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ANALYSIS OF OPTIMIZATION CRITERIA FOR THE PROCESS OF SWITCH DISPLACEMENT IN A DC RAILROAD TURNOUT

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Досліджена динаміка переміщення гостряків стрілочного переводу з прямим пуском електродвигуна та регульованим електроприводом постійного струму в середовищі MATLAB. Фокус при моделюванні спрямовано на дослідження процесів, що відбуваються в кінематичних ланках стрілочного переводу в динаміці переміщення його гостряків. Оцінка здійснювалась за критеріями оптимізації процесу переміщення гостряків: імпульс удару гостряка об рамну рейку, пружність сили в робочій тязі та час переводу гостряка. У результаті моделювання нерегульованого електроприводу стрілочного переводу гостряків стало зрозуміло, що значення цих параметрів незадовільні.

Математичні моделі регульованого електроприводу стрілочного переводу гостряків розглядались як двомасові електромеханічні системи з підлеглим регулюванням основних координат та за принципом модального керування. Результати математичного моделювання процесу переводу гостряків переконують у тому, що числові значення критеріїв оптимізації процесу регульованого переводу поліпшуються. При збільшенні часу регульованого переводу до 6 % від прямого пуску удар в кінематичних ланках зменшується. При припущенні щодо виключення технологічного зазору в редукторі, зменшення удару гостряків при початку переводу становить 6–8 %. Водночас, порівняння ударів на початку переводу гостряків з урахуванням технологічного зазору в редукторі та без нього показує зменшення амплітуди пружної сили на 250 %. Удар (імпульс моменту гостряків) при закінченні переводу може бути зменшено на 20–24 %.

Аналіз критеріїв оптимізації процесу переміщення гостряків показав ефективність регульованого електроприводу у порівнянні із прямим пуском електродвигуна. Це дозволяє не тільки розширити функціональні можливості роботи стрілочного переводу гостряків, а і знизити затрати на поточний технічний огляд, ремонт у цілому, а також збільшення міжремонтного періоду

Ключові слова: електромеханічна система, електродвигун постійного струму, система регулювання, критерії оптимізації процесу переміщення

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1. Introduction

At present, quite widespread is the electric drive for a railroad turnout based on a sequentially-excited DC electric motor. Such drives are open and non-regulated, which leads to more often disorders in the mechanical part of a railroad turnout.

It is an obvious decision to upgrade existing electric drives by introducing new control systems in combination with available electromechanical systems that would make it possible to regulate the coordinates of current, speed, and displacement. This could contribute to the improved operational efficiency and reliability of railroad turnouts.

In addition, a railroad turnout is operated under different weather conditions and various combinations of perturbating factors, which is why investigating the dynamics of railroad turnouts should take into consideration all technological features of the structure. These include gaps, the forces of elasticity and internal viscous friction, that is, a varying value for the coefficient of friction between switches and crossing surfaces.

To effectively manage the process of switch turning, one considers control systems over electric drive with the help of modal and subordinate regulation systems. The system with subordinate regulation of coordinates, as the most widespread in the DC electric drives, in which the minimum number of feedbacks successfully implements the required dynamics and a possibility to limit controlled coordinates. In modal control systems, the negative feedback along any coordinate of the control object stabilizes this coordinate, that is, in one way or another it maintains it constant under the task unchanged and influences that perturb within the circuit. Therefore, if one closes the control object along the coordinates that characterize its state at any time, then it becomes possible, at a corresponding selection of values for feedback coefficients, to obtain the desired characteristics of the control object in terms of initial coordinates.

Thus, the systems for subordinate regulation and with modal control make it possible to investigate all possible depth of control over a railroad turnout for speed and position.

The relevance of our study is predetermined by that the fleet of railroad turnouts includes many switch drives with DC motors. This is an outdated type of the electric drive, so there is a need to find techniques for improving the performance of such drives, including the use of a regulated drive.

2. Literature review and problem statement

Searching for techniques to improve performance operational characteristics and operational quality of the turnout electric drive as a device of railroad automatics implies several directions. Such directions of scientific search relate to the modernization of DC electric motor itself, the replacement or application of new types of sensors and switch locking mechanisms. It is possible to completely replace the assembly with a new (often regulated) electric drive with an asynchronous, synchronous, linear, or valve-induction type of motor. Since the devices with DC motors still account for a significant share in the railroad fleets of turnouts, it is necessary to pay attention to which of these areas should be preferred.

Thus, paper [1] shows that the extended range of DC and AC motors for railroad turnouts (MSP–0,1, MSP–0,15, MSP–0,25 and MST–0,3; MST–0,3a; MST–0,3b; MST–0,3v and MST–0,6; MST–0.6a) leads to significant current costs for maintenance and repair. The authors proposed using a single DBU-type collector-free engine or the universal valve-induction motor with electronic control unit EMSU. They proved the economic efficiency of such a decision (reduction in the current labor costs by 40–42 people/h per a station with 21 RT over a year). An electronic control unit enables to execute smooth engine start and stop. In addition, it is proposed to abandon the outdated structural elements in the kinematics of a turnout, such as friction clutch and auto-switch. This direction is undoubtedly promising and appropriate, but it requires rather high capital investments for the production, implementation, updating technical and normative documentation for a railroad or a separate station. In contrast, paper [2] applies a three-winding reactive induction electromechanical converter that serves as an electronic motor control unit, but it is also a path that requires large investments.

Work [3] considers issues related to design improvement and better characteristics of a DC electric motor, used in the drives of railroad turnouts. The authors described transitional processes under the start and reverse modes of electric motors with electromagnetic and magnetoelectric excitation systems. They showed the advantage of electric motors for turnouts with the magnetoelectric system of excitation in comparison with the currently operated electric motors with the electromagnetic excitation system. However, assuming the advantages of such a solution, a significant drawback is the direct start of the motor, which leads to impacts at the onset and end of turning.

Paper [4] gives an overview of the simplest solutions from the point of view of investments, partial modernization of standard drives of SP-6m types by replacing the elements that fail most often – an auto-switch, friction clutch, whorl mechanism, etc. Such an approach might improve certain characteristics of a railroad turnout, but it leads to the extension of its product range, which is undesirable, and such drives demonstrate the same shortcomings that are inherent in a direct-start EM.

Study [5] emphasized the drives with AC electric motors, given their high reliability and ease of use. Despite this, most turnouts in railroad network are still equipped with DC motors. It should also be noted that DC motors are preferred at shunting hills, due to technological conditions of operation, as the motors could be accelerated by supplying 200 % of voltage.

A lot of attention has been paid to improvement of control systems over a railroad turnout on sensory and microprocessor base, for instance, paper [6] considered adding to a standard drive SP-6m technical means of wireless control (GSM channel) and diagnosing a drive's elements. The technical platform applied is Arduino. However, the degree of reliability of such a solution is unclear, because the GSM channel should be protected and reliable, and in the event of its failure a dangerous situation in the railroad traffic may arise. In particular, the use of equipment and microcontrollers of ELC-12 type made by company xLogic (China) should replace unreliable devices, such as the OK polarized relay in a two-wire relay control circuit in a railroad turnout. This basic element of the relay control system was the subject of modeling of the boundary conditions for its operation in the course of research for high-speed railroads [7], which determined that for the voltage range 62.6...72 V the enable current could be 0.4...0.75 A. This is a rather sensitive analog device, so replacing it with the digital analogue xLogic must be explored in more detail. Paper [8] investigated replacing the existing, as well as designing new, elements for a railroad turnout. The authors considered the construction of a mathematical model, which would take into consideration the static and dynamic loads on a railroad turnout's element and could help improve such elements. However, this study lacks attention to the processes taking place in the pair wheel–rail. These processes were considered in [9]; the authors built a mathematical model to study processes at which elements within the mechanical part of a railroad turnout may fail. However, the cited study did not pay attention to such processes as a switch break-up at the end of turning, which could also lead a railroad turnout to fail. The importance of monitoring such processes is shown in [10], where a mathematical model was constructed to investigate the dynamic influences along high-speed railroads on bridges where requirements for traffic safety are maximal.

