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**МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ДЕРЖАВНИЙ УНІВЕРСИТЕТ ІНФРАСТРУКТУРИ ТА
ТЕХНОЛОГІЙ**

**ЗБІРНИК
НАУКОВИХ ПРАЦЬ
ДЕРЖАВНОГО УНІВЕРСИТЕТУ
ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ**

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І ТЕХНОЛОГІЇ»**

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Creation of a model of automated traction control of shunting locomotives by using artificial intelligence methods

In the paper, a mathematical model of the automated traction transmission control system of the shunting locomotive was developed, using methods of fuzzy logic and the method of expert evaluations. The Mamdani algorithm was used for the proposed model. The algorithm includes the knowledge base of an intelligent system, which uses a production model to formalize and represent knowledge in memory, combining elements of logical and network management approaches. The resulting automated traction transmission control model of the shunting locomotive offers its optimal driving mode for a specific train and section. The model uses the generated fuzzy knowledge base. The result of the model calculation is a control signal for the movement of the shunting locomotive on 4 motors, using partially the 3rd and fully the 4th and 5th positions of the driver's controller. This mode of movement allows to reduce fuel consumption for shunting of the locomotive with partial loads on the traction electric transmission.

Keywords: railway transport, rolling stock, diesel locomotive, traction electric transmission, Mamdani method.

Introduction. The development of railway transport requires constant improvement of locomotive management methods, in particular, shunting locomotives, which play an important role in the organization of railway transport. Efficient use of locomotives is a major task for railways. For the years 2021-2023, the main operating indicators of railway transport have significantly deteriorated: freight traffic, passenger traffic, average daily locomotive productivity. The operating fleet of shunting locomotives has exaggerated its average age by almost 40 years. Operating diesel locomotives during shunting work mostly use partial load modes. To improve operating conditions, it is necessary to carry out modernization and introduce new modern methods of automated control and diagnostics of locomotives.

Analysis of recent research and problem statement. In the materials of the international conference [1], the methods and prospects of using artificial intelligence in railway transport were considered. The paper [2] presents the theoretical rationale for the development of a knowledge base for intelligent locomotive DSS. The approach and structure of the self-learning system of intelligent DSS is proposed, the advantage of which is the presence of a fuzzy classifier that works according to the set criteria and determines a fuzzy image of the current train situation. The works [3 ,4] propose an approach to intelligent operation of trains based on a combination of expert knowledge and data mining algorithms,

also investigated the operation of the urban rail transport system (URTS) with the support of machine learning (ML), including obstacle perception, infrastructure perception, passenger flow forecasting, forecasting train delays, failure forecasting, remaining service life forecasting, train operation and control optimization, train dispatch optimization and train ground communication optimization. The article [5] discusses the general control algorithms of the automatic train control system, namely: control using artificial neural network algorithms and fuzzy control using a fuzzy controller, which is an important part of the whole system, which consists of fuzzification, defuzzification, knowledge base and fuzzy conclusion. In the study [6], the technology of fuzzy forecasting is used to ensure effective operating conditions of rolling stock. Analysis of foreign articles [7, 8] reveals the essence of energy modeling of railway transport. Locomotive traction force simulations are a fundamental part of such models. In the article [9], the structure of an intelligent decision support system for locomotives is developed. Formal indicators of the quality of the train management process were obtained. The work theoretically substantiates the definition of weighting factors for each partial criterion of management quality. The study [10] presents a systematic review of the literature on the current state of artificial intelligence in railway transport, covering maintenance, automatic control of rolling stock, traffic safety. In [11], an efficient analysis method based on fuzzy data and fuzzy thinking is proposed for large volumes of data of China's high-speed train control system. In work [12], a mathematical model was developed for determining the traction and energy indicators of the ChME3 shunting locomotive when working on four and two parallel-connected traction electric motors. As a result of the use of various options for connecting the TM, it is possible to save fuel for maneuvering work at partial loads, depending on the operating conditions.

Analyzing the above literature, it can be noted that the process of controlling locomotives using artificial intelligence methods is in a stage of constant development. The advantages of the works include the prepared theoretical base for the creation of intelligent management systems. In each work, the factors that affect the movement of the locomotive and the control signals necessary for individual elements of the control system are investigated. Among the shortcomings should be attributed: the lack of consideration of the work of each of the elements of traction electric transmission of locomotives separately, for the possibility of creating an adequate fuzzy knowledge base of the automated control system; inflexibility of systems that are designed for a specific type of locomotive and use a limited knowledge base.

Having considered the disadvantages and advantages of the above works, it is possible to say that the most promising methods for creating a model of automated control of traction transmission of a shunting locomotive at partial loads are methods of fuzzy logic. One of the most convenient programming tools in the field of fuzzy logic is the Fuzzy Logic (MATLAB) environment. To create the model, the Mamdani method [13] is used, whose activity diagram consists of the formation of the base and rules, fuzzification, aggregation of preconditions, activation of subassembly, accumulation of conclusions, and defuzzification.

The purpose and tasks of the study. The main purpose of the research is the development of a mathematical model of automated traction control of shunting locomotives by using artificial intelligence methods. To solve this problem, it is proposed to use methods of fuzzy logic, in particular, the Mamdani algorithm. With the help of the algorithm, a fuzzy knowledge base and a scheme of automated control of traction transmission of a shunting locomotive are formed. The quality of the system directly depends on the structure, content and management algorithms of the knowledge base. The main functions of knowledge bases include: collecting and analyzing information, creating and storing rules, as well as the possibility of self-learning and adaptation [14, 15, 16].

Research Objectives.

1. Develop the structure and operational algorithm for a fuzzy knowledge base of the intelligent traction transmission control system of the shunting locomotive.
2. Perform fuzzification of the model's input data using fuzzy logic methods.
3. Design a structural diagram of an automated traction transmission control system of the shunting locomotive with self-learning capabilities.

Materials and methods of research. To date, intelligent control systems have received significant development in technology [17, 18, 19]. Intelligent control systems are systems that are able to «Understand» and learn, taking into account the object of control, the external environment and operating conditions. The main difference between such systems is the presence of a mechanism for complex knowledge processing. A key architectural feature that distinguishes intelligent control systems from traditional control systems is the ability to acquire, store, and process knowledge to perform control functions. Intelligent systems based on methods of fuzzy logic, artificial neural networks and genetic algorithms are increasingly used in various industries, including railway transport. These technologies make it possible to create more adaptive, reliable and efficient systems that are able to better respond to changing conditions and uncertainties than traditional control methods [20, 21].

The creation of intelligent control systems is based on two main principles of Fig. 1.

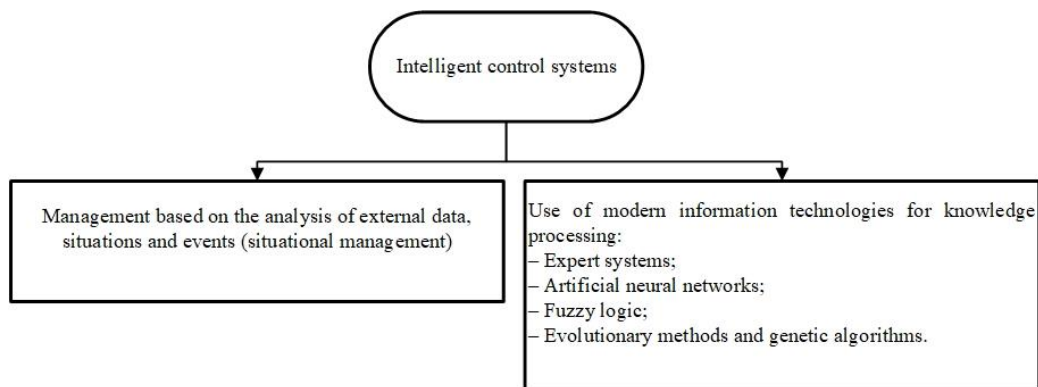


Fig. 1. Basic principles of creating an intelligent control system

The concept of intelligence involves:

- the ability to work with formalized human knowledge (as in the case of expert systems and fuzzy logic);
- the use of human learning and thinking methods (as in artificial neural networks and genetic algorithms).

The quality of work of artificial intelligence systems directly depends on the structure, content and algorithms of knowledge base management. The main functions of knowledge bases include: collecting and analyzing information, creating and storing rules, as well as the possibility of self-learning and adaptation. In addition, the integration of new data, its validity, and the effective use of information for decision-making are important aspects.

For intelligent automated control of traction electric transmission of a shunting locomotive, the following system with the possibility of self-learning is proposed, shown in Fig. 2.

Self-learning is a complex of methods and algorithms for setting up and functioning of automated control systems for traction transmission of shunting locomotives [2, 9].

The Mamdani algorithm is used to create the system. The algorithm works according to the "black box" principle [13]. In the intermediate stages, the apparatus of fuzzy logic and the theory of fuzzy sets are used. Due to the use of fuzzy systems, it is possible to manipulate the usual numerical data, but to use the flexible possibilities that fuzzy inference systems provide. It is implemented due to the rules (Rule), which consist of conditions (Condition) and conclusions (Conclusion), which in turn are fuzzy statements (Statement). A fuzzy statement includes a linguistic variable (Variable) and a term that is represented by a fuzzy set (Fuzzy Set). A membership function is defined on the fuzzy set, the value of which can be obtained using the `getValue()` method. This is a method defined in the `FuzzySet` interface. When performing the algorithm, it will be necessary to use the "activated" fuzzy set (Activated Fuzzy Set), which in a certain way redefines the membership function of the fuzzy set (`FuzzySet`). The algorithm also uses the union of fuzzy sets (Union of Fuzzy Sets). A union is also a fuzzy set and therefore has a membership function (defined by `FuzzySet`). The Mamdani Algorithm (Mamdani

Algorithm) includes all stages and uses a rule base (List<Rule>) as input data. Also, the algorithm provides for the use of "activated" fuzzy sets (ActivatedFuzzySet) and their unions (UnionOfFuzzySets).

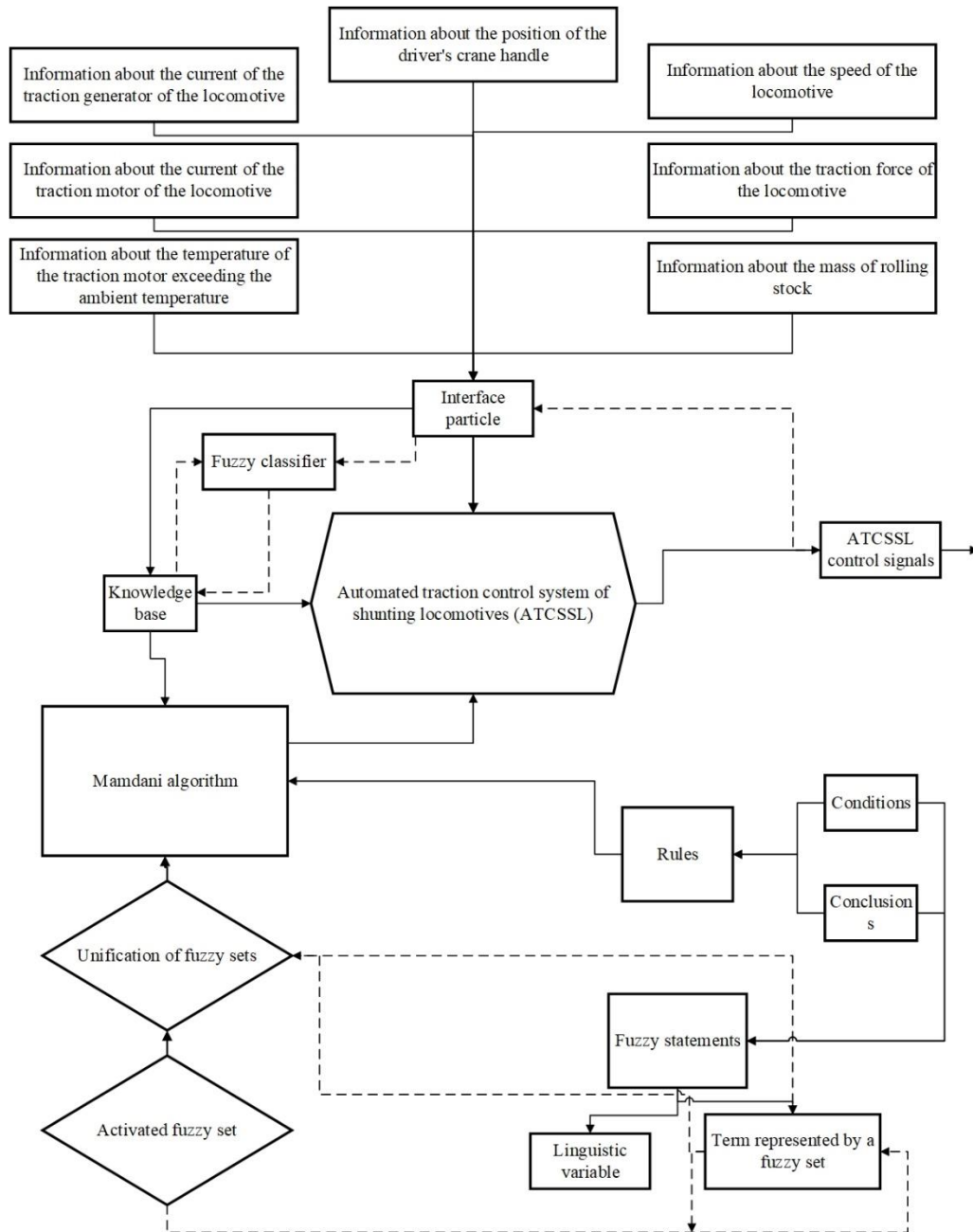


Fig. 2. Automated traction control system of a shunting locomotive (ATCSSL)

Before moving on to the operation of the algorithm itself, it is necessary to familiarize yourself with the following definitions:

A fuzzy variable has the following form:

$$\langle \alpha, X, A \rangle, \tag{1}$$

where α – the name of the fuzzy variable;
 X – the definition area of the fuzzy variable;

A – the fuzzy set on the universe X.

The linguistic variable has the following form:

$$\langle \beta, T, X, G, M \rangle, \quad (2)$$

where β – the name of the linguistic variable;

T – the set of its values (terms);

X – the universe of fuzzy variables;

G – the syntactic procedure for creating new terms;

M – the semantic procedure that forms fuzzy sets for each term of a given linguistic variable.

Let's call a fuzzy expression an expression of the form:

$$\langle \beta \text{ IS } \alpha \rangle, \quad (3)$$

where β – the linguistic variable;

α – one of the terms of the variable.

Formation of the rule base of the Mamdani algorithm.

A rule base is a set of rules, where each sub-conclusion corresponds to a certain weight factor.

The rule base can look like this (for example, rules of different constructions are used):

$$\begin{aligned} \text{RULE_1: } & \text{IF } \langle \text{Condition_1} \rangle \text{ THEN } \langle \text{Conclusion_1} \rangle (F_1) \text{ AND } \langle \text{Conclusion_2} \rangle (F_2) \\ \text{RULE_2: } & \text{IF } \langle \text{Condition_2} \rangle \text{ AND } \langle \text{Condition_3} \rangle \text{ THEN } \langle \text{Conclusion_3} \rangle (F_3); \\ & \dots \\ \text{RULE_n: } & \text{IF } \langle \text{Condition_k} \rangle \text{ THEN } \langle \text{Conclusion_}(q-1) \rangle (F_{q-1}) \text{ AND } \langle \text{Conclusion_}q \rangle (F_q), \end{aligned} \quad (4)$$

where F_i - the weighting coefficients, which mean the degree of confidence in the truth of the received sub-conclusion ($i=1,2, \dots, q$), where q – the total number of sub-conclusions in the rule base. By default, the weighting factor is assumed to be equal to 1.

