Визначені параметри електропривода стрілочного переводу на базі двох лінійних двигунів та проведений аналіз отриманих результатів. Об'єкт дослідження – процеси в електромеханічній системі стрілочного переводу. Предмет досліджень – лінійні електродвигуни різних конфігурацій. Розрахована конструкція лінійного електромагнітного перетворювача і електроприводу. Знайдено технічне рішення створення безредукторного стрілочного переводу. Аналіз дослідження впливу характеристики тертя та марки переводу геометричні параметри лінійного двигуна дозволив обрати найкращий варіант з урахуванням марки рельсу

Ключові слова: стрілочний перевід, електропривід, лінійний індукторний двигун, електромагніт, методи оптимізації

Определены параметры электропривода стрелочного перевода на базе двух линейных двигателей и проведен анализ полученных результатов. Объект исследования – процессы в электромеханической системе стрелочного перевода. Предмет исследования – линейные электродвигатели различных конфигураций. Рассчитана конструкция линейного электромагнитного преобразователя и электропривода. Найдено техническое решение создания безредукторного стрелочного перевода. Анализ исследования влияния характеристики трения и марки перевода на геометрические параметры линейного двигателя позволил выбрать наилучший вариант с учетом марки рельса

Ключевые слова: стрелочный перевод, электропривод, линейный индукторный двигатель, электромагнит, методы оптимизации

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DETERMINING PARAMETERS OF ELECTRIC DRIVE OF A SLEEPER-TYPE TURNOUT BASED ON ELECTROMAGNET AND LINEAR INDUCTOR ELECTRIC MOTOR

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1. Introduction

One of the ways of increasing traffic intensity of trains is the creation of turnouts, which are able to reduce the time of switch of the rail points [1–3]. Another important aspect of traffic intensification is the automation of the ballast tamping process by special automated complexes, which work in continuous mode of motion along the main road. The shortest way of solving this problem in connection to a turnout is the introduction of sleeper-type electric drives [1]. The most promising electric drive is the drive with electromagnet or inductor type linear electric motor. They consist of a special electrical machine, electronic commutator on the power transistor modules and a microprocessor control unit.

At present, electromechanical transducers of inductor type [4] are widely used in various types of transport due to their high reliability, simple design and manufacturability. This makes it possible to use it as a motor for the turnouts that essentially simplifies their design.

One more benefit of applying linear motors in the turnout is exclusion of a reducer, which considerably increases the performance efficiency of the turnout as a whole.

In many countries of the world, the turnouts are complex electromechanical devices. The application of linear motors will not only make it possible to considerably simplify the design of a turnout, but also to increase its reliability essentially, while at the same time cutting cost of regular maintenance and repair.

2. Literature review and problem statement

The performed survey shows that, along with the improvement of the existing turnouts by replacing unreliable elements, global companies are working to create their new types, hydraulic, pneumatic or electromechanical, with the purpose to increase reliability, performance speed and achieve high velocities of the motion along the switches. At present,

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to compensate for the indicated deficiencies, a number of papers [5–7] examine various possibilities. Some [8] work on a distance computerized control of the turnout and on monitoring their condition, others [9] study a possibility of introducing to the market of turnouts drives with electric power supply from solar batteries, some [1, 10] are testing turning mechanisms, built in the sleepers. Specialized constructions are also created, intended for application on the main and station, including sorting, ways. But in this case, all efforts are mostly directed toward the turnouts with electric drives, which use rotary elements. Consequently, all this reduces reliability and service period of an electric drive, leads to high operational costs and requires conducting large volume of repair work. The drawbacks of the known sleeper-type electric drives [10] include a single-stage reducer, which leads to additional losses and necessitates its constant maintenance. There is also complexity of the control system, made in the form of a frequency converter [2]. Taken together, it all leads to the increase in the operating costs and rises its price. Furthermore, the development of microcircuitry makes it possible to design the microprocessor control systems, and to expand functional possibilities of electric drive, to use contactless sensors of new generation [5, 6], to apply electronic converting technology, electronic protection of the motor during switching. Mono-sleeper systems, in turn, will make it possible to reduce their price and prolong the life cycle of operation. One of the most successful solutions for the sleeper design of the turnout is application of the linear motors, actively implemented lately in railway transport [11]. Despite the development of the methods of control of linear motors [12] and mathematical simulation of their different types [13], there is no practice of using such motors in the turnouts in the world yet. Such devices will help not only to simplify the mechanical part of the drive and the system of the rail points control, but also to increase its performance speed.

3. The purpose and objectives

The purpose of this work is to determine parameters of electric drive of a sleeper-type turnout based on two linear motors by using various methods of optimization.

To achieve the goal, the following tasks were set:

– selection of design of a linear electromechanical converter and an electric drive of a turnout;

– multicriterion optimization of geometric dimensions of the electromechanical converter;

– conducting of comparative analysis of the obtained results for both proposed types of a linear electric motor.

4. Selection of design of the linear electromechanical converter for the turnout

The main task in the development of design was the exclusion of rotating elements of the turnout and subsequent significant simplification of its kinematic line. Fig. 1 presents transverse and longitudinal sections of the proposed unit, placed in a sleep, and the proposed design of an electric drive is represented in Fig. 2.

Such a design of the electric motor in the form of an electromagnet is characterized by its simplicity and reliability.