As regards increasing the fault-tolerance of sensors involved in the automatics of a railroad turnout, which are dependent on weather phenomena, in particular, icing in the winter period. A study into the automation units at railroads that operate without human supervision [11] indicates the need for contactless inductive sensors to determine the ambiguity in the position of a controlled object for a control system.

In general, the improved fault tolerance is also provided by diagnostic systems, in particular optimal diagnostic algorithms, examined in [12], which are based on statistical methods of failure analysis of railroad turnouts. It is possible to integrate them into modern digital systems that control stations. Results of the cited study could be combined with the results from our study, reported in this article, as the elements of a digital system to control a railroad station.

Synthesis of a dual-circuit system for subordinate regulation of switch speed by using a thyristor DC converter is considered in [13]. The authors also simulated a case when a foreign object gets between the frame rail and the switch, and demonstrated the capability of the control system to compensate for the impact exerted by such a negative scenario on the turning speed. The topic of the cited study should be further investigated as a railroad turnout, despite the speed control in most studies, has a constant displacement value, namely 154 mm. This fact was not considered by authors because they examined a dual-circuit control system. Such a disadvantage led us to the current study into a three-circuit control system with the external loop of switch positions.

The regulation accuracy of modern digital converters is 2–0.01 % of the rated engine shaft rotation velocity (depending on the presence and type of a speed sensor). By using the non-linear programming methods, set out in [14], and by installing the nonlinear robust position regulator in the programmable logic controller, the specified parameters for regulation accuracy could be improved.

It should also be noted that such a recognized manufacturer of articles for railroads as Bombardier has an entire product range of sequentially excited drives that are produced for turnouts with the frequency control EBI switch (EBI switch 700, 2000, etc.) [15]. Such devices, in addition, are used in the automated system of railroad stations EBILock made by this company, which opens the prospect of high-speed rail communication.

Therefore, modern electric drives for switches should warrant compliance with safety indicators for train traffic and be highly reliable. It is necessary to reduce the operating costs of their maintenance by creating unattended technologies, using advanced manufacturing technologies and modern materials. Trends to achieve high motion speeds put forward stricter requirements to reliability of those technical means that ensure the safety of train motion over a railroad turnout. Therefore, the organization of high-speed traffic requires a new approach to designing the railroad turnout and electric drive.

Thus, our analysis of literary data [1–15] has revealed the lack of sufficient attention in studies into the improvement of operational functionality of a railroad turnout when using a thyristor converter along with the operated motor.

That necessitates investigation into how exactly the values of the predefined quality criteria of railroad turnout operation are affected by the application of the regulated electric drive, provided that the motor and the mechanical part in general remain unchanged. Should the positive results be obtained, it would improve the operational characteristics of a railroad turnout without significant capital expenditures.

3. The aim and objectives of the study

The aim of this study is to define ways to improve the dynamics of operation and better functionality of railroad automatics by using a regulated electric drive. An analysis should be performed based on solving the problem on minimizing the basic quality indicators: turning time, the magnitudes of pulse of the switch's impact against a frame rail, the magnitude of elastic force in the working rod.

To accomplish the aim, the following tasks have been set:

– to explore the dynamics of a railroad turnout's switch displacement at direct starting of the motor, in the MATLAB environment, based on a simulated model of a switch turnout, which accounts for plasticity of the kinematic links and the linear load characteristic;

– to build, investigate simulated models of the regulated electric drive in a railroad turnout with the subordinate coordinate control and based on the principle of modal control and to assess parameters in the dynamics of switch displacements under different operational modes at smooth start;

– to compare numerical values of the optimization criteria for a switch displacement process and to estimate the operational effectiveness of regulated electric drives in railroad turnouts compared to the direct start of an electric motor.

4. Studying the dynamics of switch displacement in a railroad turnout at direct starting of the motor

The mechanical part of a turnout, whose kinematic scheme is shown in Fig. 1, is considered as a two-mass electromechanical system (EMS).

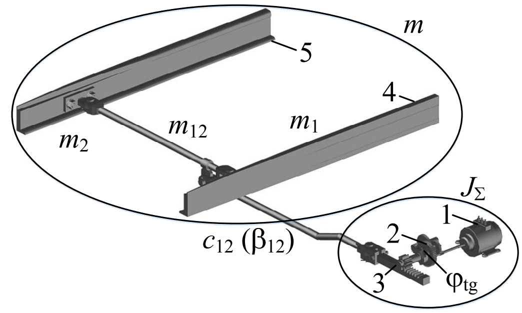


Fig. 1. Kinematic scheme of the railroad turnout SP-6 m: 1 – electric motor (EM), 2 – reducer, 3 – slide control, 4 and 5 – switch 1 and 2, respectively

Its estimation diagram is in Fig. 2. A first mass with a moment of inertia J_1 (EM armature EM J_1, exposed to electromagnetic momentum M_{EM}, reducer J_r, brough to the EM shaft, which is divided by the momentum of inertia of the first three degrees J_{1-3} and the fourth degree J_4 and the slide control) is exposed to the EM rod force F_{EM}, a second mass m (it includes the masses of two switches m_1 and m_2 and the inter-switch rod m_{12}) – to resistance force $F_c = f(v_2)$.

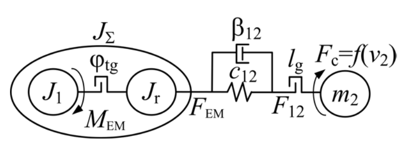


Fig. 2. Estimation diagram of two-mass mechanical system

In Fig. 2, the following designations are used: φ_{tg}=46°, l_g – technological gap between the third J_3 and J_4 fourth degrees of the reducer and the gap at points where the rod connects the slide control and a switch, respectively; F_{12} – elastic force of the inter-switch rod with a stiffness coefficient c_{12} and the internal viscous friction β_{12}.

A technological gap is necessary to facilitate the start of EM and to gain the initial kinetic energy to trigger switches at the onset of the turning process [16]. The role of the elastic link belongs to the working rod, which connects the slide control to a first switch. Converting the rotary motion of EM shaft to the switch translational movement is enabled by the slide control.

The structural diagram of a two-mass EMS is shown in Fig. 3, where U_t – task voltage, V; ω_1 – angular velocity of EM shaft, rad/s;

$$M_{12} = F_{12} \cdot \frac{R_k}{i},$$

M_{12} – elastic moment, N·m; R_k, i – a wheel's radius and a reducer's gear ratio; v_1 and v_2 – linear speeds of the slide control and switches, respectively, m/s.

The EM under consideration is the sequentially excited DC EM. Resistance force is nonlinear $F_c = f(v_2)$ and is determined from expression: $F_c = m_2 g f$, where $F_c = f(v_2)$ is the dependence of friction coefficient f on the linear speed of sliding with a corresponding mass v_2 (Fig. 4).

Friction is taken into consideration because railroad turnouts operate under different weather conditions under the influence of weather factors (fallen dry leaves, rain, snow, etc.). In addition, it makes it possible to account for the conditions when sleepers subside and there is a change in the geometry of a turnout in general. In the process of turning the railroad turnout's switches the friction coefficient of contacting surfaces is shown in the shaded area confined to two curves (Fig. 4).

The simulation model was implemented in the Simulink environment from the MATLAB software package due to its convenience, simplicity, and wide functionality.