Linguistic variables present in the conditions are called inputs, and in the conclusions, they are called outputs.

Fuzzification of input variables by the Mamdani algorithm.

This stage is often called blurring. The generated rule base and array of input data $A = \{a_1, a_2, \dots, a_m\}$, are input, where m – the number of input variables. This array contains the values of all input variables. The purpose of this stage is to obtain truth values for all preconditions from the rule base. It happens as follows: for each of the preconditions there is a value $b_i = \mu(a_i)$, where $\mu(a_i)$ – the membership function for the fuzzy set. In this way, a set of b_i values ($i = 1, 2, \dots, k$) is obtained, where k is the total number of preconditions in the rule base. The array of input data is formed in such a way that the i -th element of the array corresponds to the i -th input variable (the variable number is stored in the integer field "id").

Aggregation of sub-conditions by the Mamdani algorithm.

As already mentioned above, the condition of the rule can be complex, that is, include sub-conditions connected with each other using the logical operation "AND". The purpose of this stage is to determine the degree of truth of the conditions for each rule of the fuzzy inference system. For each condition, it is possible to find the minimum truth value of all its sub-conditions. Formally, it looks like this:

$$c_j = \min \{b_i\}, \quad (5)$$

where $j=1, 2, \dots, n$ (n – the number of fuzzy production rules);

i – the number from the set of numbers of sub-conditions in which the j -th input variable participates.

Activation of sub-conclusions.

At this stage, there is a transition from conditions to sub-conclusions. For each sub-conclusion there is a degree of truth $d_i = c_i \cdot F_i$ where $i = 1, 2, \dots, q$. Then, a set with a new membership function is assigned to each i -th sub-conclusion. Its value is determined as a minimum from d_i and the value of the membership function of the term from the sub-conclusion. This method is called min-activation, which is formally written as follows:

$$\mu_i^{\wedge}(x) = \min \{d_i, \mu_i(x)\}, \quad (6)$$

where $\mu_i^{\wedge}(x)$ – the "activated" membership function;

$\mu_i(x)$ – the term membership function;

d_i – the degree of truth of the i -th sub-conclusion.

Accumulation of conclusions.

The goal of this stage is to obtain fuzzy sets (or their union) for each of the output variables. This is done as follows: the i -th output variable is assigned a union of sets $E_i \cup D_j$ where j - the number of sub-inferences in which the i -th output variable ($i = 1, 2, \dots, s$) participates, where s is the number of input variables. The union of two fuzzy sets is represented as a third fuzzy set with the following membership function:

$$\mu_i^{\vee}(x) = \max \{\mu_1(x), \mu_2(x)\}, \quad (7)$$

where $\mu_1(x), \mu_2(x)$ – the membership functions of the combined sets.

Defuzzification of output variables.

The purpose of defuzzification is to obtain a quantitative value (crisp value) for each of the original linguistic variables [13]. The i -th output variable and the set E_i ($i = 1, 2, \dots, s$) belonging to it are considered, where s is the number of input variables. Then, using the defuzzification method, the final quantitative value of the output variable is found. In this implementation of the algorithm, the method of the center of gravity (center of gravity) is used, according to which the value of the i -th output variable is calculated according to the formula:

$$y_i = \frac{\int_{min}^{max} x \cdot \mu_i(x) dx}{\int_{min}^{max} \mu_i(x) dx}, \quad (8)$$

where $\mu_i(x)$ – the membership function of the corresponding fuzzy set E_i ;

min and max – the boundaries of the universe of fuzzy variables;

y_i – the defuzzification result.

The management process is as follows. Information about the locomotive enters the interface part. From the interface part, the information is divided into two streams. The first is a knowledge base designed to accumulate information about the traction transmission management of a diesel locomotive. The second is a fuzzy classifier (FC). FC is a fuzzy knowledge base, the input of which is provided with information about the current state of traction rolling stock. An external knowledge base is used for training (creating and clarifying the rules of a fuzzy knowledge base), which displays the spectrum of control signals depending on the current train situation. It was created based on the results of real trips in the "Darnytsia" locomotive depot and shows how drivers controlled rolling stock. At the output of

the classifier, there are the control signals generated in accordance with the rules of the fuzzy knowledge base.

The task of the Mamdani algorithm is to generate a control signal for the automated traction control system of the shunting locomotive (ATCSSL). The system, analyzing data on the state of the parameters affecting the train movement, generates control signals that are most appropriate in the current situation (that is, recommendations for controlling the traction transmission of the locomotive).

The control signal of the ATCSSL system is supplied to the motor shutdown units, which operate on the basis of thyristors.

According to the train situation, current will flow through the motor shutdown units to the traction electric motor shutdown contacts, and then to the coils of the train contactors. Based on this, the traction generator receives excitation after turning on the train contactors and supplies current to the power circuit. The current flowing through the windings of the traction electric motor creates a torque on the motor armature shafts, which is transmitted to the wheel pairs of the diesel locomotive through the traction reducers.

According to Fig. 1, FC contacts the knowledge base, which contains and updates information about the actual actions of drivers during train movement [2]. Based on these data, a training sample of M input-output pairs is formed:

$$(X_r, Y_r), r = \overline{1, M}, \quad (9)$$

where X_r – the vector of information features of the object of classification;

$Y_r \in (t_1, t_2, \dots, t_c)$ where (t_1, t_2, \dots, t_c) – the decision classes;

$r = \overline{1, M}$ – the r-th line of sample M.

Let's introduce the following notations:

P – the vector of the parameters of the membership functions of fuzzy terms of the knowledge base (9);

W – the vector of weight coefficients of knowledge base rules;

$F(K, X_r) \in (t_1, t_2, \dots, t_c)$ – the result of classification based on a fuzzy base with parameters

$K = (P, W)$ at the input value X_r from the r-th line of the sample (9).

Learning a fuzzy classifier consists in finding the vector K that minimizes the distance between the results of the logical conclusion and the experimental data. Let's consider the method of calculating this distance, which is called the learning criterion [2, 9]. The distance between the desired and actual behavior of the model can be determined by the accuracy of the classification on the training sample. Then training the fuzzy classifier

$$\frac{100\%}{M} \sum_{r=1, M} \Delta_r(K) \rightarrow \min, \quad (10)$$

$$\text{where } \Delta_r(K) = \begin{cases} 1, & \text{if } y_r \neq F(K, X_r) \\ 0, & \text{if } y_r = F(K, X_r) \end{cases} \text{ – object classification error } X_r.$$

The advantages of this criterion are its simplicity and clear meaningful interpretation. The percentage of errors is often used as a criterion for training various pattern recognition systems [9]. The objective function (10) takes discrete values, which makes it difficult to use fast gradient optimization methods, especially for small training samples.

To determine the management actions that must be implemented in a specific train situation, it is necessary to form a database [12]. An example of such a format can be the database shown in Table 1.

Table 1. An example of a database

Frame #	Values characterizing the mode of train movement						Regulation of control bodies			
	Mass of the composition, t	Traction force, kN	Speed, km/h	Traction generator current, A	TM current, A	The temperature of excess above the TM surrounding environment, °C	Operator's controller handle position	Crane handle item No. 395 position	Crane handle item No. 254 position	The number of connected TMs
1	763	187.8	1.8	1619	809	3	4	2	2	4
2	763	171.5	2.6	1513	757	5	4	2	2	4
3	763	157.7	3.3	1422	711	7	4	2	2	4
4	763	145.9	3.9	1342	671	9	4	2	2	4
5	763	135.7	4.5	1272	636	11	4	2	2	4
6	763	126.8	5.1	1210	605	13	4	2	2	4
7	763	118.9	5.6	1154	577	14	4	2	2	4
8	763	112.0	6.0	1104	552	16	4	2	2	4
9	763	105.8	6.5	1059	529	17	4	2	2	4
10	763	100.3	6.9	1018	509	18	4	2	2	4
11	763	95.4	7.3	980	490	20	4	2	2	4
12	763	90.9	7.7	946	473	21	4	2	2	4
13	763	86.8	8.1	915	457	22	4	2	2	4
14	763	83.1	8.4	886	443	23	4	2	2	4
15	763	79.7	8.7	859	429	24	4	2	2	4
16	763	76.6	9.1	834	417	25	4	2	2	4
17	763	73.8	9.4	811	405	26	4	2	2	4
18	763	71,2	9,6	789	394	27	4	2	2	4
19	763	68.7	9.9	769	384	28	4	2	2	4
20	763	66.5	10.2	750	375	29	4	2	2	4
21	763	64.4	10.4	732	366	29	4	2	2	4
22	763	62.5	10.7	715	357	30	4	2	2	4
23	763	60.7	10.9	699	350	31	4	2	2	4
24	763	59.0	11.2	684	342	32	4	2	2	4
25	763	57.4	11.4	670	335	32	4	2	2	4

Let's design an automated control system for traction electric transmission of a shunting locomotive with the following inputs:

- 1 – composition mass;
- 2 – traction force;
- 3 – speed;
- 4 – traction generator current;
- 5 – traction motor current;
- 6 – temperature rise of the traction electric motor above the surrounding environment;

For inputs, it is necessary to perform phasing. In the section «Required position of control bodies», the signals «Operator's controller handle position», «Crane handle item No. 395 position», «Crane handle item No. 254 position» and «Number of connected TMs» should be implemented as distinct sets. On the basis of Table 1, a fuzzy knowledge base of the form of Table 2 is formed.

Table 2. Knowledge base example

Rule #	The value of the signal level at the input						Required position of the controls			
	1	2	3	4	5	6	Operator's controller handle position	Crane handle item No. 395 position	Crane handle item No. 254 position	The number of connected TMs
1	middle	low	very_low	low	high	middle	position is 4ps	position is 2	position is 2	nted is 4ted
2	middle	middle	very_low	middle	high	middle	position is 4ps	position is 2	position is 2	nted is 4ted
...
n	middle	very_high	very_high	very_high	high	middle	position is 4ps	position is 2	position is 2	nted is 4ted

The number of rules n in the knowledge base is determined by the number of all possible combinations of input signal levels. For each variant, its own combination of signals is formed at the input, which go to the control bodies.

The self-learning process consists in the fact that during the movement of the train, a periodic survey of the values of the input signals and the signals of the number of connected TMs is performed. The current value of the signals from the control bodies for this rule is compared with the values in the knowledge base. Next, the section of the knowledge base «Number of TMs connected TMs» is adjusted taking into account the new experience gained during movement.

For the formalization and presentation of knowledge in the memory of information systems, there are a number of models that can be structured as follows:

- Logical models – use formal logical systems, where knowledge is presented in the form of facts and rules, with the help of which conclusions are made. They are based on logical operators and form the basis for building logical conclusions.
- Network models – represent knowledge in the form of graphs or networks, where nodes correspond to objects, and edges between them reflect relations. An example can be a semantic network that illustrates the relations between concepts.
- Frame models – knowledge is organized in the form of frames, which are data structures for representing stereotyped situations. The frame contains slots corresponding to the attributes of the object and values describing the state of the object. Frames are useful for modeling knowledge in the context of situations or scenarios.
- Production models – use a set of "if" rules (productions) that determine which actions should be performed under certain conditions. These rules allow to draw conclusions and make decisions based on the available information.

Each of the models of knowledge representation in artificial intelligence has its limitations and shortcomings.

A production model combining elements of logical and network approaches is used for the task of controlling the traction transmission of a shunting locomotive. From logical models, the concept of inference rules, which are called products, is borrowed, and from network models – the representation of knowledge in the form of a semantic network.

A semantic network (Fig. 3) is a form of graphical representation of knowledge, where nodes represent objects or concepts, and edges between nodes reflect relations between these objects or concepts. This structure allows to visually represent and model knowledge, establish edges and draw logical conclusions.

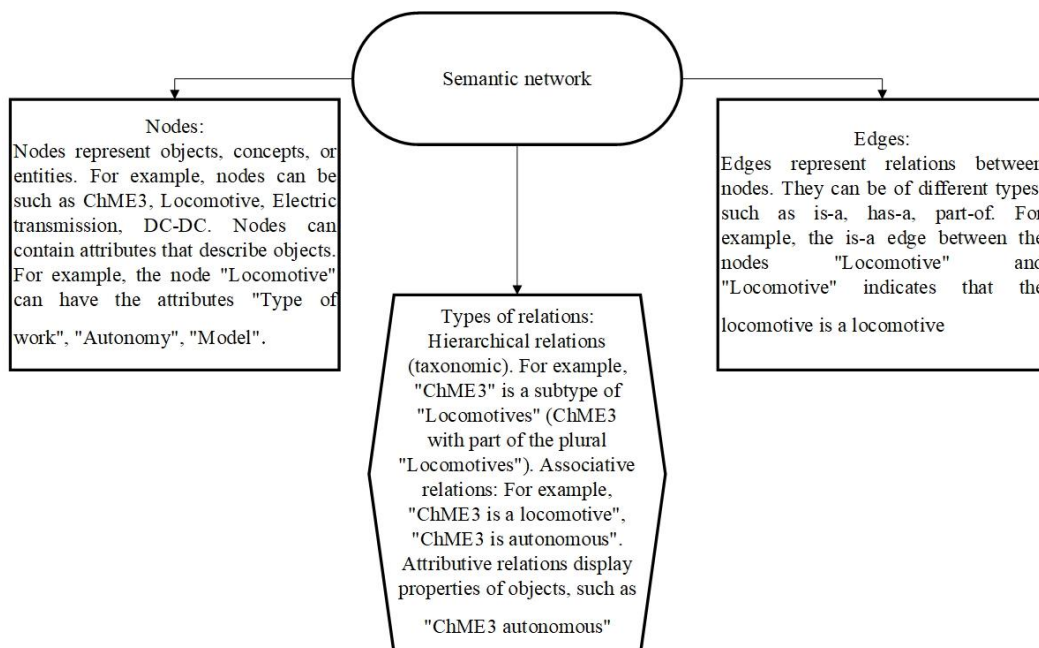


Fig. 3. Basic elements of the semantic network

In general, the production model can be presented in the following form:

$$N = \langle A, U, C, I, R \rangle, \tag{11}$$

where N – the name of the product;
 A – the scope of product application;
 U – the condition of product use;
 C – the product core;
 I – the post-conditions of products, which are actualized in case of positive sales of products;
 R – the comment, informal explanation (justification) of products, time of entry into the knowledge base, etc.

To design the knowledge base of traction transmission control of a shunting locomotive, it is necessary to determine the parameters U, C, I. Parameter A will be the same for all products belonging to the base being designed, and parameter R does not directly participate in the operation of the system and is auxiliary.

The product core can be presented in the following form:

$$C = (z_{j1} \& z_{j2} \& \dots \& z_{ji} \Rightarrow d_{j1} \& d_{j2} \& \dots \& d_{ji}), \quad (12)$$

where $z_{j1}, z_{j2}, \dots, z_{ji}$ – the value of the conditions;

$d_{j1}, d_{j2}, \dots, d_{ji}$ – the value of actions.