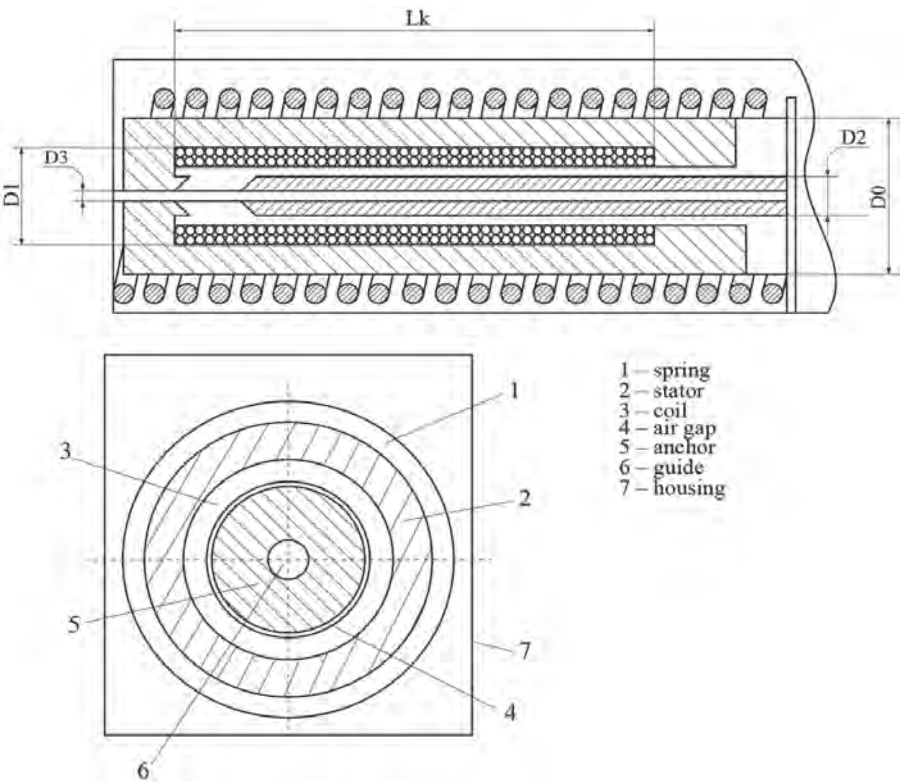

Fig. 1. Design of a linear motor in the sleep

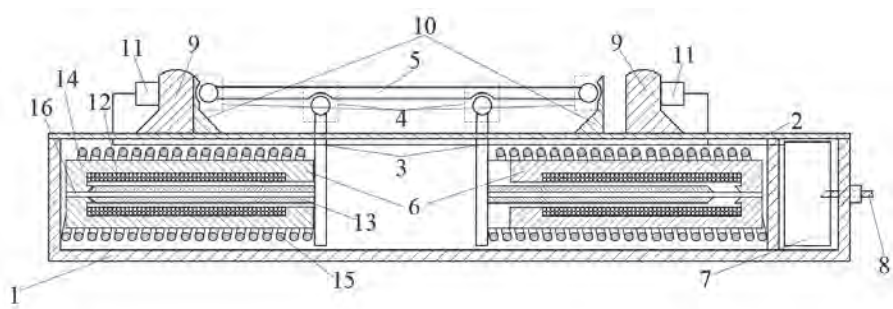

Fig. 2. Arrangement of equipment in a mono-sleeper type turnout with electromagnets:
1 — housing; 2 — cover; 3 — transverse thrusts; 4 — articulated joints; 5 — longitudinal thrust; 6 — linear electric motor; 7 — control unit; 8 — cable; 9 — stock rail; 10 — rail points; 11 — position sensors of rail points; 12 — electric motor coil; 13 — anchor of electric motor; 14 — stator of electric motor; 15 — spring; 16 — guide

In this case, linear electric motor (6) consists of stator (14), made of charged electrical steel, coil (12) and anchor (13). Depending on the signal of sensor of the rail points (11), the power converter, located in the control unit (7) and made on the base of field or IGB transistors, connects the coil of the stator (12) to the power source. In this case, the electric motor converts electrical energy to mechanical, setting in motion the anchor (13). In its turn, the anchor, moving along the guide (16), transmits the force through transverse (3) and longitudinal (5) thrusts to the rail points (10). Electric drive of the turnout consists of two electromagnets for reverse work. The application of springs (15) is predetermined by insufficient value of electromagnetic force in the beginning of the switch, as well as by the provision of the necessary force in the case of rail point freezing to the stock rail. The control unit (7) is equipped with different types of speed regulators. Contactless sensors (11) are placed on the outer side of the stock rail (9) and provide control of the tight fit of a rail point to it.

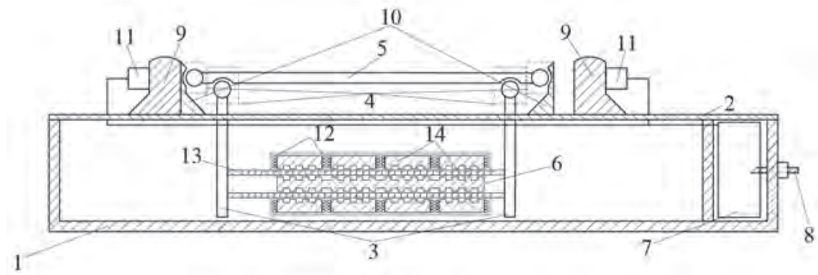

Fig. 4. Arrangement of equipment in a mono-sleeper type turnout with the induction motor: 1 — housing; 2 — cover; 3 — transverse thrusts; 4 — articulated joints; 5 — longitudinal thrust; 6 — linear electric motor; 7 — control unit; 8 — cable; 9 — stock rail; 10 — rail points; 11 — position sensors of rail points; 12 — the coil of electric motor; 13 — the anchor of electric motor; 14 — the stator of electric motor

In order to conduct a comparative analysis of the work of linear motor in the turnout, it is proposed to use one more type of electromechanical converter – induction (Fig. 3).

A four-phase electromechanical converter (6) consists of two stators (14) (internal and external) that makes it possible to obtain maximum air gap in the intertooth zone at minimum dimensions of the unit, concentrating the magnetic flux in the tooth zone. The alternating start of the phases (12) of electric motor (A, B, C, D) ensures uniform distribution of electromagnetic force during anchor motion (13). With the increase in the number of coils (phases), it is possible, if need be, to substantially decrease the fluctuations of the force, acting on the anchor, during its motion.

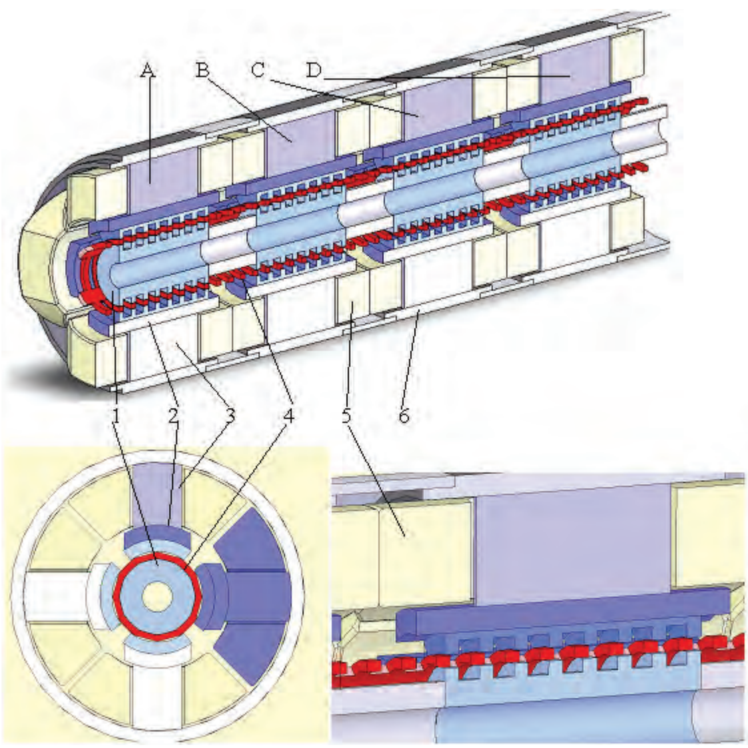

Fig. 3. Design of inductor type motor: 1 — internal stator; 2 — pole pieces of external stator; 3 — poles; 4 — anchor; 5 — the coil of phases; 6 — housing

Such a linear motor requires implementation of a more complex system of control, compared to the electromagnet, and, consequently, a more complex engineering solution, but it ensures reverse work without the use of additional springs. The proposed design of electric drive with induction machine is represented in Fig. 4.