Simulation implied an electric motor, the type of MSP-0.25, under the following parameters: P_n=250 W; M_n=1.47 Nm; n_n=1,700 rpm.; U_n=160 V; I_n=2.5 A; R_a=7 Ohm; J_n=0.005 kg×m^2; F_n=0.042 Wb.

The dependence of friction coefficient on sliding speed $F_c = f(v_2)$ is given by the approximate characteristic in the form of a piecewise-linear function [17].

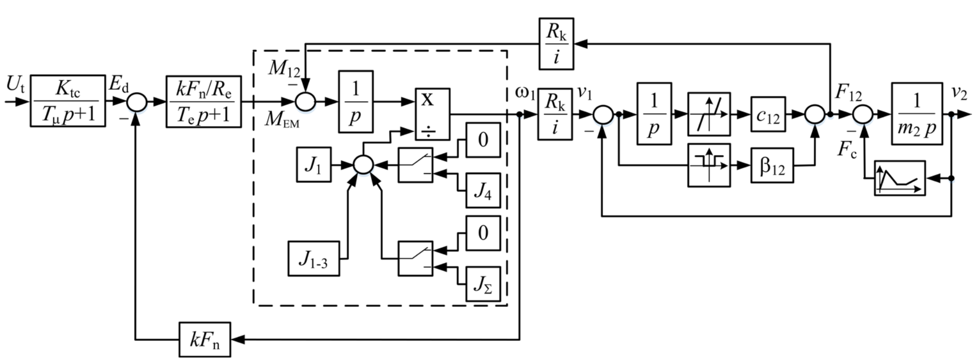


Fig. 3. Two-mass structural diagram of a railroad turnout

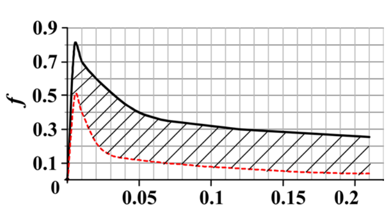


Fig. 4. Range of change in friction coefficient

In the synthesis of control system with a thyristor converter for a railroad turnout, it was assumed, according to its existing estimation diagram (Fig. 2), that the technological gap in the reducer is excluded from the kinematic link of a turnover.

This is dictated by the following. The need for a technological gap is predetermined by the lack of a technical capability to generate a significant motor's torque at start. Such an opportunity exists for the case where a modern thyristor converter is applied, so it would be advisable to exclude the gap because its presence has a negative impact on the links of the kinematic line. Fig. 5, *a, b* shows transient processes in the kinematic links of a railroad turnout, taking into consideration the technological gap at the direct start of the motor and when starting by the thyristor converter. Fig. 5, *c* – when starting the motor by the thyristor converter without taking into consideration the technological gap.

At direct starting of the motor taking into consideration the technological gap the value of elastic force is 12,962 N (Fig. 5, *a*). Fig. 5, *b, c* demonstrates that when starting the motor by the converter the exclusion of a gap between the third and fourth degrees of the reducer leads to a decrease in the values of elastic force by almost 2.5 times. The value of the elastic force criterion is reduced from 12,094 N to 4,367 N.

Thus, given the use of modern technology, the exclusion of a gap φ_{tg}=0° from the kinematic link of a railroad turnout is an advisable approach to reduce the impact when a switch is detached from its place. The driving force required for this would be provided by using a digital thyristor converter with a closed-loop control system.

Parameters for the switch motion dynamics in a railroad turnout should be estimated according to criteria from [13]:

– the time of switch turning t_s, s:

$$t_s = \int_0^{t_3} v(t)\,dt, \tag{1}$$

where t_3 is the assigned time of switch turning, s.

– the criterion of pulse of the momenta of switches hitting the frame rail at the end of turning M_i, kg/s. Due to the high speed of switches, the end of turning is accompanied, as the result of their hitting the frame rail, by their pushing outside. During prolonged braking, the time of switch turning is increased, and if the braking time is short, it is not possible to reduce the kinetic energy to the values that do not lead to the "switch release". Therefore, one needs to find such a range of values for the moment of braking start t_2, which, at a slight increase in the time of switch turning, would provide for a reduction in the magnitude of impact along the kinematic line of a railroad turnout. To assess the impact strength in a collision of the moving mass of the system including two switches interconnected by a rod against the frame rail, which is at rest, we introduce a quantity that is numerically equal to the pulse of the impact, or the switch torque pulse:

$$M_i = (m_1 + m_2 + m_{12}) \cdot v_2, \qquad (2)$$

where m_1 is the mass of the first rail, kg; m_2 is the mass of the second rail, kg; m_{12} is the mass of an inter-switch rod, kg; v_2 is the linear velocity of the second rail, m/s.

– the criterion of an elastic force in the working rod during turning F_{12}, N.

As a result of a jump-like surge in supply voltage, at impact, at the point of fastening a connecting rod, upon passing all gaps, the magnitude of elastic force F_{12} increases sharply. A very slow increase in supply voltage U_t delays the full turning time t_s. Therefore, one needs to find such a range of values for acceleration time t_1 so that they provide for a minimum F_{12} at acceptable values t_s:

$$F_{12} = F_d - m\frac{dv_1}{dt}, \qquad (3)$$

where F_d is the reduced traction power of a motor, N; m is the total weight of a moving mass, kg; v_1 is the speed of slide control motion, m/s.

Graphic explanation of the F_{12}, M_i and t_s criteria under condition of EM direct start is given in Fig. 6.

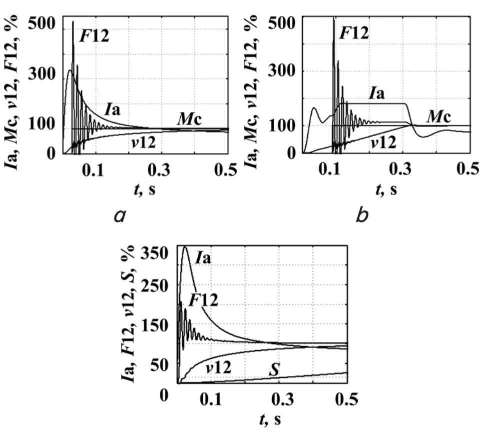


Fig. 5. Transient processes in the kinematic links of a railroad turnout: *a* — at direct starting of the motor with a gap; *b* — when starting the motor by the converter with a gap; *c* — when starting the motor by the converter without a gap

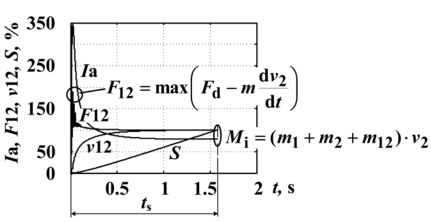


Fig. 6. Graphic illustration of optimization criteria

Fig. 6 shows that the criterion for a maximum of elastic force is the peak magnitude of the elastic force curve, arising at the start of the motor. The moment pulse criterion changes almost proportionally to the last abscissa along the coordinate for a switch linear velocity. Likewise, the criterion for a turning time of a railroad turnout is the abscissa of the last point the curve of switch displacement, which corresponds to the time of switch turning.

Thus, when starting an electric motor by a converter without taking into consideration the technological gap (Fig. 5, *c*) the time of switch turning is t_s=1.5754 s; a maximum of elastic force – F_{12}=5,053.78 N; the momentum pulse – M_i=214,8511 kg·m/s.

5. Investigating the dynamics of a railroad turnout's switch displacement in the system of subordinate regulation of switch position under various operational modes

A closed-loop system of automatic control with negative feedback on the position should be considered for a railroad turnout being an object of regulation when implementing the process of switching the switches from one position to another. Solving the problems on synthesis of the closed systems of electric drives, which have a high speed and desirable character of transient processes, most often employs the method of synthesis of consistent correction with subordinate regulation of coordinates (SCC). Underlying this method is the development of multi-circuit systems, when the synthesis results in that each loop is described by a transfer function and ensures optimum control over its original regulated coordinate based on the modular (MO) or symmetrical (SO) criteria of optimal setting.