For each serial number of the conditions, a set of values is defined during the design of the base, i.e. $z_{ji} \in Z_i$.

For example, there is a set of conditions Z_k – «Tractive force». In the process of designing the base, it is determined that the values given in Table 3 should be entered into this set. In fact, the values of the elements of the set given in Table 3 are fuzzy linguistic variables. Therefore, their acquisition is completely determined by the methods of fuzzy logic.

The use of linguistic values makes it possible to design the base using the usual language of communication, which greatly simplifies both the design process itself and the analysis of the system's performance.

Table 3. Value of the «Traction force» set

Designation of the element of the set	The value of the element of the set
Z_{1k}	"very low"
Z_{2k}	"low"
Z_{3k}	"middle"
Z_{4k}	"high"

However, there are also such sets where the use of fuzzy variables is impossible. To describe the set "Operator's controller handle position" in the knowledge base, the following values are used: «1st position», «2nd position», «3rd position», «4th position», «5th position», «6th position», «7th position», «8th position»; the set «Crane handle item No. 254 and No.395 position» consists of one position «2-train», if necessary, the set can be expanded to include all braking positions of the cranes; the set «Number of connected TMs» has three positions: «Work for 2 TMs», «Work for 4 TMs», «Work for 6 TMs». The given values are formal and the signals from the corresponding sensors are used in the base without transformations.

Similarly, to the description of the conditions, for each sequence number of the action, a set of values is defined during the design of the base $d_{ji} \in D_i$ i.e., where D_i – the type of the decision function.

Both distinct and phased variables are used to describe actions $d_{j1}, d_{j2}, \dots, d_{ji}$.

One of the most convenient programming tools in the field of fuzzy logic is the Fuzzy Logic environment of the MATLAB application program package [22, 23, 24]. Rules in the form of logical products "If a condition, then an action" were used to create a knowledge base [25]. For its study, the

"Number of connected TEDs" on the partial loads of the traction electric transmission was chosen as the control action.

When designing a fuzzy knowledge base of the automated traction control system of a shunting locomotive, the structure shown in Fig. 4, 5. The input signals of which correspond to the data in Table 1.

```

Editor - C:\Users\dzaik\Desktop\ISK_CHME3 ver3.fis
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3 Type='mamdani'
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6 NumOutputs=4
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8 AndMethod='min'
9 OrMethod='max'
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11 AggMethod='max'
12 DefuzzMethod='centroid'
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16 Range=[0 1]
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19 MF2='low':'trimf',[0 0.191 0.45]
20 MF3='middle':'trapmf',[0.202 0.45 0.55 0.8]
21 MF4='high':'trimf',[0.55 0.8 1]
22 MF5='very_high':'trimf',[0.9 1 1]
23
24 [Input2]
25 Name='Fk'
26 Range=[0 1]
27 NumMFs=5
    
```

Fig. 4. M-file of the structure of input and output data of the knowledge base

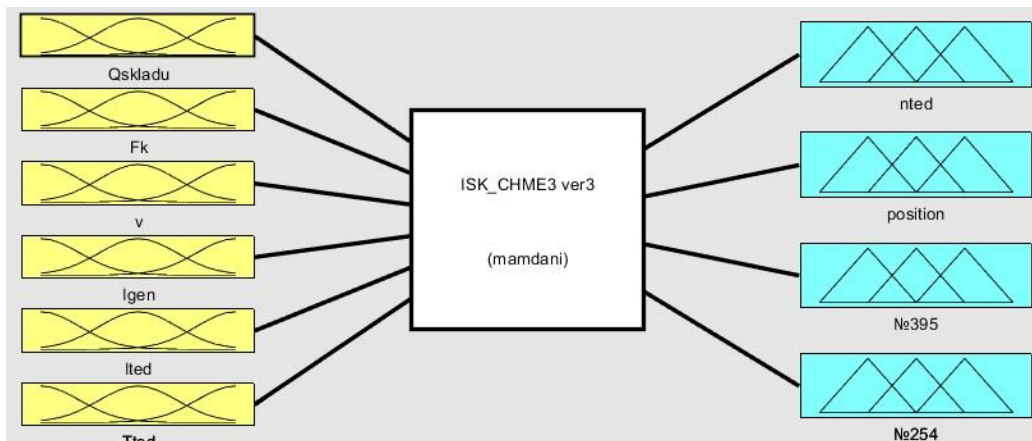


Fig. 5. The structure of input and output data of the knowledge base

All input signals are normalized in the interval [0;1]. To represent them in the form of fuzzy values, a set of characteristic functions is assigned for each input signal [2, 26]. Figures 6 and 7 show the fuzzification of part of the input values, namely: «Component masses», «Traction forces». They are represented by the following fuzzy values: «very_low», «low», «middle», «high», «very_high».

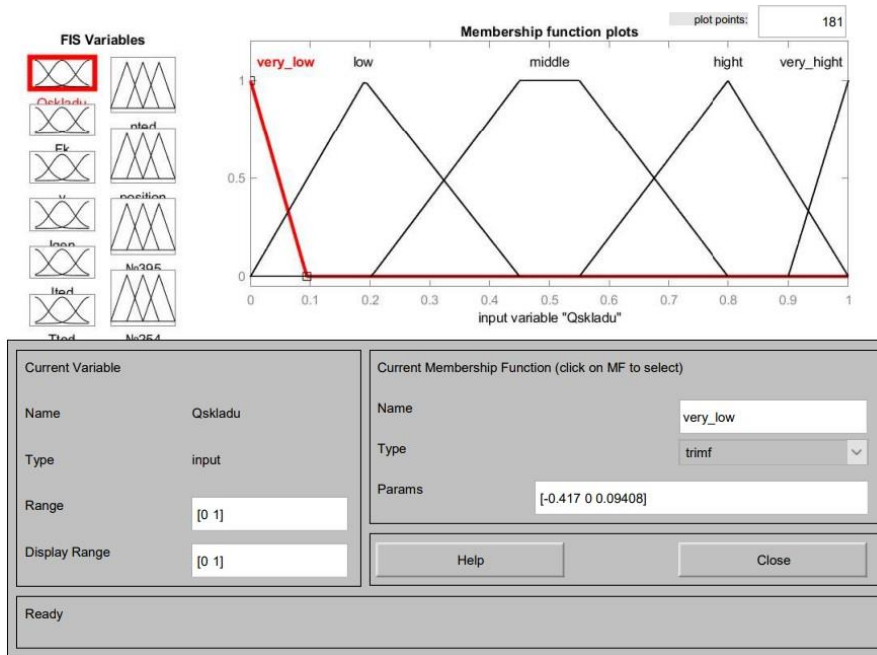


Fig. 6. Fuzzification of the «Composition mass» value

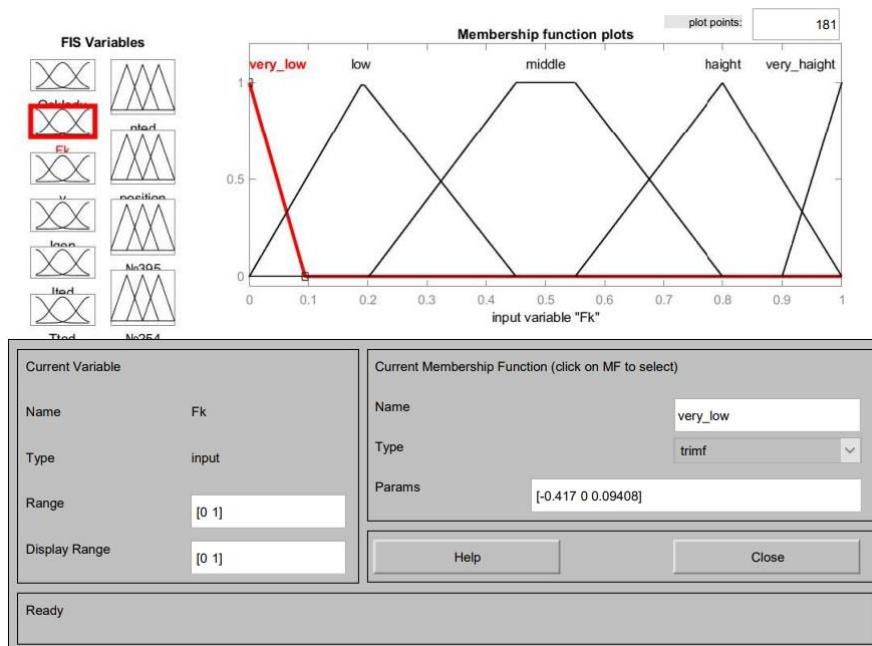


Fig. 7. Fuzzification of the «Traction force» value

Figures 8 and 9 show the phasing of the output distinct values "Operator's controller handle position" and "Number of connected TMs".



Fig. 8. Fuzzification of the «Operator's controller handle position» value

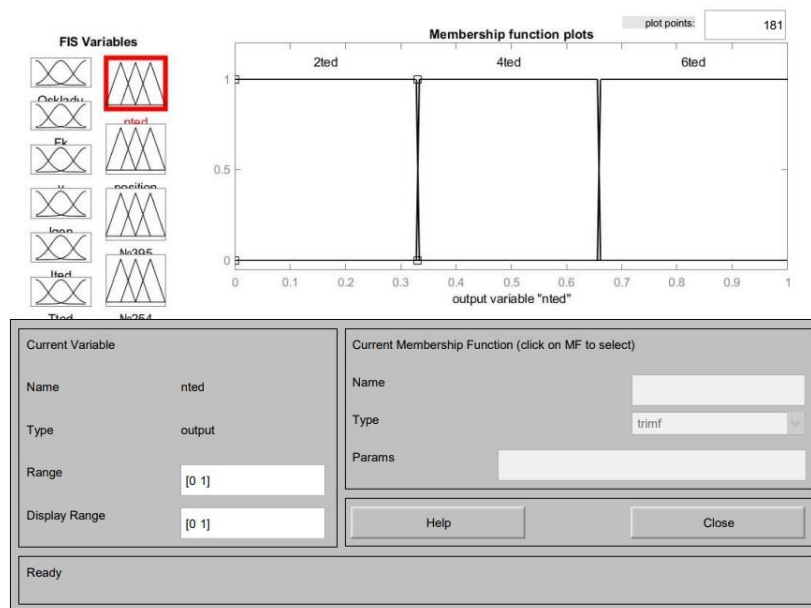


Fig.9. Fuzzification of the «Number of connected TMs» value

Using the method of expert evaluations and the logic of managing traction rolling stock in the Fuzzy Logic Designer package, a knowledge base was created, part of which is presented in Fig. 10.

Several lines from the knowledge base shown in Figure 10 have the following form:

If (Qskladu is middle) and (Fk is low) and (v is very_low) and (Igen is low) and (Ited is haight) and (Tted is middle) **then** (nted is 2ted)(position is 3ps)(№395 is 2)(№254 is 2) (1);

If (Qskladu is middle) and (Fk is middle) and (v is very_low) and (Igen is middle) and (Ited is high) and (Tted is middle) **then** (nted is 4ted)(position is 3ps)(№395 is 2)(№254 is 2) (1).

The results of the calculation of the model of the automated control of the traction transmission of the ChME3 shunting locomotive make it possible to investigate the dependence of the output variable on the input using the Fuzzy Logic Surface function (Fig.11-Fig 13).

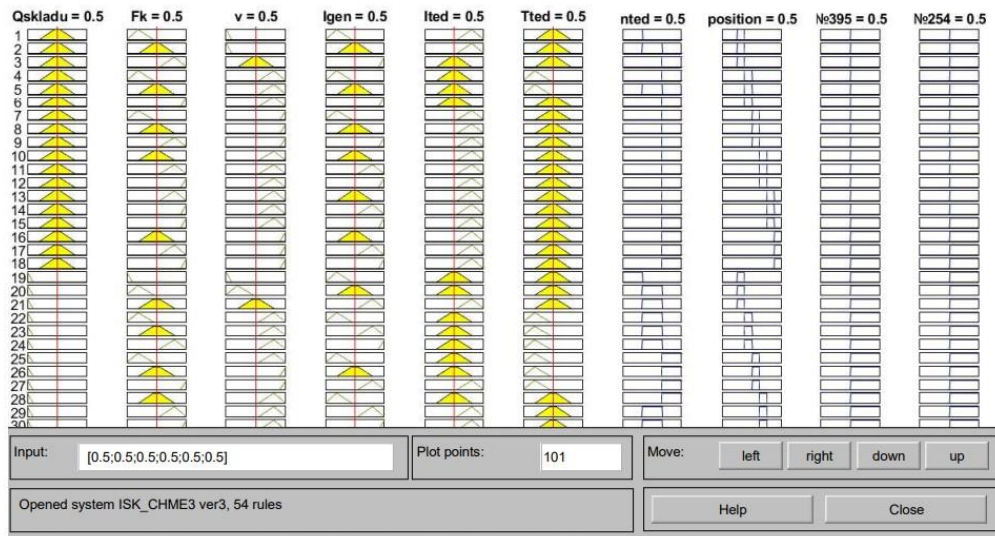


Fig.10. General view of the rules in the knowledge base

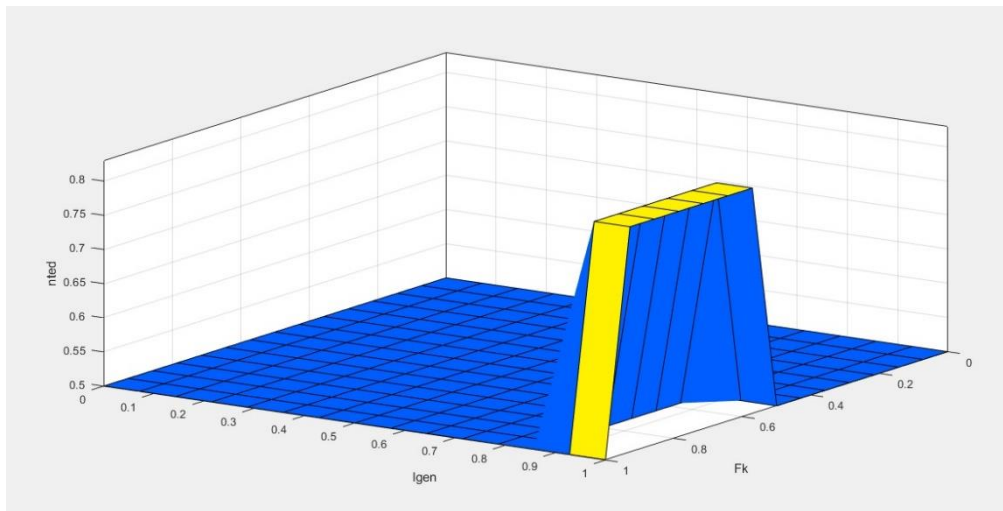


Fig.11. Three-dimensional surface of the dependence of the «Number of connected TMs» output variable on the «Traction force» and «Traction generator current» inputs