5. Diagrams of force distribution in the proposed electric drive of a turnout on the example of an electromagnet

The force of a turnout switch depends on the weight of its moving parts, the type of rails, the joints of switching thrusts and the coefficient of friction of rail points against the pillows. All indicated magnitudes, with exception of the latter, are known. The magnitude of the coefficient of friction depends on the condition of a switcher, quality of the lubricant of the switching pillows, quality of their surfaces treatment, as well on the soles of the rail points, and other factors [14, 15].

Considering the foregoing, the diagram of force distribution in the examined system is represented in Fig. 5.

At the beginning of switch, the distance between the anchor and the stator corresponds to the distance between the rail point and the stock rail (X1) and is 152 mm. In line with the D'Alembert's principle, to perform the switch of rail points, it is necessary that the sum of three of those acting in the system forces would satisfy the following inequality:

$$\sum F = F_{el} + 2 \cdot F_{sp} + F_c > 0, \quad (1)$$

where F_{el} is the force of electromagnet (electric motor); F_{sp} is the force of spring; F_c is the resistance force.

The electromagnetic force of linear motor depends on the anchor's movement and can be described by the following expression:

$$F_{el} = -\frac{dW}{dx}, \qquad (2)$$

where x is the anchor's movement; W is the energy of electromagnet, mostly concentrated in the magnetic gap, without regard to saturation, it is possible to approximately determine it as follows

$$W = \int_0^i \Psi di = \int_0^i BSdi = \int_0^i \mu_0 HSdi =$$
$$= \int_0^i \frac{\mu_0 iS}{(X1 - x)} di = \frac{\mu_0 i^2 S}{2(X1 - x)}, \qquad (3)$$

where Ψ is the flux linkage of the coil of linear motor; i is the magnetomotive force of the coil of linear motor; B is the magnetic induction in the air gap; S is the cross section of the anchor of linear motor; μ_0 is the magnetic permeability of air; H is the magnetic field strength in the air gap.

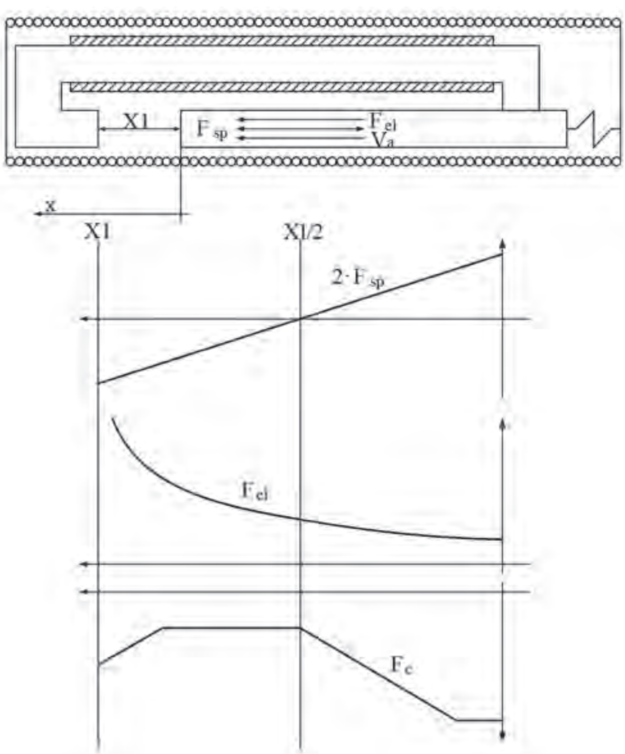

Fig. 5. Interaction of forces of electric drive

After substituting formula (3) to the formula (2), we will obtain the expression for electromagnetic force in the final form:

$$F_{el} = -\frac{d}{dx}\left[\frac{\mu_0 i^2 S}{2(X1 - x)}\right] = \frac{\mu_0 i^2 S}{2(X1 - x)^2}. \qquad (4)$$

Let us express the cross section of the anchor through the anchor and guide diameters:

$$S = \left(\frac{D_p + D_н 10^{-3}}{2}\right)^2 \frac{\pi}{4} = \frac{\pi\left(D_p + 5\cdot 10^{-3}\right)^2}{16}, \qquad (5)$$

where D_p is the anchor diameter; $D_н$ is the guide diameter.

Let us determine maximum magnetomotive force:

$$i = J \cdot S_L, \qquad (6)$$

where J is the current density; S_L is the longitudinal section of the coil.

The longitudinal section of the coil can be expressed through the expression:

$$S_L = \left(\frac{D_к}{2} - \frac{D_p}{2}\right) \cdot L_к, \qquad (7)$$

where $D_к$ is the coil's outer diameter; D_p is the outside anchor diameter; $L_к$ is the length of the coil.

Assuming current density equal to $J = 5 \cdot 10^6$ A/m^2, the formula for finding magnetomotive force will take the following form:

$$i = \frac{J}{2}\left(D_к - D_p\right) L_к. \qquad (8)$$

An important component of electric drive is the pair of springs, which balance each other in the mid-position of the anchor and which create additional force on it in the moment of start, when resistance force provides maximum resistance. The force of the spring depends on the degree of its compression (anchor's movement) and on the coefficient of rigidity:

$$F_{sp} = K\left(x - \frac{X1}{2}\right), \qquad (9)$$

where K is coefficient of rigidity of the spring; X1 is the maximum distance between the rail point and the stock rail.

With the accepted approximation (Fig. 3), the resistance force can be described by the following system of equations

$$F_{!} = \begin{cases} -b_1; & 0 \le x \le x_1, \\ -k_1 x - b_2; & x_1 < x \le x_2, \\ -b_3; & x_2 < x \le x_3, \\ k_2 x - b_4; & x_3 < x \le x_4. \end{cases} \qquad (10)$$

The last design parameter, necessary for calculating the spring, is the coefficient of rigidity, computed by the expression:

$$K = \frac{G\, d_D^4}{8\, d_F^3\, n}, \qquad (11)$$

where G is the shear modulus (for steel — $8 \cdot 10^{10}$ H/m); d_D is the wire diameter; d_F is the diameter of coil; n is the quantity of turns of the spring.

With the use of previously obtained expressions, the program for calculating the electromagnetic force, as well as coefficient of rigidity of the spring, was written in the MATLAB package. The 1/22 type of the turnout with the maximum weight of rail points was used as the load. Based on this program, we obtained the characteristic of force distribution of electric drive from the gap S between the rail point and the stock rail (Fig. 6).