The results reported in [13] show that the systems of subordinate control over the position of switches have advantages compared to the currently used direct start based on the speed of turning. This is reflected by the stability of maintaining speed and the possibility of smooth acceleration and braking.

The functional diagram of the electric drive in a railroad turnout as a closed two-mass EMS, built on the principle of subordinate regulation, is shown in Fig. 7.

According to the functional scheme, the adjustment of current control circuits and the speed of EM shaft rotation is ensured by a digital thyristor converter produced industrially [DCM, Siemens, DCS, ABB] as a standard. It implements a dual-speed SCC of the shaft rotation speed of an EM armature and hosts the built-in current and speed controllers (so-called technological), which are operated and adjusted by user according to own technological object [18].

A programmable logical controller (PLC) is designed for the process of turning the switches from one position to another. The position sensor used is an induction position sensor whose input receives a signal from the working body (WB).

A station attendant console is the command element.

According to the functional diagram, we built a structural three-circuit SCC for the electrical drive of a railroad turnout taking into consideration the elastic links and the nonlinear load characteristic (Fig. 8).

The accuracy requirements to railroad turnouts are not very strict (acceptable error up to 4 mm), while the dynamic characteristics, on the contrary, must meet enhanced demands, so the speed circuit is adjusted to the modular optimum (MO). In the current loop, the object of control is the EM armature chain, which is the aperiodic link with a gain factor $1/R_e$ and is a large time constant T_e.

The thyristor converter that powers the EM armature circuit is considered as an aperiodic link with a gain factor based on voltage of thyristor converter K_{tc} and a small uncompensated time constant, which is determined by the rectifying scheme T.

The current sensor is a proportional link with a transfer function $W_{cs}(p)=K_{cs}$.

The current controller is a proportional-integrated link (PI-controller) with a transfer function:

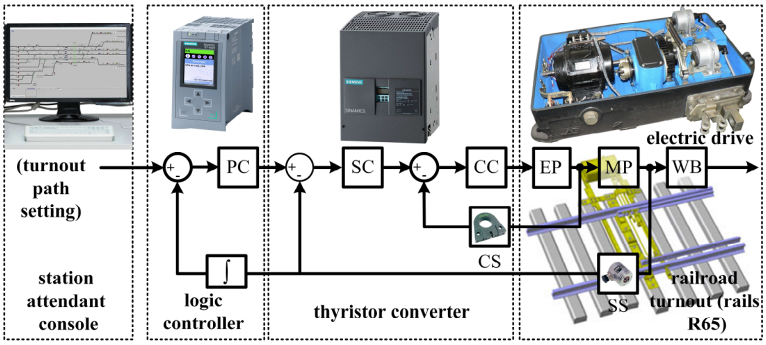


Fig. 7. Functional diagram of the electric drive for a railroad turnout built on the SCC principle: PC — position controller; SC — speed controller, CC — current controller, EP — electric part of electric motor, MP — mechanical part of electric motor, WB —working body, SS — speed sensor, CS — current sensor

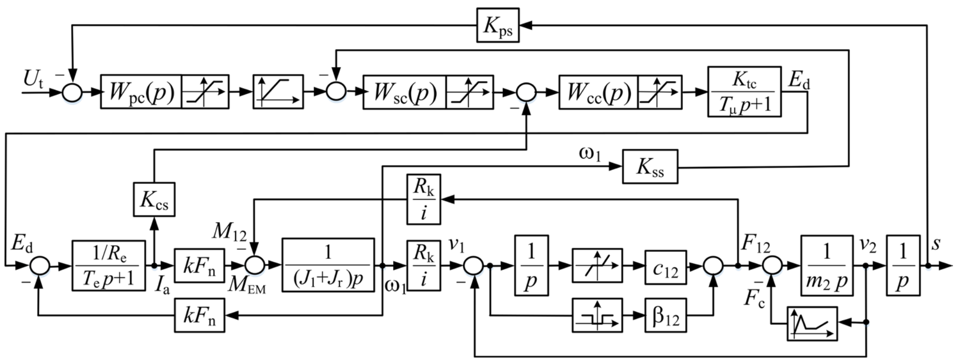


Fig. 8. Structural diagram of SCC of the position of regulated ED of a railroad turnout

$$W_{cc}(p)=\frac{R_e\cdot(T_e p+1)}{\alpha_{cc}T_\mu K_{tc}K_{cs}p}=K_{cc}+\frac{1}{T_{ic}p}, \qquad (4)$$

where

$$W_{cc}(p)=\frac{R_e\cdot(T_e p+1)}{\alpha_{cc}T_\mu K_{tc}K_{cs}p}=K_{cc}+\frac{1}{T_{ic}p}$$

– gain factor of current controller; α_{cc}=2 – adjustment coefficient of current loop on MO;

$$T_{ic}=\frac{\alpha_{cc}T_\mu K_{tc}K_{cs}}{R_e}$$

– time constant of the integration of a current controller.

The speed contour is set to MO. In the speed contour, controlled object is the mechanical part of the electric drive in a railroad turnout with a transfer function

$$W_{mp}(p)=\frac{kF_n}{(J_1+J_r)p}.$$

The closed current loop without taking into consideration the EMF response is described by the transfer function of second order

$$W_{\text{closed currentloop}}(p)=\frac{1}{\alpha_{cc}T_\mu^2p^2+\alpha_{cc}T_\mu p+1}.$$

For speed controller synthesis, it is convenient to use the first-order transfer function

$$W_{\text{closed currentloop}}(p)=\frac{1}{\alpha_{cc}T_\mu p+1}.$$

The speed sensor is a proportional link with a transfer function $W_{ss}(p)=K_{ss}$.

The speed controller is a proportional link (P-controller) with the transfer function:

$$W_{sc}(p)=\frac{J_1+J_r}{\alpha_{sc}T_\mu K_{ss}kF_n}=K_{sc}. \qquad (5)$$

where K_{sc} is the gain factor of speed controller; $\alpha_{sc}=2\alpha_{cc}$ – coefficient of speed circuit adjustment on MO.

Under a positioning mode, the regulation system moves the working mechanism to the preset positions, and sets it to these positions with the desired accuracy (positioning accuracy). In addition to the accuracy of positioning, one of the main quality indicators for a positioning system is the character of the transition process in the vicinity of the assigned coordinate and the time it takes to move to the assigned position. It is required that the transitional process in the vicinity of the assigned coordinate should be was aperiodic, that is, without overshooting, while the time of moving the working mechanism from the initial position to the set one should be minimized due to the optimum shape of a motion trajectory.

The nature of the transition process at completion of positioning is determined by adjusting the position adjustment circuit. Formation of movement trajectory between the source and end points of positioning is executed by selecting the shape of regulatory characteristics of the speed controller and the position controller, as well as by limiting the values of current and speed coordinates. Depending on a technological process, the positioning system can execute small, medium, or large displacements; for a railroad turnout as a controlled object, these are large movements.

Under the mode of large displacements, the system operates with a limited armature current and a speed limitation at acceptable level $\omega_{max}\leq\omega_n$. Typically, limitations of the armature current and the speed of electric motor are implemented by limiting the signals for setting current voltage U_{tc} and velocity voltage U_{ts} at the outputs of current and speed controllers.

When executing large displacements, the electric drive accelerates at maximum acceleration to the maximum speed ω_{max} and moves at this maximum speed to the specified coordinate. In this case, the acceleration of acceleration ε_a=0. At the time a control signal at the input to a speed controller passes through zero, the electric drive enters a braking mode, the armature current and the acceleration of breaking ε_b accept negative and maximum values. Positioning completion is in a linear zone and has a fading aperiodic character.