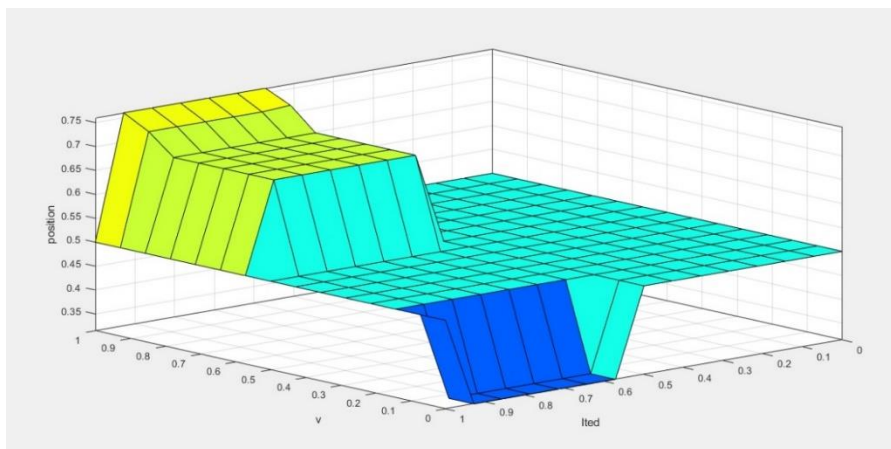


Fig.12. Three-dimensional surface of the dependence of the «Operator's controller handle position» output variable on the «Speed» and «TM current» inputs

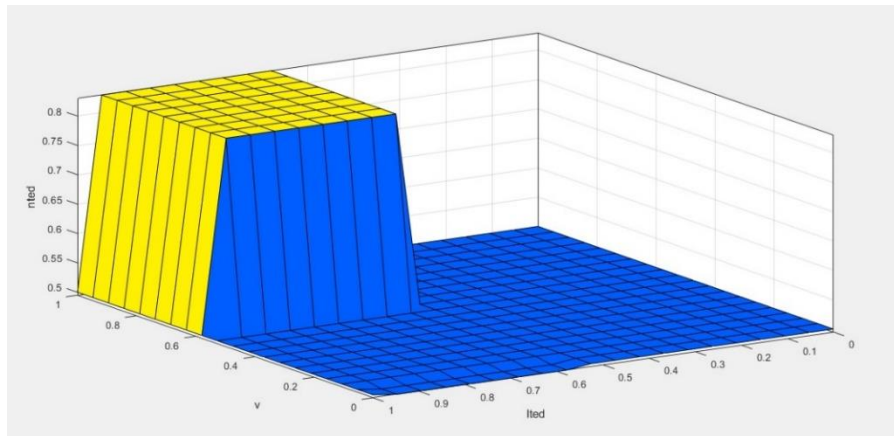


Fig.13. Three-dimensional surface of the dependence of the «Number of connected TMs» output variable on the «Speed» and «TM current» inputs

Assessment of shortcomings and prospects for the development of the given research. In the process of developing the automated system, a list of factors influencing the decision-making of the traction electric transmission of the shunting locomotive was determined (table 1). It should be noted that this list of factors may change and expand according to the locomotive series and operating conditions. A production model combining elements of logical and network approaches is used for the task of controlling the traction transmission of a shunting locomotive. The main disadvantages of which include the complexity of managing a large number of rules, when the number of rules increases, it becomes difficult to manage their order of execution and interaction. This can lead to conflicts and errors in conclusions. Performance issues, running a large number of rules can take a long time, especially if the rules are complex or have many conditions. Support and updates, changes in knowledge or rules require constant updating of the production base, which can be a time-consuming process. For the proposed system, 54 fuzzy logical rules are used, for further research it is proposed to expand the base by adding rules for the performance of shunting work by a locomotive with 15 4-axle cars. The results of the calculation of the automated model of the traction transmission control of the shunting locomotive are control signals. With the help of which, it is possible to implement the optimal mode of movement for a specific train and operation area. For further research, it is proposed to investigate various series of shunting diesel locomotives, their technical condition of traction electric transmissions. To analyze a larger number of areas of operation, for the possibility of creating a universal fuzzy knowledge base of the system.

In this form, the model of the automated traction transmission control system of the locomotive shows its adequacy. Trapezoidal and triangular characteristic functions are mainly used for fuzzification of input and output values. In further research to increase the quality and accuracy of the system, it is necessary to investigate the choice and justification of each membership function for the input signals. For the system, the range of concepts in the plural of the function is used, such as: [very low, low, middle, high, very high]. To improve the performance of the system in future studies, the list of these concepts should be expanded to: [very low, low, below middle, middle, above middle, high, very high], expanding these concepts increases the complexity of the structure, but will add flexibility to the system.

Conclusions. The paper presents a mathematical model of the automated traction control system of the shunting locomotive. Using the methods of fuzzy logic, the fuzzy knowledge base of the system has been formed and theoretically substantiated. The scheme of the automated control system of the traction transmission of the shunting locomotive with the possibility of self-learning has been developed.

The obtained results of the system work allow to realize quite a variety of control modes of the traction transmission of the shunting locomotive, which differ from those adopted during traction calculations and specified in the mode maps. Rational train driving modes vary significantly depending on operating conditions, which makes it impossible to determine a single optimal mode for all possible

traffic scenarios on a specific section. This is explained by the fact that even on the same site, operating conditions can change quite often. In addition, the technical characteristics of traction gears and individual locomotives may deviate from the passport values within certain limits depending on their actual technical condition, which also affects the choice of the optimal driving mode. The results of the operation of the automated traction transmission control model of the shunting locomotive are control signals that allow to implement your optimal mode of movement for a specific train and section. Using the created knowledge base, the system implements the movement of the shunting locomotive on 4 TMs using partially the 3rd, and fully the 4th and 5th positions of the driver's controller. This mode of movement allows to reduce fuel consumption for shunting of the locomotive with partial loads on the traction gear.

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Створення моделі автоматизованого управління тяговою передачею маневрових локомотивів шляхом використання методів штучного інтелекту

В роботі розроблено математичну модель автоматизованої системи управління тяговою передачею маневрового локомотива, використовуючи методи нечіткої логіки та метод експертних оцінок. Для запропонованої моделі використовується алгоритм Мамдані. Алгоритм включає базу знань інтелектуальної системи, яка для формалізації та представлення знань в пам'яті використовує продукційну модель, поєднуючи елементи логічних та мережевих підходів керування. Отримана автоматизована модель управління тяговою передачею маневрового локомотива пропонує свій оптимальний режим руху для конкретного поїзда та ділянки. Модель використовує створену нечітку базу даних. Результатом розрахунку моделі є керуючий сигнал для руху маневрового локомотива на 4-х двигунах, використовуючи частково 3-тю та повністю

4-ту та 5-ту позицію контролера машиніста. Такий режим руху дозволяє зменшити витрати палива на маневрову роботу локомотива при часткових навантаженнях на тягову електричну передачу.

Ключові слова: залізничний транспорт, рухомий склад, тепловоз, тягова електронпередача, метод Мамдані.

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Development of a diagnostic system for the presence of rotor eccentricity in traction induction motors

The aim of research is to develop a system for functional diagnostics of the presence of rotor eccentricity in traction induction motors of railway rolling stock. To achieve the aim, the following objectives were solved in the work: the Prony's method was adapted to perform the task of diagnosing the eccentricity of the rotor of an induction motor during the operation of the rolling stock; the algorithm of functioning of the system of functional diagnosis of rotor eccentricity based on the adapted Prony's method is proposed; a structural diagram of the rotor eccentricity diagnosis unit based on the adapted Prony's method is proposed; a structural diagram of the system of functional diagnosis of rotor eccentricity is proposed. The most important results are obtaining a mathematical model of the Prony's method, adapted to the task of diagnosing the eccentricity of the rotor of an induction motor during the operation of rolling stock. The adaptation of the Prony's method algorithm is performed by applying the Wiener-Hopf procedure to the analyzed signals. This will make it possible to apply the proposed algorithm in conditions where the process of changing the analyzed signals is stochastic in nature. This will make it possible to determine the eccentricity degree of the AM rotor with greater accuracy and to make a more correct decision regarding the AM operation with the existing eccentricity of the rotor.

Key words: induction motor, diagnosis, eccentricity, rolling stock.

Introduction. The reliable operation of traction motors of rolling stock affects the uninterrupted operation of even the railway. The sudden failure of the elements of traction electric drives during the operation of the rolling stock leads to disruption of logistics and related economic losses. In addition, the violation of established logistical tasks leads to a decrease in the competitiveness of even railway transport. In such conditions, research on the development of methods for controlling the appearance and development of defects in the design elements of traction motors of rolling stock is particularly relevant [1].

A number of damages to traction motors cause the appearance of rotor eccentricity, which is the most common mechanical malfunction of an induction motor (IM). The presence of eccentricity leads to increased wear of bearings. Catching the rotor on the stator can cause structural damage to the rotor and stator or overheating. These factors can cause a breakdown of the damaged layer of insulation in the friction zone. According to research data, eccentricity accounts for 20 to 40% of IM failures [2, 3].

During the IM operation with eccentricity, one-sided magnetic attraction occurs, which causes a decrease in efficiency, and increased heating causes a decrease in starting torque. Therefore, detection

of rotor eccentricity at an early stage of its appearance and development is an important scientific and research task.

The development of algorithms for detecting the presence of rotor eccentricity and the degree of its damage and the construction of functional diagnostic schemes based on them will allow to effectively detect the specified defect during the operation of the traction motor. This will make it possible to increase the reliability and durability of the use of traction IMs in the traction drives of railway rolling stock, which, in turn, will ensure the safety and economy of railway transportation [4].

Analysis of existing technical solutions. The nature of the rotor eccentricity is different, but the negative consequences of this defect are similar. The causes of rotor eccentricity are [5]:

- low-quality manufacturing or repair of motors;
- the influence of operational factors that cause violations of the geometry of the motor design;
- wear of bearings;
- motor shaft deflections, etc.

A characteristic feature of this type of damage is the possibility of continued IM operation without its immediate failure. However, the eccentricity leads to a decrease in the reliability and durability IM indicators, which progress over time and contribute to a decrease in technical and economic and operational indicators.

In studies devoted to the analysis of the causes of rotor eccentricity, two types of eccentricity, static and dynamic, are considered. Static eccentricity is caused by the shift of the axis of rotation of the motor relative to the axis of boring of the stator package, that is, the eccentric position of the rotor in the boring of the stator. The most common causes of static eccentricity are [5]:

- load imbalance;
- vibrations;
- misalignment of shafts;
- sharply changing loads and overloads;
- malfunction of bearings, etc.

Dynamic eccentricity is caused by the displacement of the axis of the outer surface of the rotor with respect to the axis of its rotation and is accompanied by the beating of the rotor, which occurs due to the forces of one-sided magnetic attraction as a result of poor repair or manufacturing defects.

The dynamic eccentricity is usually much smaller than the static eccentricity and for determination during motor operation for the purpose of current diagnostics of the motor condition is not of decisive importance. Therefore, for the diagnosis of damage causing eccentricity in IM, it is advisable to conduct research only on static indicators of eccentricity [5].

The following methods are known from existing studies devoted to diagnosing the occurrence of rotor eccentricity [5]:

- vibrational;
- direct measurement;
- current.

Vibrodiagnostic methods are effective for determining damage to IM elements when diagnosing on the bench, but they have not been widely used in functional diagnostic systems. This fact is explained by the need to use a large number of sensors, the lack of reference values of vibration manifestations of a number of damages and low accuracy during the operation of the mechanism with additional vibration sources [6].

The method of direct measurement of the air gap at several points is used in the repair and maintenance of motors and requires partial disassembly of the IM. This requires stopping the IM for a long time and the conditions of access to the end zone of the magnetic circuit, which excludes the use of the method during the period of operation.

Current methods are the most effective for diagnosing the occurrence of rotor eccentricity. They are based on the analysis of the main electric and magnetic parameters of the motor, namely phase currents, phase voltage, power consumption, flux linkage and magnetic field induction in the air gap during the

operation of the equipment [2]. But for the full use of current methods, a number of separate studies are needed to establish the diagnostic parameters for assessing the type and degree of the motor defect.

Due to the fact that the functional diagnostics system is based on the analysis of the parameters of the stator phase currents of the IM, the construction of such a system requires the determination of diagnostic signs, which will be used to control the presence of eccentricity in the IM. The presence of the rotor eccentricity causes a change in the amplitudes of the characteristic harmonics in the current signals [7]. Such characteristic harmonics include:

- harmonics of passage of rotor grooves;
- side harmonics of the rotor around the power supply frequency;
- harmonics at twice the supply frequency and side harmonics around it.

When diagnosing IM in order to determine the presence of rotor eccentricity, thermal processes in AM should also be taken into account. Thermal processes in IM are "white" Gaussian noise [8]. In addition, the traction drive is affected by various disturbances caused by operational factors of rolling stock [9]. These disturbances have a non-deterministic non-periodic non-Gaussian character [9]. In other words, if the signals of the stator phase currents are affected by non-deterministic non-periodic non-Gaussian influences, the application of Fourier transform algorithms is incorrect. In these cases, it is correct to use correlation analysis methods.

The methods of current IM diagnosis include the following methods:

- method of analysis of motor current signatures [10];
- method of tracking order harmonics [11];
- parametric methods [12];
- methods based on Park vectors [13];
- Prony's method [14];
- methods of artificial intelligence [15].

From the analysis of the listed methods of current IM diagnostics, it was established that the most effective method for solving the problem of diagnosing the presence of rotor eccentricity is the Prony's method. Its advantages are:

- short signal sampling;
- absence of the effect of spectral leakage;
- low sampling frequency.

Despite the listed advantages, the Prony's method has one significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic.

The analysis of existing technical solutions for the construction of a functional diagnostics system shows that an important stage in the development of the specified system is the adaptation of existing diagnostic information processing methods for continuous control and diagnosis of the presence of rotor eccentricity in traction induction motors.

The aim of this research is to develop a system for functional diagnostics of the presence of rotor eccentricity in traction induction motors of railway rolling stock.

The research contributions of this work are as follows:

- the Prony's method is adapted to perform the task of diagnosing the eccentricity of the IM rotor during the rolling stock operation;
- the algorithm of functioning of the functional diagnostics system of IM rotor eccentricity based on the adapted Prony's method is proposed;
- a structural diagram of the IM rotor eccentricity diagnosis unit based on the adapted Prony's method is proposed;
- a structural diagram of the functional diagnostics system of IM rotor eccentricity is proposed.

Adaptation of the Prony's method to perform the task of diagnosing the IM rotor eccentricity during the rolling stock operation. As a result of the analysis, it was found that the most effective method of processing diagnostic information when building a functional system for diagnosing the IM rotor eccentricity is the Prony's method. Along with such advantages as: short signal sampling; absence

of the effect of spectral leakage; low sampling frequency, it has a significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic in nature. In this section, an algorithm for adapting the Prony's method is proposed for the purpose of its application when the process of changing the analyzed signals is stochastic in nature.

In the presence of eccentricity in the current signal, the amplitudes of the harmonics change. passage of the rotor grooves. The frequencies of these harmonics are determined by the following expression [16]

$$f_{RSN} = f_s \cdot \left((m \cdot Z_B \pm n_d) \cdot \frac{1-s}{p} \pm \beta_{ws} \right) = f_s \cdot \left(m \cdot Z_B \cdot \frac{1-s}{p} \pm \beta_{ws} \right) \pm f_s \cdot n_d \cdot \frac{1-s}{p}, \quad (1)$$

where $m=1,2,3,\dots$;

n_d - eccentricity order. With static eccentricity $n_d=0$, with dynamic eccentricity $n_d=1,2,3,\dots$;

p – the number of pairs of poles;

β_{ws} – the sequence of time harmonics of the stator of the power source of the induction motor. β_{ws} takes odd values for current signals and axial magnetic flux [17];

Z_B – the number of rotor rods.

