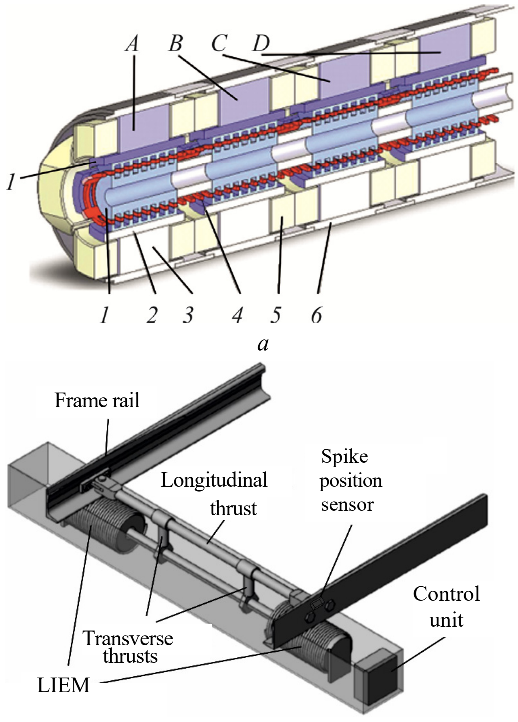


Fig. 1. Functional diagram of the electric drive of the turnout with LIEM



a

b

Fig. 2. Design of LIEM (*a*)
and placing it in one sleeper (*b*):
1 – stator; 2 – pole tips of the external stator;
3 – poles; 4 – armature; 5 – phase coils; 6 – housing

The linear electric motor has four phases *A*, *B*, *C*, *D* and consists of two stators 1 (internal and external), which makes it possible to obtain a minimum air gap in the inter-tooth area with small dimensions of the machine, concentrating the magnetic flux in the tooth area. Alternating switching on of the phases of the electric motor (*A*, *B*, *C*, *D*) ensures a uniform distribution of the electromagnetic force during the movement of the armature 4. When increasing the number of coils (phases), it is possible, if necessary, to significantly reduce the fluctuation of the force acting on the armature during its movement. Additional armature advantage of this design of the induction motor is the relatively long length of the armature compared to the electromagnet, which will allow to easily implement the movement of the spikes without changing other overall dimensions of the motor.

Depending on the signal from the sensor of the position of the spikes, which are installed on the outside of the frame rail and provide control over the tight fit of the spike to it, the power converter, located in the control unit and made on the basis of field-effect or IGB transistors, connects the stator coil to the power source.

And the electric motor converts electrical energy into mechanical energy, setting the armature in motion.

Such an electric motor requires a different automatic control system than LMEMT and, as a result, another solution, but provides reverse operation without the use of additional springs [16].

The mathematical description and simulation model of LIEM based on the solution of the Lagrange equation is given in [17] and in the normal Cauchy form has the form:

$$\begin{cases} \dfrac{di_A}{dt} = \dfrac{1}{\dfrac{\partial\Psi_A(i_A,x)}{\partial i_A}}\left(U_A - r_A i_A - \dfrac{\partial\Psi_A(i_A,x)}{\partial x}v\right); \\ \dfrac{di_B}{dt} = \dfrac{1}{\dfrac{\partial\Psi_B(i_B,x)}{\partial i_B}}\left(U_B - r_B i_B - \dfrac{\partial\Psi_B(i_B,x)}{\partial x}v\right); \\ \dfrac{di_C}{dt} = \dfrac{1}{\dfrac{\partial\Psi_C(i_C,x)}{\partial i_C}}\left(U_C - r_C i_C - \dfrac{\partial\Psi_C(i_C,x)}{\partial x}v\right); \\ \dfrac{di_D}{dt} = \dfrac{1}{\dfrac{\partial\Psi_D(i_D,x)}{\partial i_D}}\left(U_D - r_D i_D - \dfrac{\partial\Psi_D(i_D,x)}{\partial x}v\right); \\ \dfrac{dv}{dt} = \dfrac{F_{el} - F_{on} - \alpha v}{m}; \\ \dfrac{dx}{dt} = v, \end{cases} \tag{1}$$

where U_A, U_B, U_C, U_D is the voltage of power sources; r_A, r_B, r_C, r_D, i_A, i_B, i_C, i_D are the active resistances and currents in the corresponding phases of the stator; Ψ_A, Ψ_B, Ψ_C, Ψ_D are the flux linkages of the respective phases; x is the displacement of the armature; F_{on} is the resistance force; α is the coefficient of friction between the guide and the armature; v is the armature movement speed; m is the mass of the armature; F_{el} is the driving force of the electric motor.