Because when setting the position contour on MO system is static relative to perturbation for torque, the accuracy of positioning depends on the magnitude of the gain coefficient of position controller K_{pc} and the momentum of resistance M_0. To ensure that the system accurately moves the working mechanism to the predefined position, the magnitude of gain factor K_{pc} is determined from ratio:

$$K_{pc} = \frac{k_0}{K_{tc}} \sqrt{\frac{4\varepsilon_0 \left(1 + \frac{M_0}{M_{\max\,\mathrm{perm}}}\right)}{s_{sd}\left(1 \frac{M_0}{M_{\max\,\mathrm{perm}}}\right)}}, \qquad (6)$$

where ε_0 is the acceleration of breaking at $M_0=0$;

$$k_0 = \frac{\omega_n}{s_{sd} R_k},$$

k_0 is the object amplification coefficient; K_{tc} is the converter gain factor; s_{sd} is the switch displacement; $M_{\max\,\mathrm{perm}}$ is the maximally permissible torque of the motor, limited by armature current.

The structure of the control system includes a ramp generator (RG) to gradually increase the signal of setting. The specificity of adjusting the position for a controlled object under consideration is that it is not required to stop the moving rail completely, because reliable triggering of the node that locks a switch requires that it should be pressed with enough force to the frame rail. At low speed movements, this requires considerable effort, resulting in a significant increase in the armature current. To prevent such a mode of SCC operation, the turning of a turnout ends not at zero speed, but with a slightly reduced. The magnitude of speed during switch locking at which there is no heavy impact against the frame rail is within 20...60 %.

Computer simulation was carried out at the following parameters of the object: position controller: K_{pc}=1.5; T_{tc}=0.7 s; K_{ps}=649; speed controller: K_{sc}=30; T_{sc}=40 s; K_{ss}=0.56; current controller: K_{cc}=0.017; T_{cc}=1.35 s; K_{cs}=40.

The adopted input signal was a surge of different levels to the preset angular velocity (100 %, 120 %, and 140 % of the rated EM speed) at "mild" (acceleration to the rated speed in 1.0 s) and "severe" (acceleration to the rated speed in 0.4 s) starts. We have acquired oscillographs of the EM armature current, velocity of its rotation, displacement, and elastic force under a stationary mode (Fig. 9, 10), under the mode of pressed snow (Fig. 11, 12).

Fig. 9 shows that the time of switch turning at an increase in voltage setting by 40 % decreases proportionally from 1.97 s to 1.85 s (that is, by 6 %). In this case, due to the use of a "mild" RG with an acceleration time of 1.0 s the starting current is 1.27 I_n, which is an undoubted advantage of this set of SCC configuration, as the mechanical part of the controlled object does not perceive overloads; therefore, maintenance could be carried out less often.

Fig. 10 shows that if one needs to reduce the turning time, one could set the time for a ramp generator to the "severe" level of 0.4 s, which makes it possible to reduce the time of switch turning to 1.62 s. However, in this case, the starting current rises to 1.83 I_n, which is not favorable for the mechanical part; in this case, however, it is an inevitable flaw that must be put up with.

So, it becomes possible, through such settings for the SCC of switch position in a railroad turnout as the RG duration and a limit to speed setting, to achieve a decrease in turning time by 17 % (from 1.97 s to 1.62 s), limiting the stator current in this case at the level of 1.83 I_n. This is an acceptable level for overloading electric motors in the turnouts used on railroads at present.

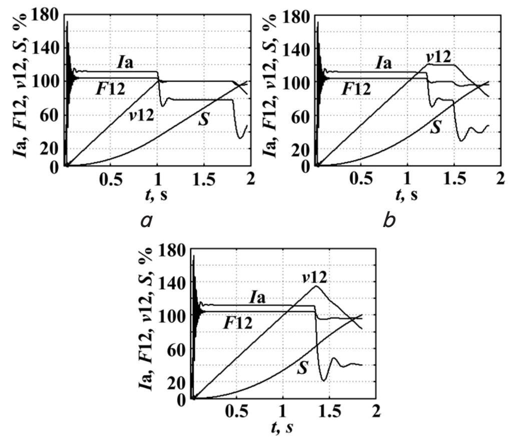


Fig. 9. Time diagrams of EM current and speed, displacement, and elastic force, at the "mild" start of ramp generator under a stationary mode: *a* – 100 % ω_n; *b* – 120 % ω_n; *c* – 140 % ω_n

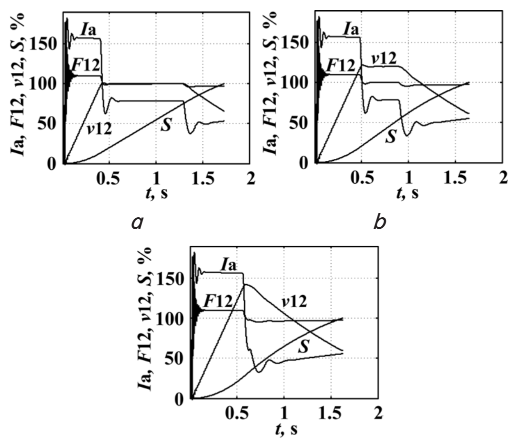


Fig. 10. Time diagrams of EM current and speed, displacement, and elastic force, at the "severe" start of ramp generator under a stationary mode: *a* – 100 % ω_n; *b* –120 % ω_n; *c* – 140 % ω_n

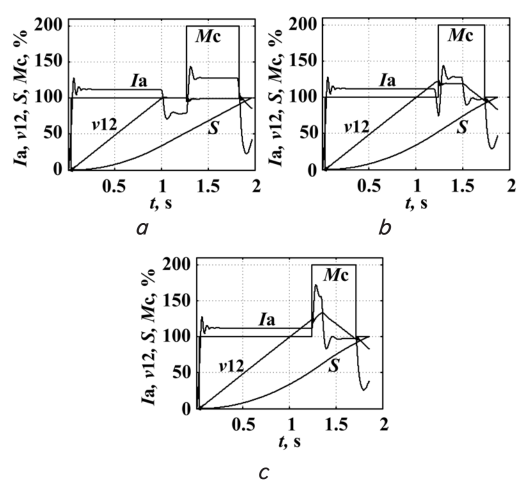


Fig. 11. Time diagrams of current, speed, displacement, and resistance momentum, in a railroad turnout when starting by TC with SCC ("mild" RG) when a foreign object (pressed ice or snow) gets between rails: *a* – 100 % ω_n; *b* –120 % ω_n; *c* – 140 % ω_n

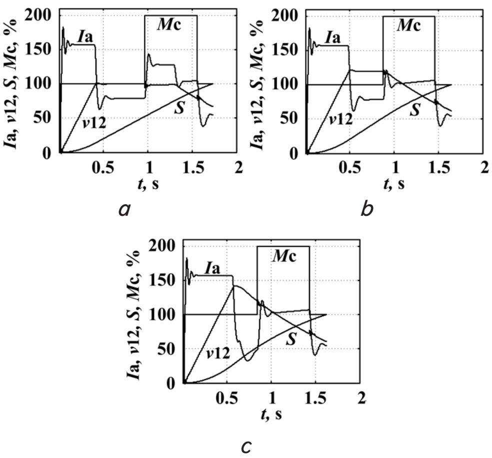


Fig. 12. Time diagrams of current, speed, displacement, and resistance momentum, in a railroad turnout when starting by TC with SCC ("severe" RG) when a foreign object (pressed ice or snow) gets between rails:
a — 100 % ω_n; *b* —120 % ω_n; *c* — 140 % ω_n

Fig. 11, 12 show patterns of change in the coordinates of the electric drive in a railroad turnout when compressed snow gets between a switch and a frame rail, which is characteristic of railroad turnout operation in winter. And such an event is the most likely at the end of turning, when a movable switch shovels all accumulated matter in front of it to the frame rail. Fig.13 shows the dynamics of switch movement in a railroad turnout at direct starting of the motor, with a clean crossing surface, and when it captures a foreign object.