In expression (1), the left term is the frequency of passage of the rotor grooves f_r :

$$f_r = f_s \cdot \left(m \cdot Z_B \cdot \frac{1-s}{p} \pm \beta_{ws} \right). \quad (2)$$

The frequencies of the side harmonics f_r around the frequency of passage of the rotor grooves are determined by the right-hand term of equation (1). Harmonics at these frequencies are called subharmonics of the rotor rotation frequency. The frequencies of these subharmonics are determined by the expression [18]:

$$f_r = f_s \cdot \frac{1-s}{p}, \quad (3)$$

The presence of side harmonics of the rotor around the power supply frequency is a sign of dynamic eccentricity [18]. The frequencies of these harmonics are determined according to the following expression:

$$f_{sbr} = f_s \pm k \cdot f_r, \quad (4)$$

where $k=1,2,3,\dots$ – any positive integer.

The analytical expression for the current signal in the presence of eccentricity has the form [18]:

$$I_{ecc}[i] = I_m \cdot \left(1 + \gamma \cdot \cos(2 \cdot \pi \cdot f_r \cdot \Delta t \cdot i + \varphi_0) \right) \cdot \cos(2 \cdot \pi \cdot f_s \cdot \Delta t \cdot i) + \beta[i], \quad (5)$$

where $I_{ecc}[i]$ – value of the IM phase stator currents in the presence of eccentricity;

γ – eccentricity degree.

From the analysis of expressions (1)-(5) it follows that the presence of lateral harmonics f_r around the frequency of passage of the rotor grooves and lateral harmonics of the rotor around the supply frequency in the spectrum of the IM stator phase currents is a sign of the presence of rotor eccentricity.

Spectral analysis methods should be used to determine the presence of harmonics at these frequencies. Subharmonic frequencies are not multiples of the supply voltage frequency (3)-(4). In addition, when diagnosing the presence of eccentricity during the operation of the traction drive, both the power frequency and the rotor speed are constantly changing. This complicates the application of Fourier transform algorithms to determine the specified subharmonics.

Fig. 1 shows a short algorithm of the stages of determining the periodogram, intended for obtaining estimates of the amplitude, attenuation coefficient, frequency, and initial phase by the Prony's method [19].

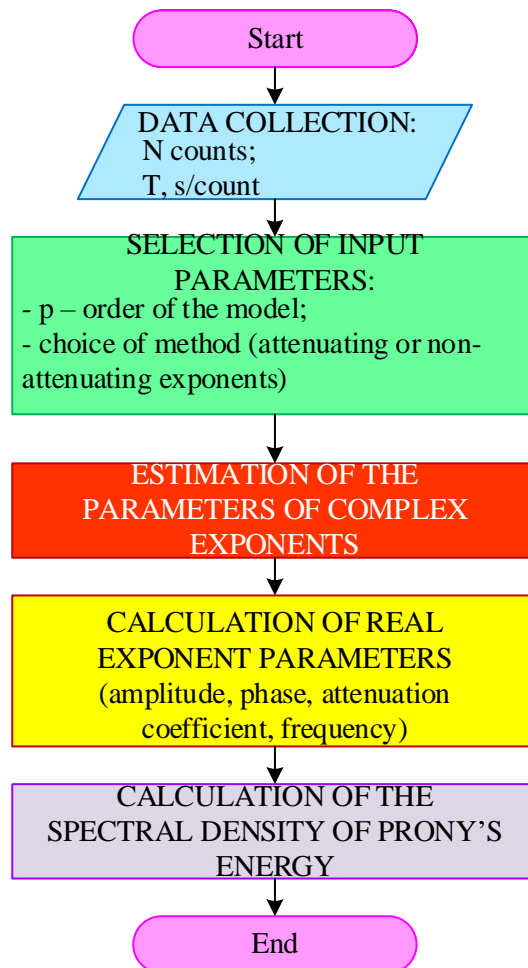


Fig. 1. A short algorithm of the stages of determining the periodogram, intended for obtaining estimates according to the Prony's method

For N readings of complex data $x[1], \dots, x[N]$, the Prony's method allows to estimate $x[n]$ using some p -term complex exponents.

The Prony's procedure for preparing p exponents for $2p$ counts of data can now be represented as the following three steps. At the first stage, the solution of equation [19] is obtained

$$\begin{bmatrix} x[p] & x[p-1] & \dots & x[1] \\ x[p+1] & x[p] & \dots & x[2] \\ \vdots & \vdots & \dots & \vdots \\ x[2p-1] & x[2p-2] & \dots & x[p] \end{bmatrix} \cdot \begin{bmatrix} a[1] \\ a[2] \\ \vdots \\ a[p] \end{bmatrix} = \begin{bmatrix} x[p+1] \\ x[p+2] \\ \vdots \\ x[2p] \end{bmatrix}. \quad (6)$$

for coefficients $a[n]$.

At the second stage, the roots of the polynomial defined by equation [19] are determined

$$\prod_{k=1}^p (z - z_k) = \sum_{m=0}^p a[m] \cdot z^{p-m}. \quad (7)$$

The solution of equation (7) with respect to the roots z_i makes it possible to calculate the attenuation coefficient α_i and the frequency of the sinusoid f_i using relations [19]

$$\alpha_i = \frac{\ln[z_i]}{T}, s^{-1}; \quad (8)$$

$$f_i = \frac{\arctg\left[\frac{\operatorname{Re}(z_i)}{\operatorname{Im}(z_i)}\right]}{2 \cdot \pi \cdot T}, \text{Hz}. \quad (9)$$

To complete the Prony's procedure, the roots of the polynomial calculated at the second stage are further used to form the matrix elements of equation (10), which is then solved with respect to p complex parameters h_1, \dots, h_p [19].

$$\begin{bmatrix} z_1^0 & z_2^0 & \dots & z_p^0 \\ z_1^1 & z_2^1 & \dots & z_p^1 \\ \vdots & \vdots & \dots & \vdots \\ z_1^{n-1} & z_2^{n-1} & \dots & z_p^{n-1} \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_p \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix}. \quad (10)$$

Each parameter h_i is further used to determine the amplitude A_i and the initial phase θ_i , which are calculated using the expressions [19]

$$A_i = |h_i|; \quad (11)$$

$$\theta_i = \arctg\left[\frac{\operatorname{Re}(h_i)}{\operatorname{Im}(h_i)}\right], \text{rad}. \quad (12)$$

The Prony's spectrum is defined in terms of the exponential approximation $\hat{x}[n]$, and not in terms of the original time sequence $x[n]$. Equation (10) can be concisely written in the form

$$\hat{x}[n] = \sum_{k=1}^p h_k \cdot z_k^{n-1}, \quad (13)$$

If the signal $x[n]$ is valid, then the exponents will appear as complex conjugate pairs $\exp\{\pm j[2 \cdot \pi \cdot f_k + \theta_k]\}$, which will ensure the formation of one cosine term $\cos(2 \cdot \pi \cdot f_k + \theta_k)$ z-transformation from (13)

$$\hat{X}_1[z] = \sum_{k=1}^p \frac{h_k}{1 - z_k \cdot z_k^{-1}}, \quad (14)$$

which converges for $|z_k| < |z|$. It is also assumed here that $|z_k| < 1$, i.e., in other words, all the attenuation parameters are negative, giving decaying exponents. If this is so, then substituting the form $z = \exp(j2 \cdot \pi \cdot f \cdot T)$ into expression (13) will give the discrete-time Fourier transform (DFT) of the time sequence $\hat{x}[n]$ with finite energy. Therefore, the Prony's spectral energy density (SED) for the one-sided exponential model under consideration will be determined by the expression [19]

$$S_1[f] = \left| T \cdot \hat{X}_1 \cdot \left(\exp[j2 \cdot \pi \cdot f \cdot T] \right) \right|^2, \quad (15)$$

which is defined in the frequency interval $-1/(2 \cdot T) \leq f \leq 1/(2 \cdot T)$. This spectrum is convenient for describing short-time signals.

To implement the algorithm shown in Fig. 1, the issue of determining the order of the model (p) remains unresolved. The authors proposed to use the autoregressive transfer function criterion to select a model [19]

$$ATFC[p] = \left(\frac{1}{N} \cdot \sum_{j=1}^p \bar{\rho}_j^{-1} \right) - \sum_{j=1}^p \bar{\rho}_j^{-1}, \quad (16)$$

where

$$\bar{\rho}_j = \frac{N}{N-j} \cdot \hat{\rho}_j. \quad (17)$$

In expression (15), the value of p is chosen in such a way as to minimize $ATFC[p]$. $\hat{\rho}_j$ in expression (16) is the sum of squared errors defined by the expression

$$\hat{\rho}_j = \sum_{n=1}^N |\varepsilon[n]|^2, \quad (18)$$

where

$$\varepsilon[n] = x[n] - \hat{x}[n] = x[n] - \sum_{k=1}^p h_k \cdot z_k^{n-1}. \quad (19)$$

This algorithm for determining the order of the model is effective in the absence of noise. Since the power part of the traction drive contains noises caused by temperature processes during the flow of current through the motor windings, the application of the specified criterion to determine the order of the model is incorrect.

It is proposed to apply the Wiener-Hopf procedure to the phase current signals of an induction motor [20]. The Wiener-Hopf theorem for determining stator phase currents for discrete signals has the form [21]

$$\begin{cases} x(t-kT, t-nT) = \sum_{i=0}^{N_1} \sum_{j=0}^{N_2} c_{i,j} \cdot K_I(t-(k-i) \cdot T, t-(n-j) \cdot T); \\ k \in N_1, \quad n \in N_2, \end{cases} \quad (20)$$

where $x(t-kT, t-nT)$ - function of mutual correlation of stator phase current signals and noise;
 $K_I(t-(k-i) \cdot T, t-(n-j) \cdot T)$ - autocorrelation function of the stator phase current signal.

The solution of equation (20) with respect to all unknowns $c_{i,j}$, the total number of which will be N_1+N_2+2 , made it possible to find the impulse function that minimizes the root-mean-square filtering errors of the stochastic value of the stator phase current.

Then the algorithm that implements the Prony's method for performing the task of diagnosing the AM rotor eccentricity during the rolling stock operation looks like it is shown in Fig. 2.

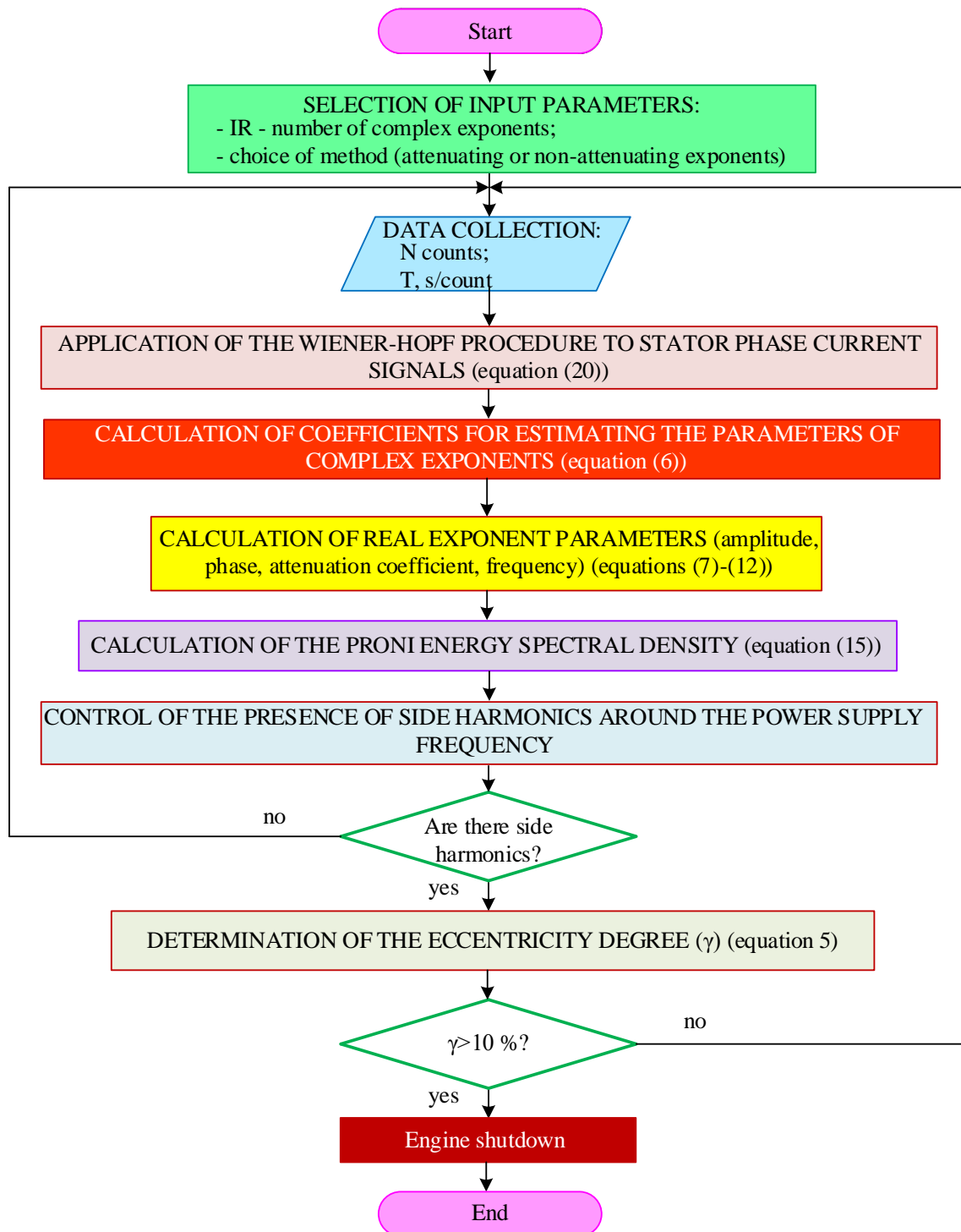


Fig. 2. Block diagram of the algorithm that implements the Prony's method for performing the task of diagnosing the AM rotor eccentricity during the rolling stock operation

In Fig. 2, the "DETERMINATION OF THE ECCENTRICITY DEGREE" unit is applied. Its use is based on such considerations. The presence of eccentricity in AM leads to the modulation of stator phase current signals by the frequencies of side harmonics (5). The presence of modulation of stator phase current signals causes the appearance of a torque on the motor shaft, which leads to a deterioration of the energy performance of the rolling stock traction drive. On the other hand, a large eccentricity degree

$$s = \frac{I_{sy} \cdot k_r \cdot R_r}{\Psi_r} \tag{23}$$

That is, two more signals are additionally output from the "Observer of rotor flux linkage" unit – rotor slip s and angular frequency of rotation of the coordinate system ω_k . Since the angular frequency of rotation of the coordinate system ω_k is determined in relative units in the "Observer of rotor flux linkage" unit, the value of ω_k should be multiplied by the nominal value of the frequency of the IM supply voltage f_{snom} . The frequency of passage of the rotor grooves f_r is determined in accordance with expression (4).

Then the structural diagram of the traction drive with IM vector control and the functional diagnostics system is as shown in Fig. 4.