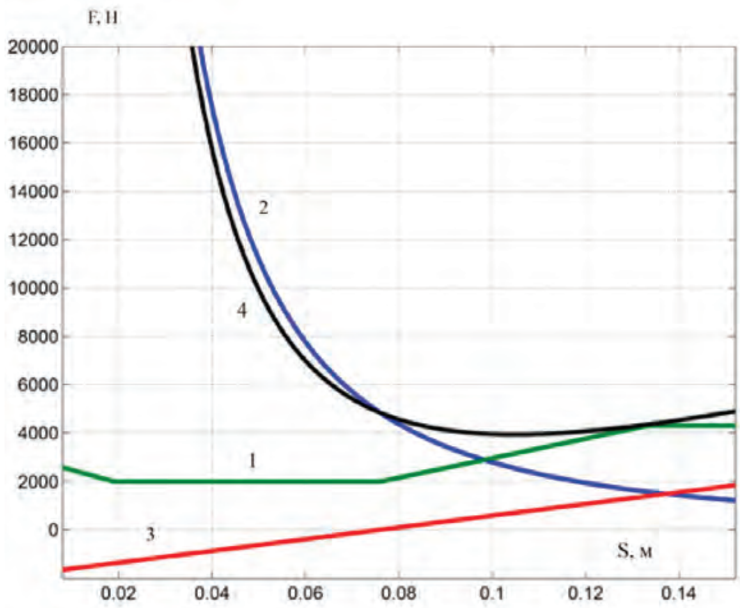

Fig. 6. Characteristic of force distribution of the linear drive of a turnout: 1 — resistance force; 2 — electromagnetic force of the linear motor; 3 — the force of the spring; 4 — the force, applied to the rail points from the side of the linear drive

This approach to development of the mathematical model, based on the simplified determination of electromechanical force, allows us to proceed to implementation of the turnout design.

The proposed design of a turnout (Fig. 2) has a large number of parameters: the diameters of stator and anchor, the sectional area of the coil or dimensions of the spring, etc. Their values can change in a sufficiently wide range. This requires applying optimization, which makes it possible, from the one hand, to minimize the cost of manufacturing the drive itself, and from the other hand, to ensure the necessary traction effort at the switch of a rail point.

The important benefit of such an approach is the fact that all arguments of objective function are calculated for the specific turnout.

Optimization is proposed to perform for the turnout with the rail of the P65 type, 1/11, the commonest one used on the railroads of Ukraine. This will make it possible in the future to optimize parameters of new electric drives on the stage of their development.

The formal formulation of the problem of conditional optimization [16] in a general form comes down to minimization of the objective function $f(\vec{x})$, where $\vec{x}=(x_1,x_2,...,x_N)$ is the vector of variable parameters, with constraints in the form of the equalities $h_i(\vec{x})=0,\ \ i=\overline{1,m}$ and the inequalities $g_j(\vec{x})\le 0,\ \ j=\overline{1,p}$, which determine the permissible area

$$D=\{\vec{x}|\ h_i(\vec{x})=0, i=\overline{1,m}; g_j(\vec{x})\le 0,\ j=\overline{1,p}\}. \qquad (12)$$

Mathematically, the task of conditional optimization is determined as follows:

$$\min_{\vec{x}\in D} f(\vec{x}). \qquad (13)$$

Most frequently, the constraints in the form of inequalities take the form $\vec{a}\le\vec{x}\le\vec{b}$, where $\vec{a}$ and $\vec{b}$ are the vectors of the lower and upper boundaries of the variable parameters, respectively. Such constraints in the space of the variable parameters determine the hyperparallelpiped $D=\{\vec{x}|\ \vec{a}\le\vec{x}\le\vec{b}\}$.

In the selection of the sleeper design of a turnout, the objective function, on the one hand, must connect by mathematical dependencies geometric dimensions of electric drive, and, on the other hand, the forces that interact in the process of the turnout switch. By using a mathematical description of these forces [17], the objective function must take a rather simple form and short computer time of calculation (for example, with the use of the MATLAB environment). Considering the foregoing, it is expedient to accept, as the objective function, the mean-square deviation of the total traction force of the proposed electric drive relative to resistance force, since minimization of this magnitude in a general case contributes to the decrease of metal consumption in the creation of the drive, as well as to obtaining higher performance efficiency both of the motor and the drive as a whole. The mean-square deviation of forces can be written down in the following form

$$\sigma=\sqrt{\frac{\sum_{i=1}^{n}(F_{Ti}-F_{Ci})^2}{n}}, \qquad (14)$$

where F_{Ti} is the i-th summary traction force of electric drive; F_{Ci} is the i-th resistance force; n is the number of calculations.

The projections of the vector of the variable parameters for the examined optimization problem are geometric dimensions of the drive:

$$\vec{x}=\begin{pmatrix}D_K & L_K & D_N & H_{SP} & K_{PR}\end{pmatrix}^T, \qquad (15)$$

where D_K is the diameter of the coil; L_K is the length of the coil; D_N is the diameter of the guide; H_{SP} is the width of the back of the stator; K_{PR} is the rigidity coefficient of the spring.

The diameter of the stator can be determined as follows

$$D_S=2H_{SP}+D_K. \qquad (16)$$

The problem of minimization of the mean-square deviation will be represented as the problem of multi-criteria optimization [18, 19]. For this purpose, at solving the problem of selection of optimal geometric dimensions, we will form a hierarchical sequence of criteria.

The highest priority will be assigned to the criterion, which combines parametric constraints and which characterizes the degree of violation of the hyperparallelpiped D of the permissible area of change in the vector of variable parameters:

$$U_1(\vec{x})=\sum_{i=1}^{5}\left(\max\{0;a_i-x_i\}+\max\{0;x_i-b_i\}\right), \qquad (17)$$

where a_i, b_i are the limiting values of geometric parameters of the motor.

As the problem of optimization calculation is determining geometric dimensions for the purpose of obtaining summary traction force of the drive F_T, the next must be the equality of summary traction force F_T and the set value of resistance force F_C. However, for simplification of the work of optimization procedure, it is more expedient to proceed to the constraints

$$1.01F_C \le F(\bar{x}) \quad (18)$$

and to write down this criterion in the form of penalty function for the violation of this constraint:

$$U_2(\bar{x}) = \max\{0; F(\bar{x}) - 1.01F_C\}. \quad (19)$$

This function evaluates the degree of violation of the assigned resistance force. It is accepted here that the constraint is satisfied if the summary traction force is larger than the assigned resistance force by not less than 1 %.

We assume the last criterion to be the objective function — the mean-square deviation:

$$U_3(\bar{x}) = \sigma(\bar{x}). \quad (20)$$

The three set criteria $U_1(\bar{x})$, $U_2(\bar{x})$, $U_3(\bar{x})$ with regard to their priority are necessary to minimize. The vector function is formed for this

$$F = (U_1(\bar{x}), U_2(\bar{x}), U_3(\bar{x})).$$

When selecting the range of variation of the parameters, it is necessary to obey design peculiarities of the proposed drive. On the one hand, they must be limited in the permissible dimensions by strength, on the other hand, by dimensions of the hollow sleep for the elements of the drive. It is also necessary, after performing optimization, to conduct a draft study with the purpose of determining the axial length of the motor and, consequently, the capacity of its fitting into the assigned assembly volume. Considering the foregoing, the range of variation of the parameters is given in Table 1.