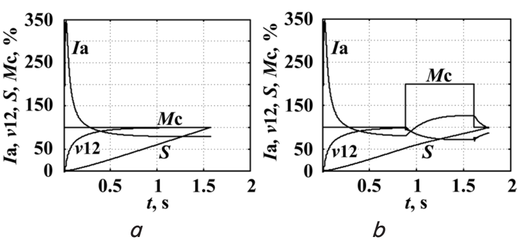


Fig. 13. Time diagrams of current, speed, displacement, and resistance momentum, in a railroad turnout at direct start:
a — clean crossing surface; *b* — crossing surface covered by ice

Thus, Fig. 13 shows that an increase in resistance momentum by 2 times (modeling a piece of pressed snow) shortly before braking does not lead to significant changes in the turning time, because a speed drop is not more than 5 %, and the increase in the turning time – not larger than 1 %. The stator current in this case, both for the case of "mild" and "severe" start of RG reaches a peak value of 2.1 I_n, but this makes it possible to minimize the drop in speed. Therefore, we could conclude about the warranted time of switch turning in winter, and, in general, under conditions of operation of mechanics under open sky. Such a characteristic of SCC is important under conditions of high-speed traffic.

Estimation of criteria for optimizing the process of switch turning at direct starting of the motor and SCC for each case is given in Table 1.

Analysis of the criteria for optimizing the process of switch displacement in a railroad turnout at direct starting of the motor, in comparison with the results from studying SCC, reveals a possibility to improve operational conditions for the kinematic line's links. Increasing the speed of switch turning within 5 % decreases the acceleration time and the impact against a frame rail at the onset and end of turning (marked with color).

Table 1

Comparison of criteria for estimating the EMS of a railroad turnout at direct starting of the motor (DS) and in SCC

EMS estimation criterion	DS	RG, s	SCC		
			100 % ω_n	120 % ω_n	140 % ω_n
time of switch turning t_s, s	1.57	1.0	1.96	1.87	1.85
		0.4	1.72	1.64	1.62
elastic force maximum F_{12}, N	5,054	1.0	4,177	4,177	4,177
		0.4	4,302	4,302	4,302
momentum pulse M_i, kg·m/s	215.8	1.0	183.2	177.7	179.8
		0.4	141.5	131.3	127.9

6. Studying the dynamics of switch displacement in a railroad turnout within the system of modal control over switch position in a railroad turnout under different modes of operation

Among the basic requirements put forward to the electric drive of a railroad turnout are the high indicators of operational reliability, as well as accuracy and performance, when executing control over switch movements. However, the principles of subordinate coordinate regulation are not always effective to ensure the desired quality of control in systems with elastic links. In this regard, we addressed the issue about studying a control system over the electric drive of a turnout with the modal controller (MC), since it makes it possible to determine the desired characteristic polynomial of the system.

The advantages of modal control include: a possibility to obtain any damping and high-speed performance within a "small" linear electric drive of any complexity; to achieve any complexity of the mechanical characteristic at the assigned damping; robustness of the control system.

The disadvantages of modal control include: the desired dynamics is achieved "in small"; a large number of coordinates to be measured, that is the increased need for sensors.

Fig. 14 shows the structural diagram of a railroad turnout with a modal controller.

To illustrate the practical implementation of the procedure for synthesizing the system of modal control, we simulated operation of the electric drive in a railroad turnout under different modes in the MATLAB software package environment at the same parameters of the object and under the same assigned conditions as in the above system. We acquired oscillograms of the EM armature current and the speed of its rotation under stationary mode (Fig. 15, 16), and when pressed snow gets inside (Fig. 17, 18).

Fig. 15 shows that at the "mild" RG the time diagrams of regulated coordinates are not significantly different from SCC. In this case, there is a difference in the time of SCC turnout turning, it is lower by 2–3 %; increasing the speed of turning increases this difference. A maximum of elastic force is the same under both control systems. A pulse of the momentum varies from that with SCC at 100 % ω_n. It is smaller by 4 %; and when increasing the speed of turning it is greater by 20 % and is approaching the same magnitude as is the case at direct start. This is predetermined by that at a relatively large (1 s) acceleration time and, on the other hand, the same great speed of turning (140 % ω_n), the system "has no time" to brake.

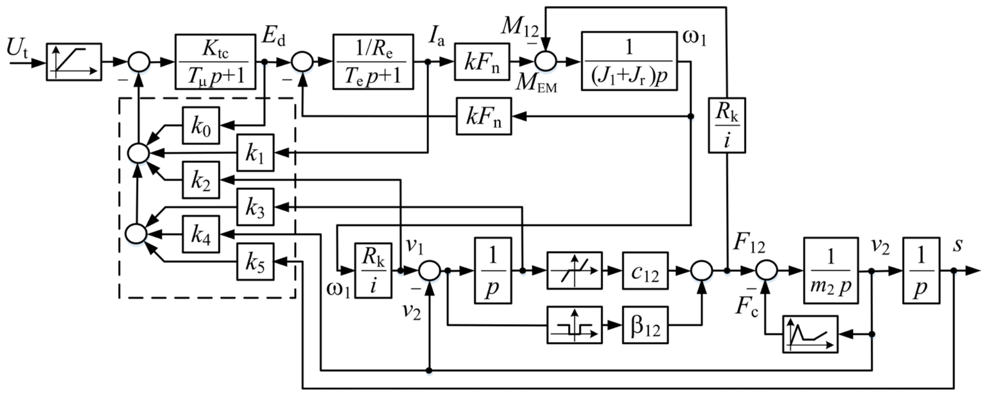
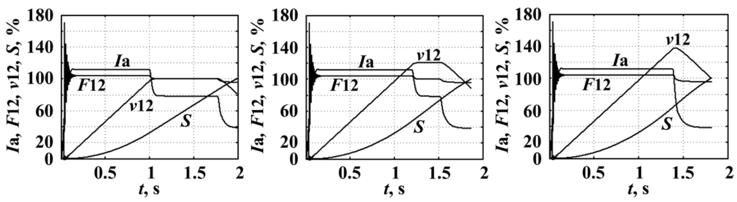


Fig. 14. Structural diagram of the two-mass EMS for a railroad turnout with a modal controller

When snow gets between a rail and a switch, Fig. 17, 18, it does not, similar to the system with SCC, lead to significant changes during turning, as a speed drop is not more than 5 %, and the increase in turning time is not more than 1 %.