An electronic switch is required to connect the motor phases to the power source and adjust the voltage on it. Since the operation of the LIEM does not depend on the direction of the current in the phase, a half-bridge circuit is usually used to switch the current in it [18]. A fragment of the circuit of the electronic switch (for phase *A*) is shown in Fig. 3.

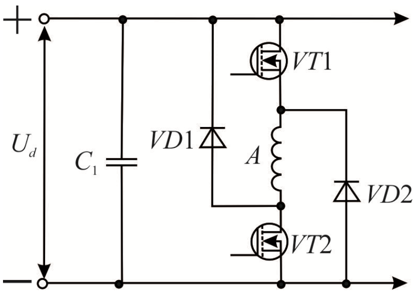


Fig. 3. Schematic of phase *A* of the electronic switch for a 4-phase LIEM

Phases (*A*, *B*, *C*, *D*) are included between semiconductor switches (phase *A* – *VT*1 – *VT*2; phase *B* – *VT*3 – *VT*4; phase *C* – *VT*5 – *VT*6; phase *D* – *VT*7 – *VT*8) operating in PWM mode depending from the position of the spikes and the direction of their movement. Protective diodes (for phase *A* – *VD*1 – *VD*2; for phase *B* – *VD*3 – *VD*4; for phase *C* – *VD*5 – *VD*6; for phase *D* – *VD*7 – *VD*8) ensure the flow of current after closing the upper or lower switches in the phases.

To control the LIEM, a digital PID speed controller was synthesized, which is described by the transfer function:

$$W_p(z) = K_p + K_i\frac{T_0 z}{z-1} + K_d\frac{z-1}{T_0 z}, \tag{2}$$

where K_p is the transfer coefficient of the proportional component; K_i is the transfer coefficient of the integral component; K_d is the transfer coefficient of the differential component; T_0 is the period of discretion, s.

Based on the transfer function (2), a difference equation was obtained that describes the algorithm of the discrete PID controller:

$$\begin{aligned} u[n] &= K_p e[n] + K_i\left(u[n-1] + T_0 e[n]\right) + \\ &+ \frac{K_d}{T_0}\left(e[n] - e[n-1]\right) = \\ &= K_p e[n] + K_i T_0 e[n] + \frac{K_d}{T_0}\left(e[n] - e[n-1]\right) + K_i u[n-1]. \end{aligned} \tag{3}$$

According to (3), the structural diagram shown in Fig. 4 is built.

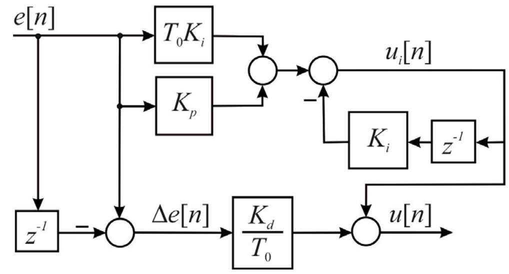


Fig. 4. The structure of the discrete PID controller

Since the LIEM is described by a nonlinear function [17], the standard methods used for adjustment of linear objects are not suitable for adjustment of the coefficients of the PID controller [6, 19]. Therefore, their calculation was performed according to the Chien-Hrones-Reswick method [20], which allows obtaining a larger stability margin than the traditional Ziegler-Nichols method [21, 22].

According to the Chien-Hrones-Reswick method for calculating the coefficients of the PID controller the response of the control object to the step input signal is observed. The elements of the control object, which have an aperiodic characteristic (Fig. 5), are approximated by the serial connection of the aperiodic link and the delay link.