Table 1

Range of variation of the parameters

Parameter	Range of variation
Coil diameter, m D_K	0,1...0,25
Coil length, m L_K	0,2...0,7
Guide diameter, m D_N	0,01...0,03
Stator's back width, m H_{SP}	0,005...0,015
Spring's coefficient of rigidity, N/m K_{PR}	10000...600000

Thus, we selected the parameters and criteria, as well as defined their hierarchy, for solving optimization problem of geometric dimensions of the turnout. The problem is posed of the global multi-criteria optimization of the functions of five real variables [20].

The set problem was solved by different methods: the Hook-Jeeves method (1), the Nelder-Mead method (2), the method of steepest descent (3), the Fletcher-Reeves method (4), the Polak-Ribière method (5), the Newton-Raphson method (6), the Newton method (7), the Weyl method (8), the method of cyclic minimum (9), the Gauss-Seidel method (10), the Powell method (11).

For finding the optimal solution, all the methods indicated above were used with the use of different starting points (maximum, minimum and average values). The results of the search solution are given in Table 2.

Table 2

Result of the search solution for optimization

No. of method	Starting point	Geometry of motor				
		D_K	L_K	D_N	H_{SP}	K_{PR}
1	1	0.1	0.2	0.02	0.015	10000
	2	0.1995	0.4993	0.0195	0.0145	300000
	3	0.2353	0.6853	0.0153	0.0053	600000
2	1	0.1	0.2	0.02	0.015	10000
	2	0.1999	0.5005	0.0198	0.0138	300000
	3	0.2469	0.6958	0.0168	0.005	600000
3	1	0.1	0.2	0.02	0.015	10000
	2	0.1995	0.5	0.0196	0.0143	300000
	3	0.2283	0.6828	0.0157	0.00791	600000
4	1	0.1	0.2	0.02	0.015	10000
	2	0.1995	0.5	0.0196	0.0143	300000
	3	0.2253	0.6798	0.0143	0.0878	600000
5	1	0.1	0.2	0.02	0.015	10000
	2	0.1995	0.5	0.0196	0.0143	300000
	3	0.2131	0.6661	0.01	0.0186	600000
6	1	0.1	0.2	0.02	0.015	10000
	2	0.1995	0.5	0.0196	0.0143	300000
	3	0.2131	0.6661	0.01	0.0186	600000
7	1	0.1	0.2	0.02	0.015	10000
	2	0.1989	0.498	0.0194	0.0142	300000
	3	0.2286	0.6812	0.0168	0.0105	600000
8	1	0.1654	0.5068	0.01371	0.01176	44782
	2	0.1654	0.5068	0.01371	0.01176	44782
	3	0.1654	0.5068	0.01371	0.01176	44782
9	1	—	—	—	—	—
	2	0.1393	0.5327	0.01247	0.01169	47333
	3	0.25	0.2595	0.01	0.00633	68471
10	1	0.1	0.2	0.02	0.015	10000
	2	0.1958	0.2888	0.02	0.015	68475
	3	0.1848	0.288	0.03	0.02	68491
11	1	0.1	0.2	0.02	0.015	10000
	2	0.16	0.5	0.02	0.005	67213
	3	0.1083	0.7	0.03	0.02	42413

As the results demonstrate, obtaining optimal solution largely depends on the starting point. It was noted earlier that reaching any magnitude of the traction force of the motor is possible at different combinations of geometric dimensions. There are cases when the solution was not found at all. This testifies to the set of local minimums, i. e., to the fact that the objective function is multi-extremal. Therefore, the operators of optimization procedure must contain, along with the determined, the stochastic components, capable of reviving the search process with its dying down in the local minimums of relief of the objective function. The trajectories of the search process for optimum point for three variable parameters (D_K, H_{SP}, K_{PR}), with the use of the method of cyclic minimum and the Weyl method, are presented in

Fig. 7, 8, respectively, where a circle designates a starting point and rhombs display optimal solution.

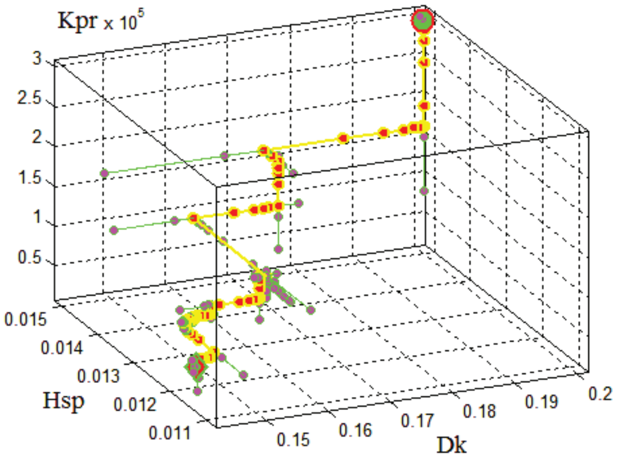

Fig. 7. Trajectories of the search process for optimum point by the method of cyclic minimum

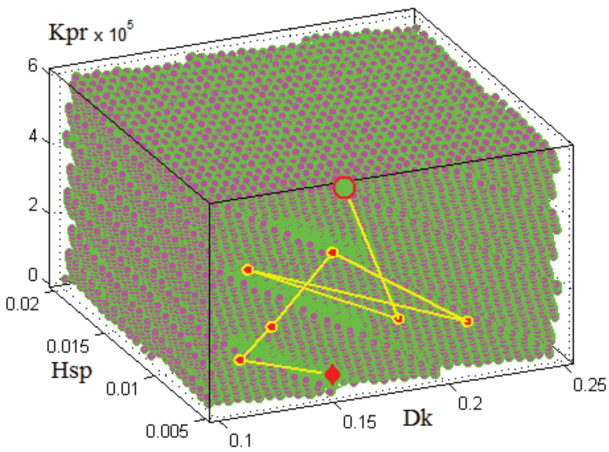

Fig. 8. Trajectories of the search process for optimum point by the Weyl method

The evaluation of optimization solution may be conducted with the aid of the curves of force distribution of the drive at its optimized parameters. In this case, the most appropriate are those parameters, at which the mean-square deviation of the forces $\sigma(\bar{x})$ will be minimal, i. e., the summary traction force will as closely as possible skirt the load curve.

The obtained values of the mean-square deviation of forces at optimization parameters of the linear electric drive are given in Table 3 and the characteristics of force distribution for particular methods are presented in Fig. 9.