Estimation of optimization criteria for the process of switch displacement at direct starting of the motor and for the system with a modal controller for each case is given in Table 2.



a b c

Fig. 15. Time diagrams of EM current and speed, displacement, and elastic force, at the "mild" start by a ramp generator under a stationary mode: *a* – 100 % ω_n; *b* – 120 % ω_n; *c* – 140 % ω_n

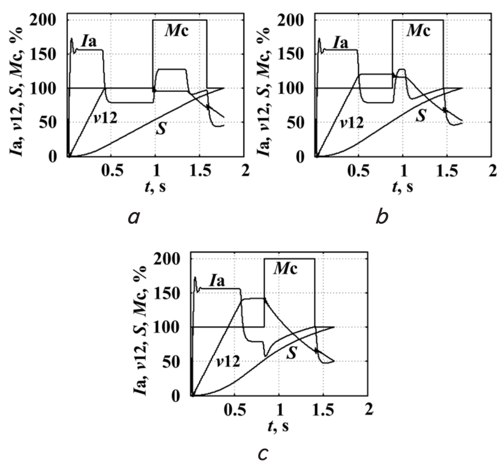
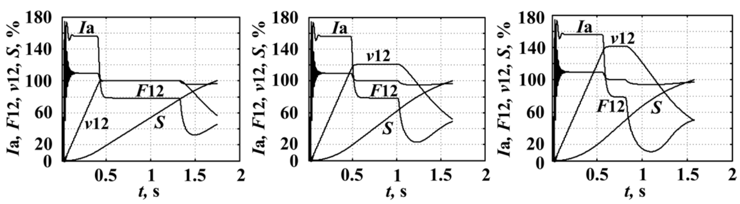
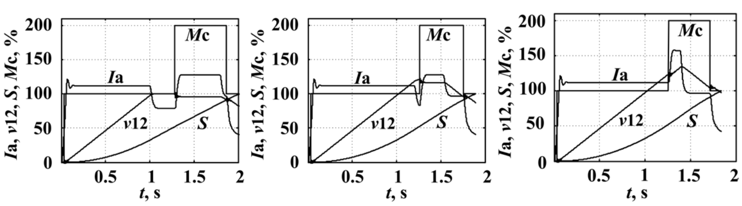


Fig. 18. Time diagrams of current, speed, displacement, and resistance momentum, in a railroad turnout when starting in the system with a modal controller ("severe" RG) when a foreign object (pressed ice or snow) gets between rails: *a* – 100 % ω_n; *b* –120 % ω_n; *c* – 140 % ω_n



a b c

Fig. 16. Time diagrams of EM current and speed, displacement, and elastic force, at the "severe" start by a ramp generator under a stationary mode: *a* – 100 % ω_n; *b* – 120 % ω_n; *c* – 140 % ω_n



a b c

Fig. 17. Time diagrams of current, speed, displacement, and resistance momentum, in a railroad turnout when starting in the system with a modal controller ("mild" RG) when a foreign object (pressed ice or snow) gets between rails: *a* – 100 % ω_n; *b* –120 % ω_n; *c* – 140 % ω_n

Table 2

Comparison of assessment criteria for a railroad turnout EMS at direct starting of the motor (DS) and in the system with a modal controller

EMS assessment criteria	DS	RG, s	System with a modal controller		
			100 % ω_n	120 % ω_n	140 % ω_n
switch turning time t_s, s	1.57	1.0	1.99	1.86	1.81
		0.4	1.74	1.63	1.58
elastic force maximum F_{12}, N	5,054	1.0	4,155	4,155	4,155
		0.4	4,257	4,257	4,257
momentum pulse M_i, kg·m/s	215.8	1.0	175.3	191.2	215.1
		0.4	122.5	111.8	106.5

At the "severe" RG, Fig. 16, the pattern changes slightly, although there are no significant differences. Turning time is as small as with SCC, by 2–3 %, the shortest time is achieved with MC and is equal to 1.58 s. A maximum of elastic force is also the same in both control systems. However, the momentum pulse with MC at lower values for RG becomes less than that of SCC by 12–15 %, as over a lesser time the RG system is able at the same time, as at direct start, to slow down to 50–60 % ω_n, reducing, thereby, the pulse of switch momentum at the impact against a frame rail. With SCC, a decrease in speed is achieved to the level of 57–62 % ω_n.

Our analysis of comparison of the optimization criteria for the process of switch displacement in a railroad turnout at the direct starting of the motor with a modal control system testifies to the same trend as is the case for SCC. There is a decrease in the time of acceleration and there is an impact of switches against a frame rail at the onset and at the end of switch turning with the speed increase within 5 % (indicated by color).

Systems with the synthesized modal controller have a small advantage over SCC. This is reflected in the reduction of turning time and (at certain parameters for RG) the reduction in momentum pulse, as well as a smaller amplitude of the coordinates of speed and current under non-stationary modes.

7. Estimation of numerical values of optimization criteria for the process of switch displacement in the controlled electric drives of railroad turnouts compared to the direct starting of the motor

Visual comparison of the quality indicators for the examined control systems (Fig. 19, 20) is appropriate to assess the quality of the turning process.

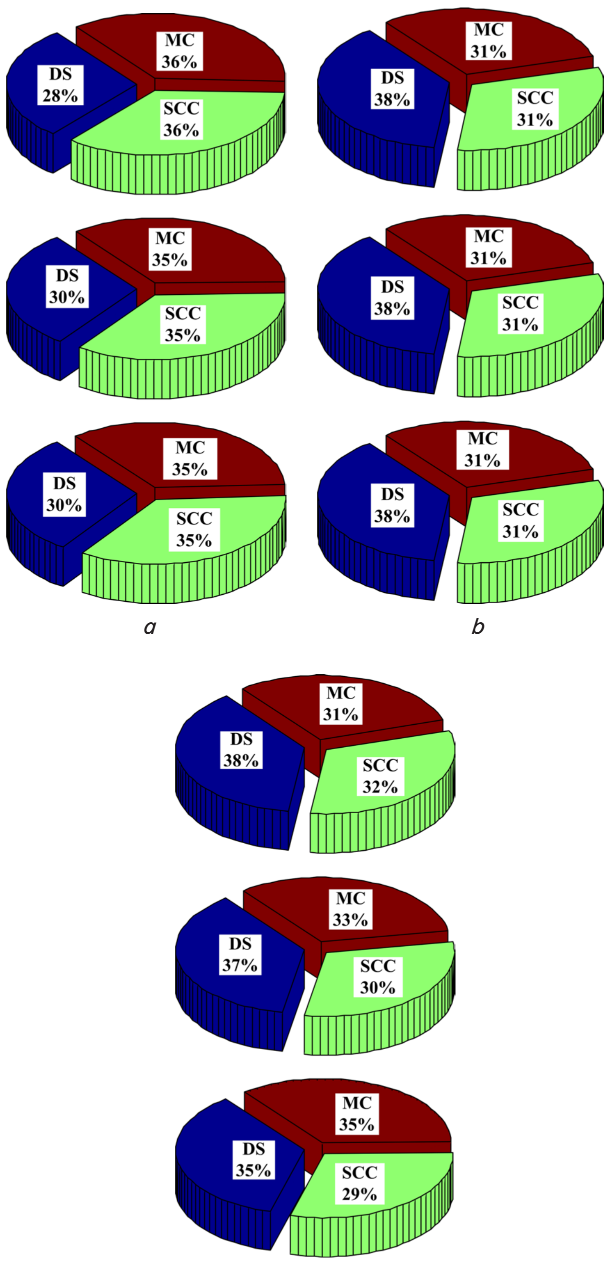


Fig. 19. Comparison of criteria for assessing EMS of a railroad turnout at "mild" RG for different values of speed setting: *a* — t_s, s at 100 %, 120 %, 140 % of ω_n; *b* — F_{12}, N at 100 %, 120 %, 140 % of ω_n; *c* — M_i, kg·m/s at 100 %, 120 %, 140 % of ω_n