From Fig. 5 it can be seen that two parameters *a* and *L* are used to calculate the coefficients of the PID regulator using the Chien-Hrones-Reswick method. Their calculation was performed under the conditions of the absence of overregulation (CHR0%) and its presence in 20% (CHR20%). The formulas by which the coefficients K_p, K_i and K_d are calculated are given in Table 1.

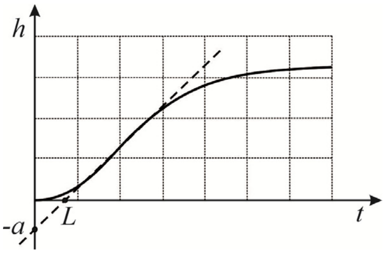


Fig. 5. An example of the acceleration curve of the control object

Table 1
Calculation of the coefficients of the PID regulator according to the Chien-Hrones-Resvik method in the absence of overregulation and its presence

Method	K_p	K_i	K_d
CHR0%	$\frac{0,6}{a}$	$\frac{L}{K_p}$	$\frac{0,5L}{K_p}$
CHR20%	$\frac{0,95}{a}$	$\frac{1,4L}{K_p}$	$\frac{0,47L}{K_p}$

The calculated parameters of the PID controller were adjusted manually to improve the quality of the control, since the analytical expressions are based on simplified models of the object and give an error. Adjusting the parameters of the regulators is performed according to the following rules: an increase in the proportional coefficient K_p increases the speed of operation and reduces the margin of stability; with a decrease in the integral component K_i, the adjustment error decreases faster over time; reduction of integration constant T_i reduces the margin of stability; increasing the differential component K_d increases the speed.

After adjusting the coefficients of the PID speed controllers, they take the form shown in Fig. 6.

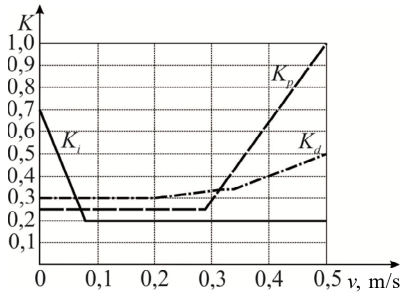


Fig. 6. Coefficients of the PID regulator

From Fig. 6 it can be seen that all coefficients depend on the speed of movement of the spikes, namely: the coefficient of the proportional link K_p increases sharply from 0.25 to 1 at speed above 0.3 m/s; the coefficient of the integral link K_i has a sharply decreasing linear characteristic at low speeds of movement up to 0.08 m/s and changes in the range from 0.7 to 0.2; the coefficient of the differential link K_d has a gentler characteristic and varies from 0.3 to 0.5 at the speed of movement of the spikes above 0.2 m/s.

Taking into account this Fig. 4 will look as shown in Fig. 7.

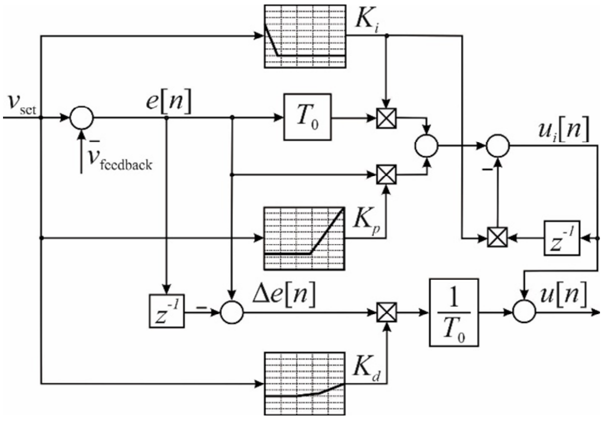


Fig. 7. The structure of the discrete PID speed controller with adjusted coefficients according to the Chien-Hrones-Resvik method

The detailed functional scheme of the turnout transfer is shown in Fig. 8, where LIEM with a sensor of the position of the spikes, an electronic switch (Fig. 3), a distributor with a pulse converter and a speed regulator (Fig. 7), which are parts of the control unit, is separated by dashed line.

The control system of the mono-switch lie type turnout is considered as a two-loop system of subordinate coordinate regulation with a PID speed controller, which, together with the LIEM, is reduced to a general simulation model in MATLAB [23, 24], taking into account all elements, parameters and relationships between them in Fig. 9, and Fig. 10 shows the diagram of the mechanical part.