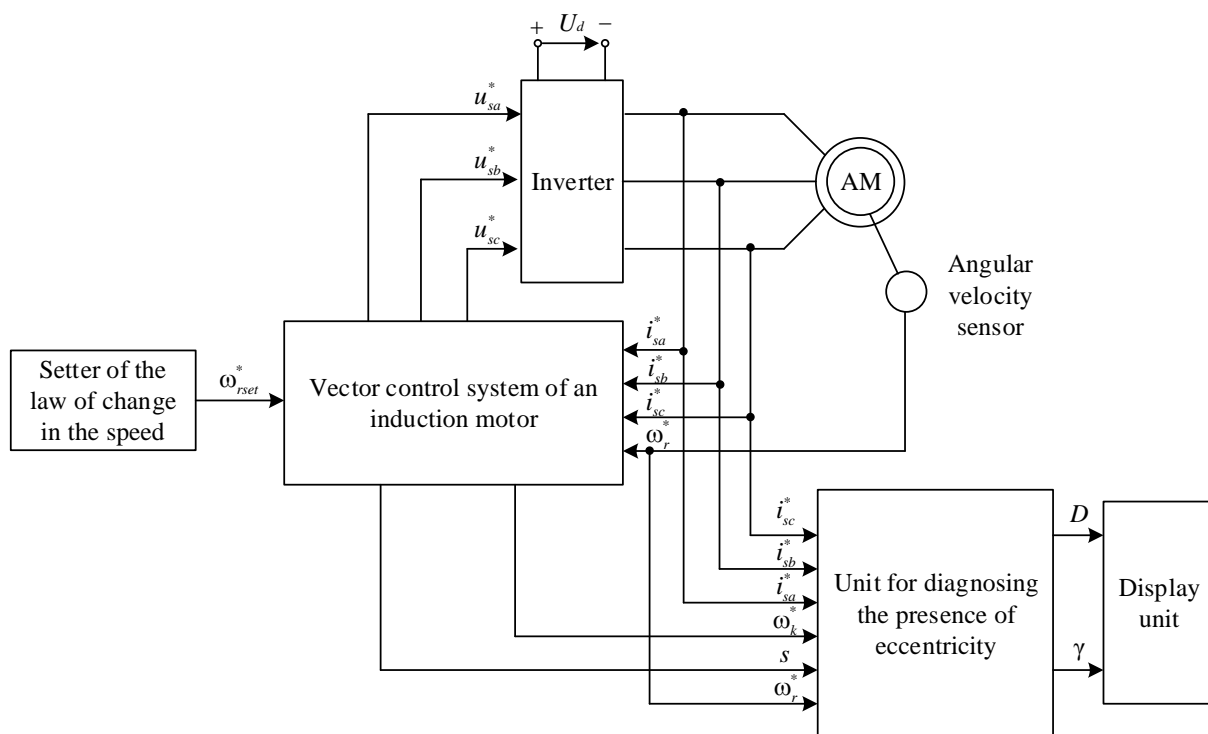


Fig. 4. Structural diagram of traction drive with IM vector control and functional diagnostics system

The structural diagram of the unit for diagnosing the presence of rotor eccentricity is shown in Fig. 5. In the "Unit of conversion from relative units to real values" the values of physical quantities coming from the control system are converted from relative units to real ones. For currents, real physical quantities are determined in accordance with the expression

$$I_s = i_s^* \cdot I_{snom}, \tag{24}$$

where i_s^* – the value of the phase current in relative units;
 I_{snom} – the nominal value of the stator phase current.

For the supply voltage frequency, the real physical quantity is determined in accordance with the expression

$$f_s = \omega_k^* \cdot f_{snom}, \quad (25)$$

where ω_k^* – the value of the angular speed of rotation of the coordinate system in relative units; f_{snom} – the nominal value of the supply voltage frequency.

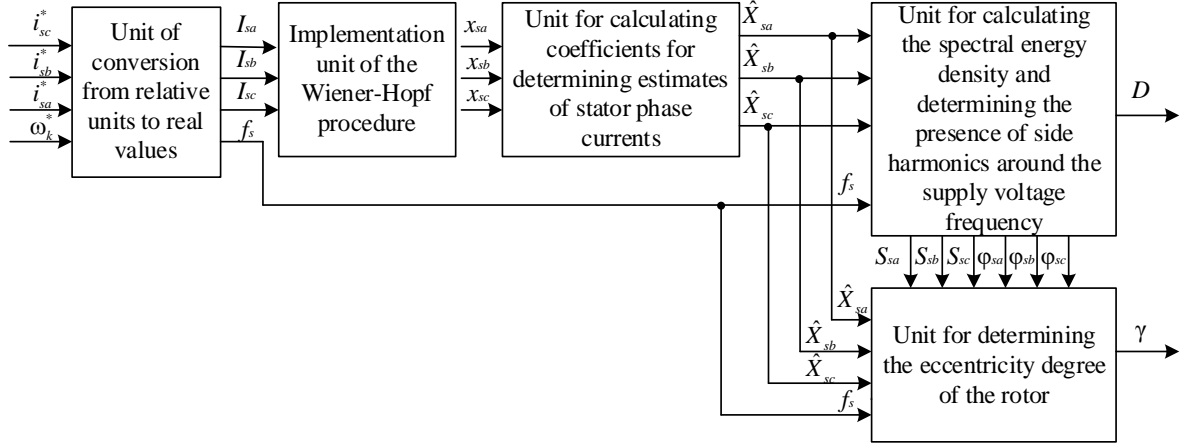


Fig. 5. Structural diagram of the unit for diagnosing the presence of eccentricity

In the Wiener-Hopf procedure implementation unit, the Wiener-Hopf procedure is applied to the stator phase currents. Stator phase current signals, from which noise has been removed (I_{sa}, I_{sb}, I_{sc}), are sent to the "Unit for calculating coefficients for determining estimates of stator phase currents" where their estimates ($\hat{X}_{sa}, \hat{X}_{sb}, \hat{X}_{sc}$) are determined. On the basis of the received estimates of the phase currents of the stator in the "The unit for calculating the spectral energy density and determining the presence of side harmonics around the supply voltage frequency", their spectral components are determined. In the presence of side harmonics around the frequency of the supply voltage, a $D=1$ signal is sent to the output of the specified unit, in the absence of a $D=0$ signal. When the signal value is $D=1$, the amplitude (S_{sa}, S_{sb}, S_{sc}) and phase ($\varphi_{sa}, \varphi_{sb}, \varphi_{sc}$) energy components of the lateral harmonic components are sent to the "Unit for determining the eccentricity degree of the rotor".

The transition from the energy of side harmonics to their amplitudes is carried out in accordance with the expression

$$I_{sm} = \frac{1}{T} \cdot \sqrt{S_s}. \quad (26)$$

The eccentricity degree is determined in accordance with expression (5). In expression (5) instead of $I_{ecc}[i]$ the value $\hat{X}_s[i]$ is substituted, and instead of $I_m - I_{sm}$. In order to avoid an error in determining the eccentricity degree, the reference number is chosen so that it does not correspond to $\frac{1}{4}$ and $\frac{3}{4}$ of the interval under investigation. Since the Wiener-Hopf procedure was applied to the signals of the stator phase currents, that is, the noise was removed, in equation (5) $\beta[i]=0$. The value of the eccentricity degree γ is displayed on the information display block. After that, the driver makes a decision about the need to disconnect the IM with eccentricity.

In the absence of asymmetric regimes of IM windings caused by their damage, the phase currents of the stator are symmetrical. In this case, it is possible to control the presence of eccentricity based on the analysis of the phase current of the stator of one of the phases. However, during the operation of the traction drive, there is a change in the parameters of the locomotive movement all the time. This leads to the appearance of unstable modes in the traction drive, which are characterized by the presence of quasi-asymmetric modes, even in the absence of damage to the IM windings. To avoid errors in diagnosing the presence of eccentricity, it is proposed to analyze the spectral components of the stator

phase currents of all IM phases. Information about the eccentricity degree is derived based on the largest value of γ obtained.

Conclusions. In this work, a system for diagnosing the presence of rotor eccentricity in traction IMs is proposed. The following results are obtained:

- the analysis of the existing methods of processing diagnostic information for the diagnosis of rotor eccentricity in traction IMs was carried out. As a result, it was established that the most effective method of processing diagnostic information when building a functional system for diagnosing the eccentricity of the IM rotor is the Prony's method. Despite its advantages, it has a significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic;

- the Prony's method algorithm was adapted for conditions when the process of changing the analyzed signals is stochastic. This will make it possible to obtain more correct results when diagnosing the eccentricity of the rotor in the conditions of real operation of the traction drive of the rolling stock;

- a structural diagram of the IM rotor eccentricity diagnosis unit based on the adapted Prony's method was developed;

- a structural diagram of the system for functional diagnostics of the IM rotor eccentricity as part of the traction drive with a vector control system was developed.

In order to avoid errors in determining the eccentricity degree of the rotor under conditions of unstable modes in the traction drive, it is proposed to determine the eccentricity degree for the phase currents of the stator of all IM phases. The decision to turn off the motor should be made based on the value of the largest eccentricity degree of the rotor.

The continuation of this work can be research devoted to the construction of a complex functional system of diagnostics of both a separate traction IM and the entire traction drive of rolling stock.

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Розробка системи діагностики наявності ексцентриситету ротора в тягових асинхронних двигунах

Метою роботи є розробка системи функціональної діагностики наявності ексцентриситету ротора в тягових асинхронних двигунах (АД) рухомого складу залізниць. Для досягнення поставленої мети в роботі були вирішені такі задачі: адаптовано метод Проні для виконання задачі діагностування ексцентриситету ротора асинхронного двигуна під час експлуатації рухомого складу; запропоновано алгоритм функціонування системи функціональної діагностики ексцентриситету ротора на основі адаптованого методу Проні; запропоновано структурну схему блоку діагностики ексцентриситету ротора на основі адаптованого методу Проні; запропоновано структурну схему системи функціональної діагностики ексцентриситету ротора. Найбільш важливими результатами є отримання математичної моделі методу Проні, адаптованого до виконання задачі діагностування ексцентриситету ротора асинхронного двигуна під час експлуатації рухомого складу. Адаптація алгоритму методу Проні виконана шляхом застосування до сигналів, що аналізуються, процедури Вінера-Хопфа. Це дозволить застосовувати запропонований алгоритм в умовах, коли процес зміни аналізованих сигналів носить стохастичний характер. Це дозволить визначати ступінь ексцентриситету ротора АД з більшою точністю і приймати більш правильне рішення щодо експлуатації АД з наявним ексцентриситетом ротора.

Ключові слова: асинхронний двигун, діагностика, ексцентриситет, рухомий склад

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Development of a functional system for diagnosing the presence of rotor damage in induction traction motors

The aim of this work is to develop a system for functional diagnostics of rotor bar breakage in induction traction motors of railway rolling stock. In order to achieve this aim, the following tasks have been solved: developed an algorithm for diagnosing the condition of rotor bars based on the statistics of fractional moments; developed a block diagram of the unit for diagnosing the condition of rotor bars of the induction motor based on the statistics of fractional moments; developed a block diagram of the system for functional diagnosis of rotor bars condition as part of the traction motor with direct torque control. The most important result consists in obtaining a mathematical model of fractional moment statistics with less volume of calculations and improved sensitivity of the method. This result was achieved by determining the information-frequency range, which made it possible to analyze not all the spectral components of the analyzed signal, but only that part of it where there may be spectral components typical for the breakage of rotor bars of the induction motor. This approach to diagnosing the condition of rotor bars can also be applied in traction motors of rolling stock with vector control system of induction motors.

Keywords: *induction motor, fractional moment statistics, rotor bars, direct torque control*

Introduction. The railway is one of the critical infrastructure facilities, an element of which is rolling stock. Therefore, improving the reliability of rolling stock operation has always been an urgent task [1, 2]. The most effective way to improve the reliability of rolling stock is the use of the systems for diagnosing its condition during operation (operational diagnostic systems) [3]. Traction motors are the elements of rolling stock that most often suffer damage. [4].

Induction motors (IM) are increasingly used as traction motors in railway rolling stock. This fact is explained by the simplicity of their design, low production cost and ease of maintenance [5]. The reliable operation of IM directly affects the operational stability of traction motors used in the rolling stock. In case of damage to traction motor, economic losses can be significant. One of the most common defects in IM is the breakage of rotor bars. This defect accounts for approximately 10% of all IM failures [6]. This defect is characterized by its invisibility and gradualness, which makes it difficult to detect it in the early stages. Untimely detection of a defect leads to an increase in the degree of its malfunction during the IM further operation. In connection with this fact, detecting a defect at an early stage is an important task.

The use of functional diagnostics diagrams will allow for effective detection of rotor bars damage at an early stage of the occurrence of this defect during the rolling stock operation. To build such diagnostic

diagrams, it is necessary to develop algorithms for diagnosing and determining the degree of the specified defect at an early stage, taking into account the railway rolling stock operational factors [7].

Analysis of existing technical solutions. The following signals can be used to diagnose damage to rotor bars in IM:

- signals of phase currents of the ID stator [8];
- vibration signals [9];
- acoustic signals [10];
- signals of instantaneous power [11];
- signals of flux linkages [12].

The analysis of the specified diagnostic methods conducted in the work [12] showed that due to their availability and non-invasiveness, the method of analyzing IM stator current signatures was the most widely used in diagnosing damage to rotor bars. It should be noted that despite its advantages, this method has one drawback: it does not work correctly in the conditions of IM idle operation or at low loads [14]. This is explained by the fact that the sideband frequency, which is a diagnostic sign of the defect presence, coincides (at IM idle operation) or is located too close (when operating with low loads) to the frequency of the IM supply voltage. Therefore, to detect a defect, you should have algorithms with a high spectral resolution.

To solve this problem, the following methods were proposed to effectively eliminate the fundamental frequency harmonic of the stator phase currents:

- rejection filter [15];
- extended Kalman filter [16];
- matched filter [17];
- sparse Bayes filter [18].

These methods, in addition to eliminating the harmonics of the fundamental frequency of the stator phase currents and noise, weaken the characteristic harmonics of the defect, which can lead to a false diagnosis of IM rotor bar defect at early stages.

In a number of studies, high-frequency resolution methods were used in order to distinguish the sideband frequency accurately, which indicates the presence of a defect, from the frequency of the supply voltage. These methods are based on the decomposition of current signal values into signal and noise subspaces. The resolution can be improved by applying special ratios between subspaces. Thus, in the work [19] we used the classification of multiple signals to detect rotor defect under different conditions of load and speed. In the work [20], we used the estimation of signal parameters based on the method of rotational invariance instead of the fast Fourier transform (FFT) to diagnose rotor bar breaks. This algorithm, unlike the IM stator current signature analysis method, is capable to increase effectively the resolution of the spectrum estimation and improve the sideband detection with limited data. The disadvantage of these two methods is that they require a significant amount of computation and their speedwork depends on the selected parameters of the model.

Another approach to eliminating harmonics of the supply voltage frequency is the use of modulation methods. In these methods, the harmonic of the frequency of the supply voltage is converted into a direct current component. In the work [21], we used the Park's vector method to diagnose the rotor bar breakage. To diagnose the said defect, in the work [22] we used the sum of adjacent productions. To use these two approaches, it is necessary to have data on two- or three-phase IM stator currents.