Table 3

Values of mean-square deviation of the forces

Optimization method	Mean-square deviation, σ, N
The Hook-Jeeves method	20868
The Nelder-Mead method	20863
The Fletcher-Reeves method	20842
The Newton-Raphson method	20806
The Gauss-Seidel method	2497,2
The Powell method	2450,9
The Weyl method	680,9
The method of cyclic minimum	959

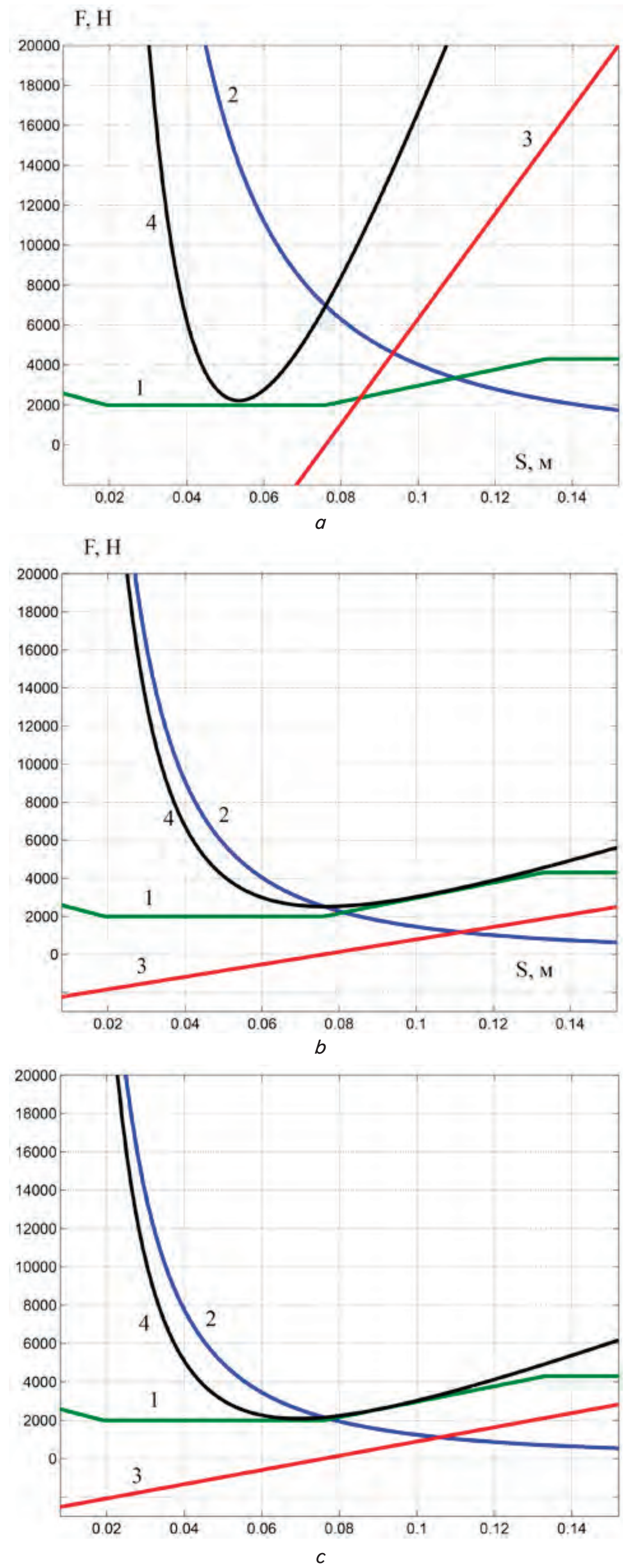

Fig. 9. Characteristic of force distribution of the linear drive: *a* — the Newton-Raphson method; *b* — the method of cyclic minimum; *c* — the Weyl method

In the graphs Fig. 9: 1 — resistance force; 2 — electromagnetic force of the linear motor; 3 — the force of the spring; 4 — the force, applied to the rail points from the side of linear drive.

Table 3 clearly demonstrates that the best results in solving the set optimization problem were displayed by the method of cyclic minimum and the Weyl method.

Thus, the conducted optimization of geometric dimensions of electric drive by the method of cyclic minimum and by the Weyl method made it possible to obtain the required form of the traction characteristic, to decrease expenses for the materials, which, in turn, leads to obtaining the higher performance efficiency of both the motor and the drive as a whole.

The force of the turnout switch depends on the weight of the moving parts of the turnout, the type of rail, the place of fixing conversion thrusts and the coefficient of friction of rail points against the pillows. All the indicated magnitudes, with one exception for the latter, are known, and they are presented in Table 4 for all common types of turnouts.

Table 4

Basic data of switching masses

Rail type	Switching type	Rail point length, m	Rail point weight, N	Number of pillows
P75	1/11	8.3	4150	16
P65	1/9	7	3000	12
P65	1/11	8.3	3600	16
P65	1/18	15.5	6700	28
P65	1/22	18.5	8000	34

Coefficient of friction is a rather uncertain magnitude. It may vary in the range from 0.05 to 0.8 and it depends on various factors, such as: condition of the switcher, quality of the lubricant of the switching pillows, quality of their surfaces treatment, as well as the soles of the rail points, etc.

With the purpose of determining the influence of characteristic of friction and the type of turnout on parameters of the linear electric drive, the optimization study was carried out by the method of cyclic minimum, in the course of which the rigidity of load characteristic and the type of turnout changed. As a result of this study, we obtained characteristics of the change in the optimized parameters, depending on the condition and the type of a turnout in the form of the three-dimensional surfaces, which are shown in Fig. 10.

The graphs show that the result of optimization search for geometric dimensions of the motor, in particular, of dimensions of the coil, depends on the type of a turnout. They change within considerably wide range, especially so with different types of the switcher: diameter of the coil varies from 150 mm to 210 mm and its length – from 300 mm to 600 mm. In this case, the thickness of the stator's back remains practically unchanged, in the range of 11–16 mm. In its turn, coefficient of the spring changes quite strongly in connection to both rigidity of the friction characteristic and to the type of the switcher, and it can accept values from $5 \cdot 10^4$ N/m to $12 \cdot 10^4$ N/m.

Similarly, we carried out multicriterion optimization of geometric dimensions of induction machine (Fig. 3). The following variable magnitudes were accepted as the input data for various methods of optimization: D_d – motor diameter (limits from 190 mm to 210 mm); L_f – length of each coil (limits from 100 mm to 300 mm); D_r – anchor diameter (limits from 50 mm to 100 mm); H_r – anchor walls thickness (limits from 3 mm to 10 mm); H_Z – stator tooth height (limits from 2 mm to 15 mm). A number of teeth N_Z in each section of stator was also different but it depended on the coil length L_f and the anchor walls thickness H_r. The width of the stator tooth W_Z, as well as the width of the intertooth area W_b, were accepted as equal to the anchor walls thickness during calculations.