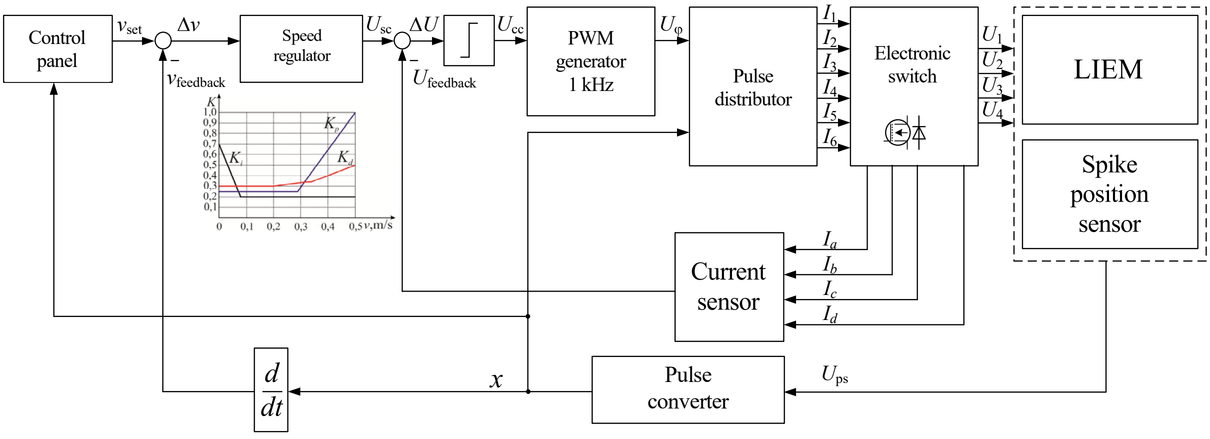


Fig. 8. Expanded functional scheme of the electric drive of the turnout with LIEM

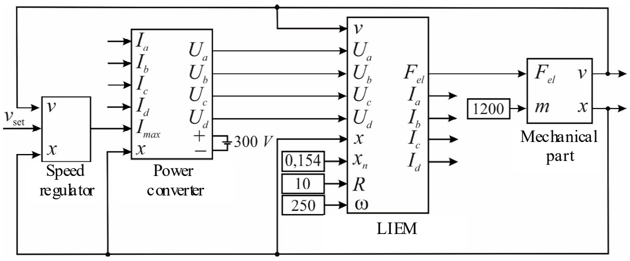


Fig. 9. Generalized simulation model of turnout with LIEM in the MATLAB environment

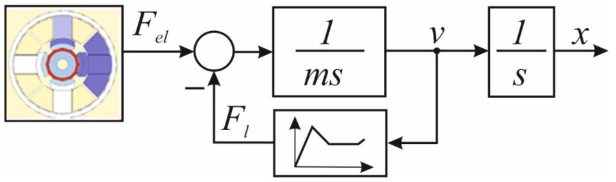


Fig. 10. Structural diagram of the mechanical part of the turnout with LIEM

In the feedback of the system, there is a load block $v = f(F_c)$, which reflects the friction characteristic [25], since the turnouts operate in different weather conditions under the influence of random factors (fallen leaves, rain, snow, substances that spill from the cars, etc.). The average values of the coefficient of friction on the rail-cushion surface (steel-steel) are given in the Table 2.

Table 2

Coefficient of friction at rest and sliding

Friction materials	Coefficient of friction			
	at rest		in a sliding state	
	without lubrication	with lubrication	without lubrication	with lubrication
rail – cushion	0.8	0.5-0.4	0.15-0.3	0.05-0.18

Figures 11, 12 show the transients of the electric drive of the turnout, namely the movement of the spikes and the speed of the turnout with a PID speed controller, taking into account the nonlinear characteristic of friction at different settings of the speed of movement of the spikes.