In this study [23] we proposed to use Teager-Kaiser energy operator for the diagnosis of IM rotor damage. To demodulate IM stator phase current signals based on the approach proposed in [23], it is necessary to have only three consecutive sampling points. This allows for excellent speedwork. However, such calculations represent causal processing and can lead to signal distortion and non-ideal filter characteristics. In [24], we proposed to use the method of normalized energy operator in the frequency domain to diagnose the breakage of IM rotor bars. Instead of using causal processing, in this method we use Hilbert transform to calculate the energy operator. But at the same time, the volumes of calculations increase. In contrast to the above considered approaches, in this work [25] we proposed a technique based on the spectral analysis of rectified current signals. This technique can be implemented

either in hardware (using a simple rectifier) or in software (by saving current signal counts). All demodulation algorithms considered above are based on FFT, which provides complete information about the spectra of the analyzed signals. In the works considered during the analysis, it was noted that the frequency that determines the presence of breaks of the rotor bars is located in the low frequency range. Therefore, when developing diagnostic algorithms to determine this frequency, it is enough to focus on the analysis of spectrum within the low frequency range. In addition, for the implementation of the algorithms given in the works [23-25], it is required to have information about the angular speed of motor shaft rotation, for the determination of which, it is required to use angular speed sensors.

A new statistical approach, called Statistics of Fractional Moments (SFM), is given in [26] for distinguishing signals with a low signal-to-noise ratio [26]. The signals are transformed in the space of fractional moments, where they can be distinguished and grouped according to the level of their correlation with each other. SFM is extremely sensitive to very small differences between signals under study. This makes it possible to imagine and describe any random sequence of data in the space of fractional moments [27]. The function of the generalized average (FGA) is approximated by a linear combination of exponential functions, thanks to which random sequences are presented as a small number of parameters (much less than the number of data). This representation is convenient for comparing different sequences that have different numbers of points in the studied samples. It should be noted that it is impossible to compare samples with different numbers of points in ordinary statistics. FGA and other functions obtained within the SFM framework are widely used to solve classification tasks. This approach has great potential for application in IM diagnostics, since classification tasks in diagnostics are one of the main ones. SFM approaches have not been previously used in IM diagnostics, but they have great potential as they can be implemented in continuous monitoring systems of IM technical condition due to their efficiency and high sensitivity.

The purpose of this work is to develop a system for functional diagnostics of the presence of breaks of rotor bars in induction traction motors of the railway rolling stock.

The research contributions of this work are as follows:

- developed an algorithm for diagnosing the condition of rotor bars based on fractional moments statistics;
- developed a block diagram of the unit for diagnosing the condition of rotor bars of the IM based on the statistics of fractional moments;
- developed a block diagram of the system for functional diagnosis of rotor bars condition as part of the traction motor with direct torque control.

Development of an algorithm for monitoring and diagnosing the condition of induction motor rotor based on the method of fractional order moments. The proposed method of fractional order moments for solving the tasks of monitoring and diagnosing technical condition of motors includes of the following basic steps:

1. Measurement of one or more IM stator phase currents signals.
2. Application of the Fourier transform to the measured signal to display the signal in frequency domain.
3. Calculation of the function of the generalized average (FGA) for the spectrum obtained at the previous step according to the expressions (1) and (2).

The FGA for a moment of order p is calculated according to the following expression

$$\Delta_{(mom_p)} = \left(\frac{1}{L} \cdot \sum_{i=1}^L y_i^{mom_p} \right)^{\frac{1}{mom_p}}, \quad (1)$$

where y_i – input sequence;
 L – number of points;
 $p=1, 2, \dots, P$ - positive integer;
 mom_p - moment of order p .

Moment of order p is calculated according to the expression:

$$mom_p = exp \left\{ min + \frac{p}{P} \cdot (max - min) \right\}, \quad (2)$$

min , max and P – are FGA parameters. min and max parameters determine the range of moments in a logarithmic scale;

P - is the coefficient that determines the permission of moment orders.

4. Comparison of the obtained FGA with the FGA obtained for IM in different technical conditions. If the FGA obtained for the IM in good condition is “close” to the FGA obtained for the motor under test, then a decision is made that the motor is in good condition. Otherwise, a decision is made that there are anomalies and possible malfunctions. The method of comparing FGA and the “closeness” criterion is determined in the specific implementation of the proposed method. For example, in the works [27] the tangent of the angle of inclination between the FGA obtained for the tested motor and the FGA obtained for a fault free motor are calculated to compare FGA. In order to solve the tasks of diagnosing defects, it is necessary to obtain FGA of the motors with malfunctions and to compare with the FGA of the motor under test not only with the FGA of a fault free motor, but also with the FGA obtained for motors with defects. The proposed method does not depend on the specificity of the measured signal and is free from model assumptions about the signal.

Signal processing algorithm contains the stage of signals pre-processing, which includes: α - β transformation, decimation, FFT and selection of informative frequency ranges (IFR), as well as the stage of main processing, which includes: calculation of the function of the generalized average (FGA) and calculation of the slope of the current FGA with respect to the FGA obtained for a fault free IM, comparing the slopes with tabulated values and deciding on the IM technical condition.

Block diagram of the algorithm is shown in Fig. 1.

The algorithm includes the following steps:

1. α - β transformation

The three-phase IM stator currents are represented as a rotating space vector in the frame of reference, which is attached to the stator phase plane. The real axis α is connected to the axis of one of the stator windings, and the imaginary axis β is shifted in phase by 90 degrees. The transformation of coordinates from the measured currents of phases i_a , i_b , i_c to coordinates i_α and i_β is determined by the operation

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \quad (3)$$

2. Decimation

Modern measuring equipment provides an opportunity to increase the sampling frequency significantly. Moreover, modern sensor technologies allow measuring signals at high frequencies without increasing the noise. High-frequency information may contain diagnostic information. However, a high sampling rate increases the memory capacity. Therefore, the proposed method uses the procedure of decimation by averaging. Thus, only the average value of several measurements is used for further analysis. The input sample of the output signal \mathbf{x} is represented as an observation vector \mathbf{x}^T using the expression

$$\mathbf{x}^T = [x_1 \quad x_2 \quad \dots \quad x_M], \quad (4)$$

$$M = T \cdot F_s, \quad (5)$$

where M - is the total number of measurements;

T - time interval of data collection;
 F_s - initial sampling frequency.

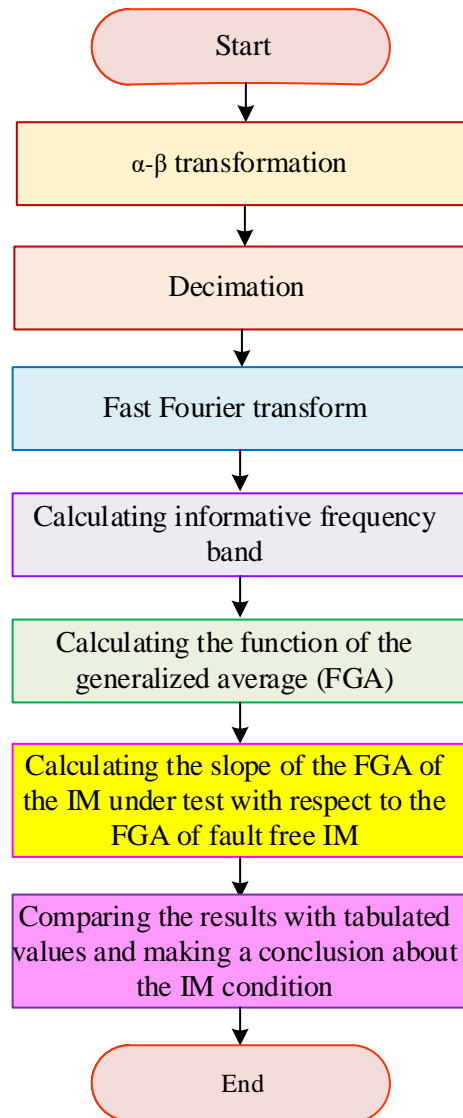


Fig. 1. Block diagram of the algorithm for processing current signals to solve the tasks of monitoring and diagnosing the IM technical condition

Decimation by an averaging process yields a signal \mathbf{y} that can be represented as an observation vector \mathbf{y}^T

$$\mathbf{y}^T = \left[\frac{1}{K_d} \cdot \sum_{n=1}^{K_d} x_n \quad \frac{1}{K_d} \cdot \sum_{n=K_d}^{2K_d} x_n \quad \dots \quad \frac{1}{K_d} \cdot \sum_{n=M-K_d}^M x_n \right], \quad (6)$$

$$K_d = \frac{F_s}{F_{dec}}, \quad (7)$$

where K_d - decimation coefficient;
 F_{dec} – frequency obtained after decimation.

Size N of vector \mathbf{y}^T after decimation is equal to:

$$N = \frac{M}{K_d}. \quad (8)$$

For further processing, it is enough to store only the signal \mathbf{y} , represented by a data buffer of size N , which is K_d times smaller than the initial vector \mathbf{x}^T .

3. Fast Fourier Transform (FFT)

Calculation of the full spectrum of the signal is performed using the FFT according to the expression

$$fftFull_k = \left| \frac{1}{\sqrt{N}} \cdot \sum_{n=1}^N y(n) \cdot e^{\frac{-(2\pi \cdot j)(n-1)(k-1)}{N}} \right|, \quad (9)$$

$$fFull_k = k \cdot \frac{F_{dec}}{N}, \quad (10)$$

where y – the signal after decimation;

N – the number of points after decimation;

$fftFull_k$ – amplitude module of the full Fourier spectrum;

$fFull_k$ – frequency of the full Fourier spectrum, $k=1, 2, \dots, N$.

In order not to consider the real and imaginary parts, a separate module is used.

4. Selection of informative frequency range

Informative frequency range (IFR) is a segment of the Fourier spectrum limited to a certain frequency range. The frequency range itself is selected depending on the type of analyzed defect. This allows to reduce the required number of calculations by increasing the sensitivity of the method, since non-informative harmonics will be absent in FGA calculations. Each defect affects the spectrum of IM signals differently. In order to analyze only the informative segment of the spectrum, the procedure of IFR selection was introduced. IFR depends on:

- (a) supply voltage frequency;
- (b) type of analyzed fault;
- (c) resulting frequency after decimation.

Selection of IFR is carried out in accordance with the following expression

$$IFR_l = fftFull_p, \quad (11)$$

$$l = 1, 2, \dots, p_{max} - p_{min}, \quad (12)$$

$$p = p_{min}, \dots, p_{max}; \quad p_{min} = floor\left(f_{min} \cdot \frac{N}{F_{dec}}\right); \quad p_{max} = floor\left(f_{max} \cdot \frac{N}{F_{dec}}\right), \quad (13)$$

where IFR – a segment of the Fourier spectrum included in IFR;

f_{min} - lower IFR limit;

f_{max} - upper IFR limit;

$floor(.)$ - rounding to a whole number.

5. Calculating the function of the generalized average (FGA)

FGA is calculated for the segments of the Fourier spectrum that are part of IFR according to the expression

$$\Delta_{(mom_p)} = \left(\frac{1}{L} \cdot \sum_{i=1}^L IFR_i^{mom_p} \right)^{\frac{1}{mom_p}}, \quad (14)$$

where L - the number of harmonics that are part of the segment of the IFR spectrum under consideration; mom_p - the moment order, which can be calculated according to the expression (2)

6. Calculation of the tangent of the inclination angle of the obtained FGA with respect to the reference FGA

The FGA calculated in the previous step is compared with the reference FGA. To compare the FGA with each other, it is required to calculate the tangent of the angle of inclination of the FGA obtained for the motor under test with respect to the reference FGA. The FGA for a fault free IM without load is proposed as the reference FGA. The tangent of the slope angle is calculated using the well-known linear least squares method. In case of complete coincidence of the studied FGA and reference FGA, the tangent of the slope angle will be equal to 1.

7. Comparison of slopes and a conclusion about technical condition

In this step, the calculated slopes are compared with predetermined values obtained for IM in different conditions. Initially, the obtained inclinations are checked for going beyond a certain confidence interval, which is selected empirically. If the inclinations go beyond this interval, a conclusion is made that the machine is not in a normal technical condition. This is the way the control of IM technical condition is implemented. Next, the value that exceeded the confidence interval of the inclination is compared with the values of the inclinations of previously obtained for various defects. If the obtained inclination value is close to the values of defect inclinations, then the corresponding fault is present in the IM under test. This is the way the diagnosis of the technical condition is implemented. The conclusion about technical condition of the motor under test is made based on this comparison.

Development of a structural diagram of the functional diagnostic system for monitoring the condition of induction traction motor rotor. The railways of Ukraine operate the rolling stock with induction traction motors with the use of field-oriented control system (FOC). In the literature, it is sometimes called a vector control system [28]. The latest trends in the design of rolling stock traction motors consider the use of a direct torque control (DTC) system [29]. Compared to FOC this system is more energy efficient, especially on rolling stock operating with frequent stops and starts, such as electric trains, shunting diesel locomotives, etc. Block diagram of the traction motor with DTC is shown in Fig. 2 [30].

Implementation of the proposed algorithm for diagnosing the rotor bars breaks of the IM rotor during the operation of the rolling stock (Fig. 1) requires the following signals: stator phase currents expressed in α - β I_α , I_β coordinates and supply voltage frequency f_s . As can be seen from Fig. 2, in the direct torque control system, the indicated currents are already determined. In the "Observer of torque and flux", in contrast to the systems with FOC [31], only the flux linkage is determined. Frequency of the supply voltage in traction motors changes in accordance with the change of the value of ω_{rset} signal. That is, during the operation of the rolling stock, the frequency of the supply voltage constantly changes.

Angular frequency of the supply voltage is defined as [31]

$$\omega_s = p \cdot \omega_r + s, \quad (15)$$

where ω_r – mechanical angular frequency of the motor shaft rotation;

s – rotor slip;

p – number of pole pairs

Rotor slip is determined from the equation [31]

$$s = \frac{I_{sy} \cdot k_r \cdot R_r}{\Psi_r}, \quad (16)$$

where I_{sy} - the value of stator current according to y coordinate;

k_r - coefficient of the rotor circuit;

R_r - resistance of the rotor circuit;
 ψ_r - flux linkage of the rotor according to x coordinate.