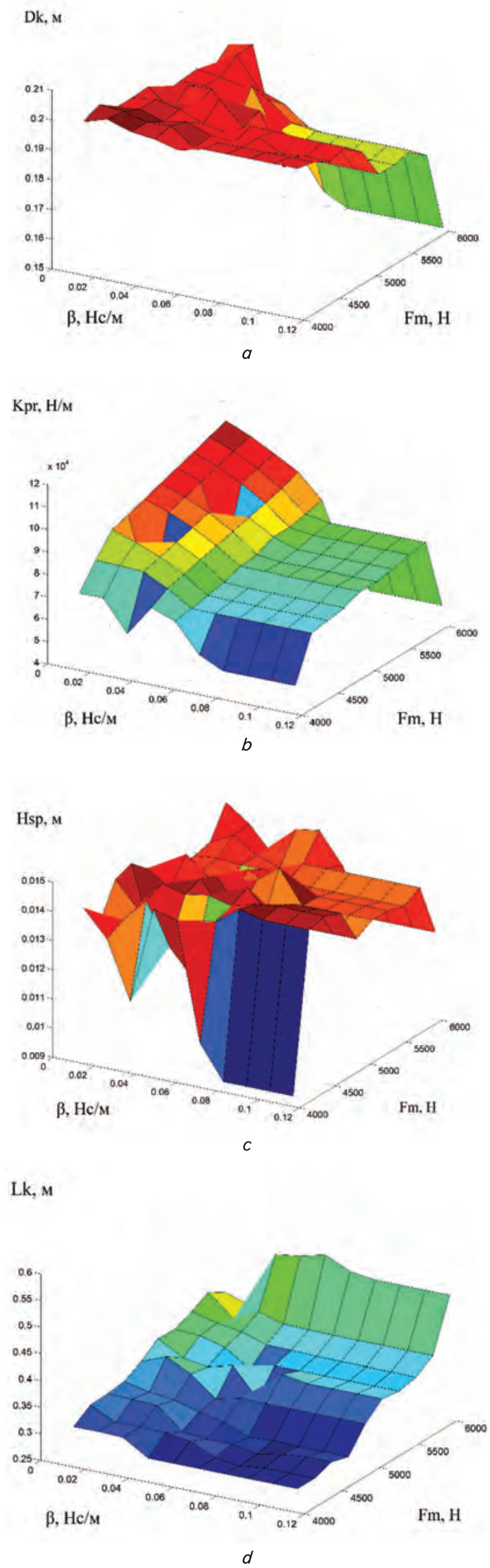

Fig. 10. Surfaces that reflect changes in the optimized parameters: *a* — coil diameter; *b* — coil length; *c* — stator's back width; *d* — rigidity coefficient of the spring

As earlier, the evaluation of results of different methods was performed by the value of the mean-square deviation of forces at optimization parameters of the linear electric drive (Table 5). In contrast to the electromagnet, the best results of optimization were displayed by the method of cyclic minimum.

Table 5

Values of the mean-square deviation of the forces

Optimization method	Mean-square deviation, σ, N
The Nelder-Mead method	18144
The Powell method	1544,9
The Weyl method	1108,2
The method of cyclic minimum	1052,3

As can be seen in Fig. 11, the result of optimization search for geometric dimensions of the motor, as earlier, strongly depends on the type of the turnout and characteristic of friction.

Thus, there is no unique solution of optimization problem of geometric dimensions of a linear electric motor for the existing turnouts, and, therefore, further research and design should be based on the switcher with the P65 type of rail as the most common.

6. Conclusions

1. A fundamentally new design solution of the drive based on two types of the linear electric motor was represented, traction calculation of the acting electromagnetic forces was carried out and the graphs of the distribution of forces in the turnout were built.

Based on the obtained results, we confirmed the possibility of using the proposed types of linear motors in the turnouts, since they provide the required forces on the thrust in the range up to 20 KN. Due to significant simplification of the turnout design, it is possible to reduce the cost of its maintenance during operation, while applying microprocessor technology will make it possible to attain the required traction characteristic.

2. The problem of multicriterion optimization of geometric parameters of the linear motors of a drive was compiled, the special feature of which is the use, as the objective function, of the criterion of mean-square deviation of the summary traction power. The rational method of solving the problem of multicriterion optimization of parameters of motors is determined. The best result in the search for global optimum was demonstrated by the Weyl method (for electromagnet) and the method of cyclic minimum (for induction motor). The estimation was conducted according to results of the optimal (minimal) value of the mean-square deviation of electromagnetic force from the resistance force.

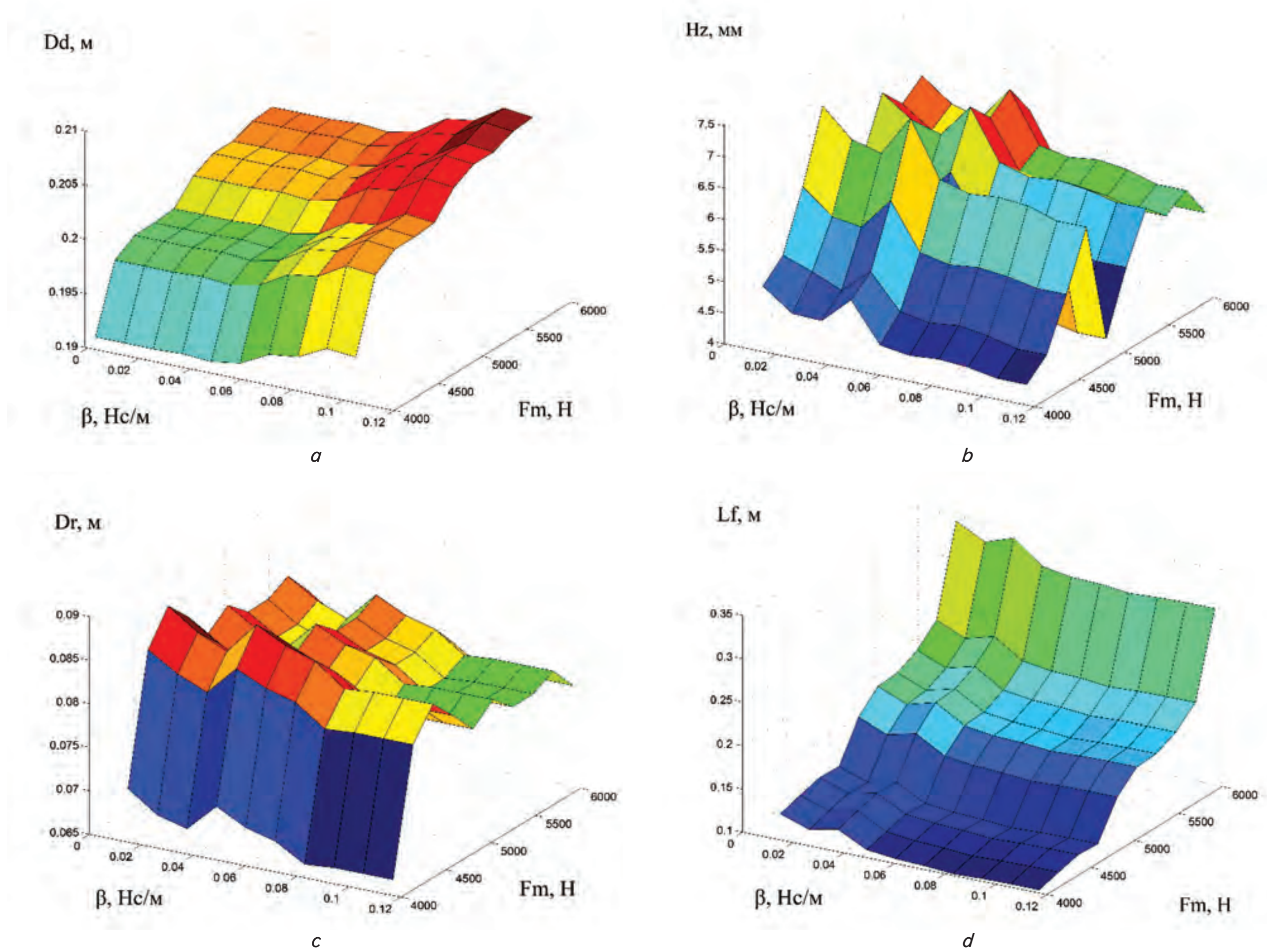

Fig. 11. Surfaces that reflect changes in the optimized parameters: *a* — motor diameter; *b* — anchor diameter; *c* — stator's tooth height; *d* — coil length

The optimum traction characteristics of the electromagnet were determined based on the simplified model for determining the electromagnetic force, which make it possible to provide the required force at working traction of 20 KN.