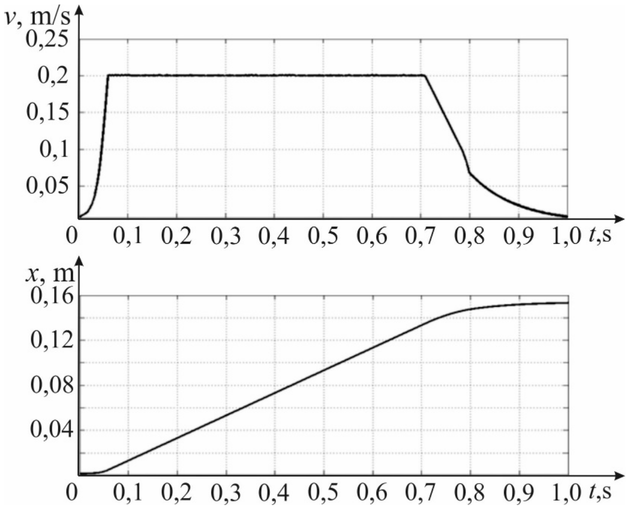


Fig. 11. Transients in mono-switch tie type with PID speed controller when setting the speed $v_3 = 0.2$ m/s

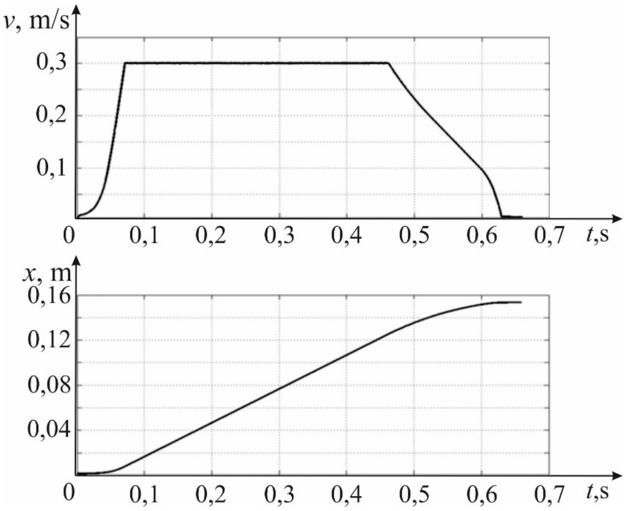


Fig. 12. Transients in mono-switch tie type with PID speed controller when setting the speed $v_3 = 0.3$ m/s

From the obtained graphs of transients, it was established that the PID controller supports the set speed of movement of the spikes of 0.2 m/s (Fig. 11) and 0.3 m/s (Fig. 12), which allows control of the position of the spikes. It also provides a transfer process with a smooth transition of the spikes to the frame rail, which protects the elements of the electric motor from mechanical overloads.

The graphs of the transients of the movement of the spikes show their impact-free tweaking to the frame rail, which is confirmed by the speed curves at the end of the transfer process at $t > 0.6$ s.

Conclusions.

1. A microprocessor-based system for automatic control of a mono-switch tie type with LIEM and a discrete PID speed controller was proposed and researched, which made it possible to improve the quality of the dynamics of its operation.

2. On the basis of the analytical methods of *z*-transformation, a discrete PID speed controller was synthesized and its simulation model was developed taking into account the nonlinear characteristic of friction, which confirmed the improvement of the dynamics of the operation of the turnout drive with LIEM.

3. Using the Chien-Hrones-Resvik method, distribution diagrams of the PID regulator coefficients were obtained depending on the speed of the armature movement: the coefficient of the proportional link increases sharply from 0.25 to 1 at speeds above 0.3 m/s; the coefficient of the integral link has a sharply decreasing linear characteristic at low speeds of movement up to 0.08 m/s and varies from 0.7 to 0.2; the coefficient of the differential link has the smoothest characteristic and varies from 0.3 to 0.5 at a speed of movement of spikes above 0.2 m/s.

4. On the basis of the study of the transients of the movement of the spikes, the possibility of shock-free bringing them to the frame rail is shown, which is confirmed by the speed curves at the end of the turnout transfer process, which go to 0 as well as the possibility of obtaining the transfer time of the spikes in less than 0.7 s

at a constant setting level of speed of 0.2 and 0.3 m/s of armature movement for LIEM.

Conflict of interest. The authors of the article declare no conflict of interest.

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