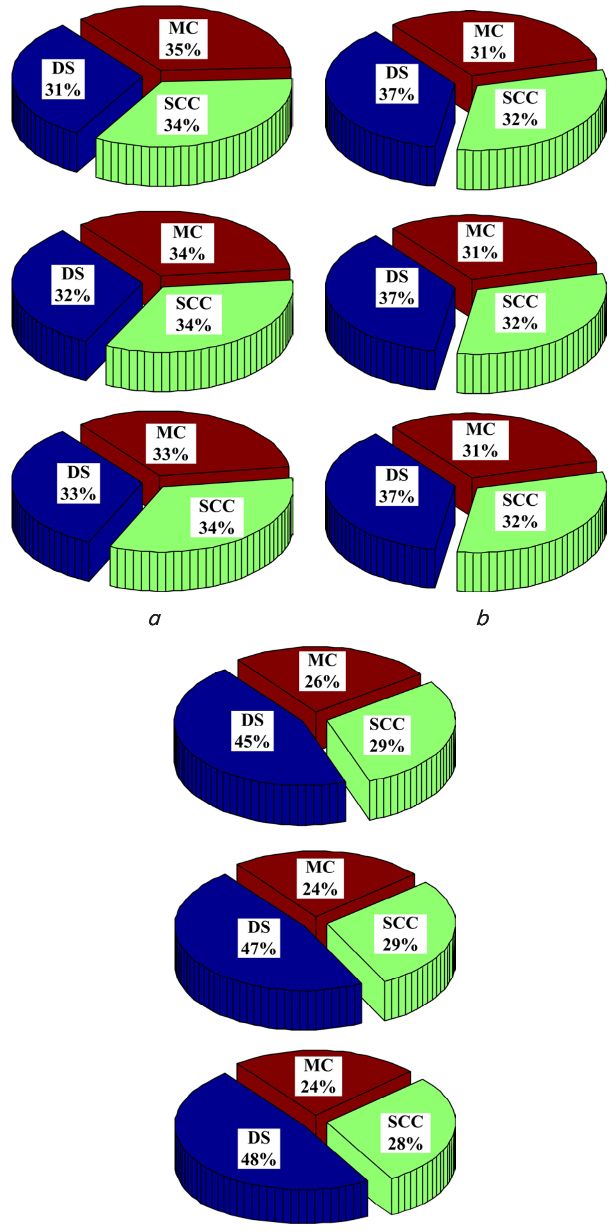


Fig. 20. Comparison of criteria for assessing EMS of a railroad turnout at "severe" RG for different values of speed setting: *a* — t_s, s at 100 %, 120 %, 140 % of ω_n; *b* — F_{12}, N at 100 %, 120 %, 140 % of ω_n; *c* — M_i, kg·m/s at 100 %, 120 %, 140 % of ω_n

Our analysis of Fig. 19, 20 shows that the use of the regulated electric drive for a railroad turnout with a DC motor, in accordance with the above quality criteria, could improve quality of the turnout turning process. Thus, at the "mild" RG, that is, a smoother start and stop, there is an obvious reduction in the magnitude of impact pulse and elastic force (6–8 % and 5–6 %, respectively); in this case, the turning time is increased by 5–8 %. Increasing the rate of setting the task and the speed level of switch turning yields a more expressive result: reduction in the magnitude of impact pulse and elastic force amount to 20–24 % and 5–6 %, with an increase in turning time by 0.5–1 %.

Thus, the basic indicators of performance estimation criterion have improved: there is a decrease in the magnitude of switch impact pulse M_i by 20–24 %; a decrease in the magnitude of elastic force F_{12} in the rod by 5–6 %; the turning time t_s increased by 5–8 % for setting the rated speed and by 0.5–1 % for setting the speed that is 40 % higher than the rated speed.

8. Discussion of results of studying the dynamics of switch turning in a railroad turnout

Studying the dynamics of switch displacement at the direct starting of the motor in the MATLAB environment has shown that accounting for the technological gap required for the direct start of the motor is not required when starting the electric motor from a thyristor converter (Fig. 5). Modern thyristor converters provide an opportunity to ensure a significant momentum of the motor at the onset of the process of switch turning, which leads to a decrease in the values of elastic force by almost 2.5 times. Therefore, it is advisable in the future to investigate systems without taking into consideration the technological gap in the kinematic links.

When studying the dynamics of switch displacement in a railroad turnout, the thyristor converter in the regulated electric drive with subordinate control of coordinates and with the modal control, which powers the armature circuit of the motor, was represented as an aperiodic link of first order.

The system of subordinate control over coordinates, in contrast to the previously investigated systems of speed regulation, was supplemented with a position loop. Owing to the position loop, it becomes possible to monitor the process of switch positioning (Fig. 8).

The system with a modal control over coordinates was also supplemented with the position loop, which makes it possible to determine the desired characteristic polynomial to derive the necessary character of switch turning (Fig. 14).

For both systems, we provided the smooth start by a ramp generator with different acceleration time to the rated speed and limitation for setting angular velocity. Simulation was performed for a standard operation of a railroad turnout and under conditions when snow or ice gets between the rails. During simulation, we observed a limitation for the stator current at the level of 1.27 I_n, which is an advantage, since the mechanical part of the control object does not perceive overloads and, therefore, maintenance could be carried out less often (Fig. 11, 12).

The analysis of operational quality of the electric drive in a railroad turnout was based on the optimization criteria for the process of switch displacement. We compared numerical values of the pulse of a switch impact against a frame rail, the elasticity of force in a working rod and the time of switch turning in the regulated electric drives with the direct start of the motor. The obtained results show high efficiency of using modern control systems to manage the process of switch turning (Table 1, 2, Fig. 19, 20). There is a decrease in the magnitude of a switch impact pulse by 20–24 %, and in the elastic force in a rod – by 5–6 %. The time of switch turning increased by 5–8 % when setting the rated value for speed and by 0.5–1 % when setting the speed above 40 % of the rated speed. According to the estimation results, we note the expediency of the effectiveness of railroad turnout operation when using various types of regulated electric drive in comparison with existing turnouts.

The advantages of our study provide for a certain freedom in the further selection of a control system; the results obtained produce approximately the same result in terms of the optimization criteria for the process of switch displacement. The current study has shown a sufficient adaptation of the regulated electric drive to the operational conditions for drives in railroad turnouts in the process of standard operation and under conditions when snow or ice gets between the rails.

The disadvantages include the lack of a practical experiment.

The present research into control systems over railroad turnouts is continuation of the topic related to using a thyristor converter as part of a turnout with DC motors. In contrast to the earlier investigated speed control systems, the current paper examines the systems of position control. Further advancement of our research implies studying a position control system with an AC drive.

Results of this study could be useful for the development of technical re-equipment of existing railroad turnouts with direct start to the regulated drive enabled by direct or alternating currents. The oscillographs and comparative tables from our study could be applied in designing new electric drives for railroad turnouts, as well as in commissioning operations with a regulated drive, as reference values for converter parameters.

9. Conclusions

1. Our study into the dynamics of switch displacement in a railroad turnout at the direct starting of the motor has produced the following values for optimization criteria: switch turning time is 1.5754 s; a maximum of elastic power is 5,053.78 N; momentum pulse is 214.8511 kg·m/s. These data underlie further comparison. Starting the motor by a converter makes it possible to exclude a technological gap and reduce impacts in the kinematic links at the onset and at the end of switch turning. This leads to a decrease in the value for an elastic force criterion from 12,094 N to 4,367 N.

2. No significant differences have been revealed in the dynamics of switch displacement in the systems of the regulated DC electric drive in a railroad turnout (SCC and modal control over switch position). The time of switch turning differs by not larger than 5 %. The dynamics of the regulated process of turning is marked by a decrease in the magnitude of impacts, as evidenced by a decrease in the values for criteria of elastic force and momentum pulse.

3. Our comparison of numerical values for the criteria of optimization of the switch displacement process indicates the positive effect of decreasing the maximum of the elastic force from the system with a direct start, by 6–8 %, and, when considering a gap in the kinematic link, by 250–270 %. The decrease in the switch impact pulse, due to the system with a direct start, is 20–24 %. The negative effect of a prolonged turning time increases, due to the smooth start and braking, by not more than 5–8 %. Since the increase in turning time is insignificant, while the reduction in elastic force and momentum pulse is quite significant, one can conclude about the operational efficiency of regulated electric drives in railroad turnouts when compared with the direct start of the motor.

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