3. We obtained results of optimization search for geometric dimensions of the motor, in particular, sizes of the coils, which strongly depend on the type of a turnout. They change within quite a wide range, especially so with different types of the switcher. Diameter of a magnet coil varies from 150 mm to 210 mm, and its length — from 300 mm to 600 mm. In this case, thickness of the stator's back remains practically unchanged, in the range of 11–16 mm. In its turn, coefficient of the spring quite strongly changes in relation to both the rigidity of the friction characteristic and to the type of a switcher, and it can accept values from $5\cdot10^4$ N/m to $12\cdot10^4$ N/m. It should be noted for the induction motor that at sufficiently wide range of the stator's teeth heights, its optimum value is within the limits from 3.5 to 6.5 mm.

References

1. Maslyi, Ar. S. Razrabotka elektropryvoda strelochnoho perevoda s ventylno-ynduktornym elektrodvyhatelem y yssledovanye na matematycheskoi modely rezhymov eho raboty [Text] / Ar. S. Maslyi, S. H. Buriakovskyi, A. D. Petrushyn, An. S. Maslyi // Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». — 2013. — Vol. 36. — P. 198–201.
2. Smyrnov, V. V. Rehulyruemyi strelochnyi elektropryvod [Text] / V. V. Smyrnov, S. G. Buriakovskyi // Mizhnarodnyi informatsii naukovo-tekhnichnyi zhurnal «Lokomotyv-inform». — 2010. — Vol. 7. — P. 8–9.
3. Kornienko, V. V. Vy'sokoskorostnoj e'lektricheskij transport. Mirovoj opy't [Text] / V. V. Kornienko, V. I. Omel'yanenko. — Nacional'ny'j tekhnicheskij universitet «Khar'kovskij politekhnicheskij institut», 2007. — 159 p.
4. Lyubars'kyij, B. G. Optymizatsiia parametriv liniinoho dvyhuna nakhylu kuzova transportnykh zasobiv [Text] / B. G. Lyubars'kyij, B. Kh. Yeritsian, D. I. Yakunin, M. L. Hliebova // Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». — 2015. — Vol. 41. — P. 58–66.
5. Hovorukha, V. V. Proektyrovanye y vnedrenye strelochnikh perevodov dlia hornikh predpryiatyi [Text] / V. V. Hovorukha // Sbornyk Donetskoho Natsyonalnoho tekhnycheskoho unyversyteta. — 2008. — Vol. 16, Issue 142. — P. 57–66.
6. Kondratenko, S. L. Avtoperekliuchatel strelochnoho elektropryvoda. Avtomatyka y telemekhanyka zheleznikh doroh Rossyy [Text] / S. L. Kondratenko // Tekhnyka, tekhnolohyia, sertyfykatsyia. — 2011. — Vol. 1. — P. 114–119.
7. EBI Switch 2000. Company BOMBARDIER. Available at: http://www.bombardier.com/content/dam/Websites/bombardiercom/supporting-documents/Sustainability/Reports/BT/Bombardier-Transportation-EPD-EBI-Switch-2000-en.pdf
8. Liudvanavicius, L., Dailydka, S., Sladkowsky, A. (2016). New possibilities of railway traffic control systems. Transport Problems, 11(2), 133–142. doi: 10.20858/tp.2016.11.2.13
9. Wang, P. Design of High-Speed Railway Turnouts. Available at: http://www.sciencedirect.com/science/book//9780323396172?via%3Dihub
10. Pat. 95497 Ukrayina: MPK(2014.01) B61L 5/00. Elektropryvid strilochnogo perevodu [Text] / Zharinova A. G. — Zayavnyky ta patentovlasnyky Buryakovskyj S. G., Maslij A. S., Maslij A. S. — # u201407676; declareted: 08.07.14; published: 25.12.14, Byul. 24. — 4 p.
11. Poliakov, V. O. Analysis and synthesis of the dynamics of electrodynamic trains with linear motor [Text] / V. O. Poliakov, M. M. Khachapuridze // Nauka ta progres transportu. — 2007. — Vol. 15. — P. 159–166.
12. Alongea, F. Adaptive feedback linearizing control of linear induction motor considering the end-effects [Text] / F. Alongea, M. Cirrincioneb, F. D'Ippolitoa, M. Puccic, A. Sferlazza // Control Engineering Practice. — 2016. — Vol. 55. — P. 116–126. doi: 10.1016/j.conengprac.2016.06.018
13. Ganji, B. Analysis and modeling of different topologies for linear switched reluctance motor using finite element method [Text] / B. Ganji, M. H. Askari // Alexandria Engineering Journal. — 2016. — Vol. 5. doi: 10.1016/j.aej.2016.07.017
14. Yvanchenko, F. K. Dynamyka metallurhycheskykh mashyn [Text] / F. K. Yvanchenko, V. A. Krasnoshapka. — Moscow: Metallurhyia, 1983. — 295 p.
15. Buriakovskyi, S. H. Matematycheskaia model elektropryvoda strelochnoho perevoda s uchetom kharakterystyky trenyia [Text] / S. H. Buriakovskyi, V. V. Smyrnov // Visnyk natsionalnoho tekhnichnoho universytetu «Kharkivskyi politekhnichnyi instytut». — 2008. — Vol. 30. — P. 329–330.
16. Altaev, V. Y. Optymyzatsyia v tekhnyke [Text] / V. Y. Altaev, V. Y. Motoryn. — Moscow: Myr, 1986. — 350 p.
17. Reznykov, Y. M. Strelochnye elektropryvody elektrycheskoi y horochnoi tsentralyzatsyy [Text] / Y. M. Reznykov. — Moscow: Transport, 1975. — 152 p.
18. Shtoier, R. Mnohokryteryalnaia optymyzatsyia [Text] / R. Shtoier. — Moscow: Radyo y sviaz, 1992. — 504 p.
19. Weise, T. Global optimization algorithms theory and application [Text] / T. Weise. — E-Book, 2008. — 820 p.
20. Severyn, V. P. Metodi mnohomernoi bezuslovnoi mynymyzatsyy [Text] / V. P. Severyn — Nacional'ny'j tekhnicheskij universitet «Khar'kovskij politexnicheskij institut», 2013. — 160 p.