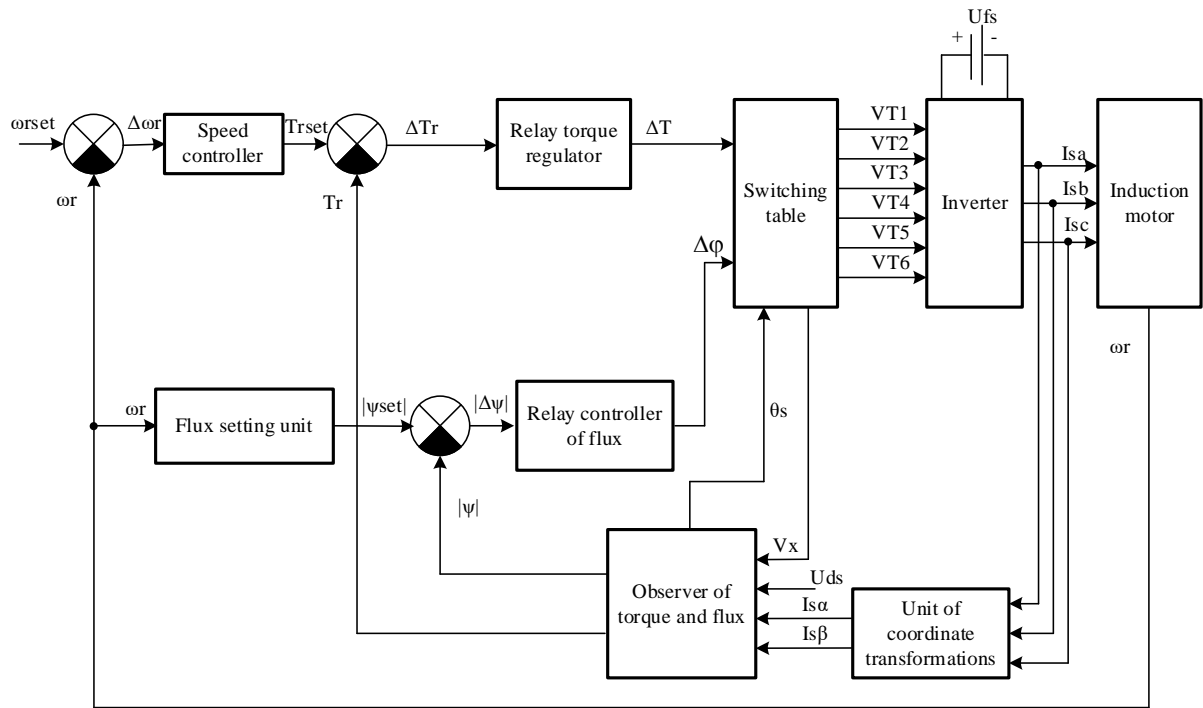


Fig. 2. Block diagram of the system for direct torque control in the induction traction motor

The rotor circuit coefficient is defined as

$$k_r = \frac{L_\mu}{L_{\sigma r} + L_\mu}, \quad (17)$$

where L_μ – inductance of the IM magnetizing circuit;
 $L_{\sigma r}$ – inductance of the rotor circuit dissipation.

To determine such values as I_{sy} and ψ_r , it is required to determine the values of the currents according to x and y . For this purpose, the Park transformation should be performed, which is defined in accordance with the expression [31]

$$\begin{cases} i_{sx} = i_{s\alpha} \cdot \cos\theta + i_{s\beta} \cdot \sin\theta; \\ i_{sy} = -i_{s\alpha} \cdot \sin\theta + i_{s\beta} \cdot \cos\theta. \end{cases} \quad (18)$$

Magnetization circuit of the induction motor can be described by the equation [31]

$$\psi_r = \frac{k_r \cdot R_r \cdot T_r}{1 + T_r \cdot s} \cdot I_{sx}, \quad (19)$$

where I_{sx} - stator current value by x coordinate;
 T_r - rotor circuit time constant.

implemented in “FFT”, where the spectral components of signal y are calculated using equations (9) and (10).

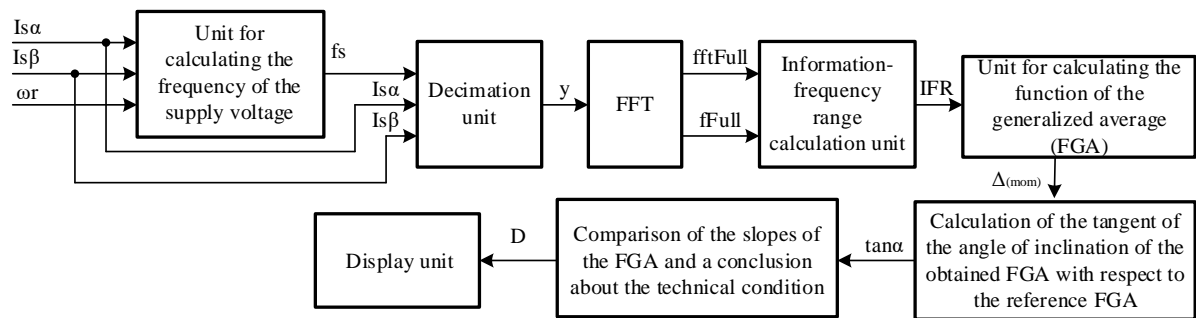


Fig. 4. Block diagram of the unit for diagnosing the presence of rotor bar breaks

In order to reduce the number of calculations and increase the sensitivity of the method, we applied the “Information-frequency range calculation unit”. It is used to calculate the informative frequency range (IFR) based on equations (11)-(13). For the calculated IFR in the “Unit for calculating the function of the generalized average (FGA)” based on equations (1) and (14), the function of the generalized average (FGA) is calculated. The calculation result is entered in the “Calculation of the tangent of the angle of inclination of the obtained FGA with respect to the reference FGA”, where FGA, calculated at the previous stage, is compared with the reference FGA. To compare FGAs with each other, the tangent of FGA angle of inclination obtained for the motor under test is calculated relative to the reference FGA. It is proposed to use the FGA for a fault free IM without load as the reference FGA. The tangent of angle of inclination is calculated using the well-known linear least squares method. In case of complete coincidence of the tested and reference FGA, the tangent of angle of inclination ($\tan\alpha$) will be equal to 1.

The values of the calculated tangent of the angle ($\tan\alpha$), i.e. the slopes of FGA, are entered the “Comparison of the slopes of the FGA and a conclusion about the technical condition”. In this unit, they are compared with the predetermined values obtained for IM in different conditions. Initially, the obtained slopes are checked for going beyond a certain confidence interval, which is selected empirically. If the slopes exceed this interval, it is concluded that the machine is not in normal technical condition. This is the way technical condition of the IM is fulfilled. Next, the value that exceeded the confidence interval of the slope is compared with the values of the slopes previously obtained for various defects. If the obtained slope value is close to the slope values of the defects, then the corresponding malfunction is present in the IM under test. In this case, the diagnostic signal D takes on a value equal to 1. In the opposite case, $D=0$. The value of the diagnostic signal is displayed on the information display device “Display unit”. Based on the value of the diagnostic signal, the driver makes a decision to shut down the traction motor with damaged rotor bars.

Conclusions. The work proposes a system for diagnosing the presence of rotor bar breakages in induction traction motor. The results of the work are as follows:

- performed analysis of technical solutions for diagnosing breakages of the rotor bars in induction traction motors, as a result of which it was established that the most effective method for diagnosing rotor bar breakages in the IM rotor is fractional moments statistics;
- developed an algorithm for diagnosing the condition of rotor bars based on the fractional moments statistics, which will allow its application in building a functional diagnostic system taking into account the operating condition of the traction motor;
- developed a block diagram of the unit for diagnosing the condition of IM rotor bars based on the fractional moment’s statistics;
- developed a block diagram of the system for functional diagnostics of the condition of rotor bars as part of traction motor with direct torque control.

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Розробка функціональної системи діагностики наявності ушкодження ротора в тягових асинхронних двигунах

Метою даної роботи є розробка системи функціональної діагностики наявності обривів стрижнів ротора в тягових асинхронних двигунах рухомого складу залізниць. Для досягнення мети були вирішені такі задачі: розроблено алгоритм діагностування стану стрижнів ротора на основі статистики дробових моментів; розроблено структурну схему блоку діагностики стану стрижнів ротора асинхронного двигуна на основі статистика дробових моментів; розроблено структурну схему системи функціональної діагностики стану стрижнів ротора в складі тягового приводу з прямим керуванням моментом. Найбільш важливими результатами є отримання математичної моделі статистики дробових моментів, зі зменшеним об'ємом обчислень та зі покращеною чутливістю методу. Ці результати були досягнені шляхом визначення інформаційно-частотного діапазону, що дозволило аналізувати не усі спектральні складові аналізованого сигналу, а тільки ту його частину, де можуть бути спектральні складові, характерні для обриву стрижнів ротора асинхронного двигуна. Даний підхід до діагностування стану стрижнів ротора може бути застосований також в тягових приводах рухомого складу з векторною системою керування асинхронними двигунами.

Ключові слова: асинхронний двигун, статистика дробових моментів, стрижні ротора, пряме керування моментом.

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Comparative assessment of resonant frequencies of the floor of suburban electric train cars

The work is devoted to the study of the resonant frequency characteristics of the floor of passenger cars for the modernization of suburban electric trains of the EPL2, EPL9 series. A horizontal vibrator loading scheme was adopted for the experiments. The aim of the study is an experimental comparative assessment of the resonant frequencies of the floor of cars with different variants of the structural structure. An experimental and computational method for determining the resonant frequency of the oscillatory system based on limited experimental data, namely the excitation frequency and the measured coefficient of reduction of the force amplitude, is proposed. Based on the tests, the frequency characteristics of the relative change in the amplitude of accelerations on the surface of the floor of different structures were obtained. The relative amplitudes are presented in the form of the amplitude growth coefficient k . It is found that the floor amplitude growth coefficient does not depend on the excitation amplitude and depends only on the frequency. The frequency characteristics of the floor design options with rubber shock absorbers differ significantly from the basic version in terms of resonant frequency – 104 Hz versus 69–75 Hz. The introduction of layers of the vibration damping membrane into the design scheme has a minor effect on the resonant frequency of the floor: 75–71–69 Hz.

Keywords: railway car, passenger comfort, floor vibration isolation, vibration levels, experimental studies.

Introduction. Suburban railway plays an important role in ensuring labor mobility of the population along the routes "suburban zone – megalopolis". The total time of daily work trips of citizens can be one to two hours. In fact, a trip to work or from work in an electric train is part of the worker's production activity. The level of passenger comfort during the trip determines the productivity of his activity and state of health. Suburban electric trains are characterized by a periodic mode of movement with frequent accelerations and braking in a wide range of speeds and frequencies of vibrations of the body floor. The level of vibrations perceived by passengers depends on the mechanism of their origin, the characteristics of the vibration transmission channel to the passenger and the quality of vibration insulation of the car floor.

Each of the above factors depends on the technical condition and characteristics of the passenger car. Today, the technical condition of passenger cars of the rolling stock of the railways of Ukraine is characterized by significant wear. About 85% of the rolling stock requires repair [1]. By order of JSC

«Ukrzaliznytsia» PJSC «Kyiv Electric Car Repair Plant» (KECRP) carries out major repairs and modernization of electric trains of the EPL2T, EPL9T etc. series. One of the main tasks of modernization is to increase the comfort and safety of passenger transportation and the working conditions of the locomotive crew. In addition, the modernized electric trains acquire a modern appearance and more efficient lighting devices. Fig. 1 shows the ED9M electric train before and after modernization at KECRP.



Fig. 1. Electric train ED9M before and after modernization

Modernization of electric trains includes measures aimed at reducing the level of vibrations transmitted to the passenger compartment through the floor. To form the modernization project, a study was conducted to determine the influence of the design and characteristics of the car floor on the level of vibrations transmitted to passengers in motion.

Analysis of recent research and problem statement. The main source of vibrations and noise perceived by passengers are dynamic processes in the contacts of wheel pairs with the track. In [2], an analysis of the parameters of vibrations arising from short rail irregularities with a wavelength of 15–20 mm is presented. It is proposed to reduce the impact of track vibrations on passengers by using vibration dampers in the range of 500–1000 Hz, which are characteristic of short rail irregularities.

In [3], the interaction of wheels with rails in the process of guiding wheel pairs along the track is considered. It is shown that significant interaction forces are a powerful source of vibrations transmitted to the running gear of the rolling stock. Passenger cars can also have additional sources of vibrations transmitted to the body from the drive and additional suspension equipment. In article [4], the level of vibrations, which depends on the technical condition of the gearboxes of passenger cars, is analyzed. The work conducted theoretical and experimental studies of the operation of gearboxes based on the analysis of the level and frequencies of vibration, on the basis of which a series of diagnostic features of the drive operation were proposed. The work did not consider the issue of reducing the level of vibrations transmitted to the body.

Article [5] contains the results of a study of the characteristics of the suspension of undercarriage equipment: transformers, traction converters, auxiliary converters, air compressors, etc. Due to the significant weight of the equipment and elastic suspension, it can be a source of powerful vibrations transmitted to the frame of the car. The conclusion is made about the need to take into account the influence of air temperature on the stiffness of rubber elements of the suspension of undercarriage equipment. It is determined that in the temperature range from -30 to $+40^{\circ}\text{C}$ the dynamic stiffness of rubber shock absorbers of the suspension of undercarriage equipment changes relative to normal conditions by -20% $+50\%$.

The article [6] presents the results of a study of vibrations affecting the level of passenger comfort using the example of the Tehran-Andymeshk train (Iran). The vibration transmitted to passengers was measured in accordance with ISO 2631-1-1997. Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration. The statistical relationship of 15 psychological and physiological disorders in passengers with age, gender, number of trips and the level of equivalent acceleration of the car was studied. The results did not reveal statistical relationships between symptoms of discomfort and

age. A significant impact on the well-being of passengers of the equivalent acceleration of the car was confirmed. The paper does not present an analysis of the influence of the parameters of the vibration of the car floor on the level of passenger discomfort.

In the article [7] local resonances of vibrations on the floor of high-speed trains, which negatively affect the comfort of passengers, are studied. Vibration peaks in the frequency range of 30–35 Hz are detected. Vibration attenuation is proposed using several subframe dynamic vibration absorbers. The results of the research show that the proposed method can reduce vibration, but only for certain modes, excluding the entire range of frequencies of vertical vibrations, which does not correspond to the modes of movement of suburban electric trains.

A feature of suburban diesel and electric trains is that passengers sit on seats or even stand on the floor throughout the trip. In the paper [8] the results of experimental studies of vibrations of the floor of railway cars are presented. The main aim of the research was to solve the problem of numbness of passengers' legs caused by vibration of the floor of railway cars. The analysis of the vibration characteristics of the floor shows that the vibration transmitted to the floor is significantly amplified in the frequency range of 20–50 Hz. This coincides with the frequency range in which the lower limbs of a person are most sensitive, which leads to numbness of the legs. To further study the vibration mechanism of the floor, a refined finite element model of the car body, including the floor panels, was developed. The results show that due to the inappropriate design of the rigidity of the elastic supports of the body, the deformations of the floor above the center of the bogie are significantly amplified for several typical modes in the frequency range of 20–50 Hz. Confirmation that at the oscillation frequencies of the car body frame, close to the natural frequencies of the floor, local resonance of the floor occurs, which is the main cause of numbness of the legs of passengers. The paper proposes optimization of the dynamic rigidity of the elastic support of the body. Experimental verification showed that as a result of the optimization of the suspension, the transmission of vibration from the chassis of the car body to the floor in the frequency range of 20–50 Hz was significantly reduced, due to which the problem of numbness of the legs was solved. Unfortunately, the proposed approach to the problem of reducing the vibration levels of the car floor based on the optimization of the spring suspension contradicts the tasks of the dynamics of the car movement.

In the article [9], the processes of vibration propagation in the material of the car floor and the influence of its structure on the properties of vibration absorption or insulation are considered. The processes of damping and vibration propagation are highlighted as separate. The types of vibrations transmitted from road irregularities and other sources from the car floor to the human body are considered. The article presents some results of the study of material vibration and an analysis of the propagation of material vibration in the floor is performed. The dominant frequency band of floor vibration is determined – these are low frequencies, between 20 and 40 Hz. In this range, the natural frequencies of the floor material can be identified. The results obtained allow determining the frequency range of the vibrator in experimental studies.

The article [10] presents the results of the assessment of vibration perceived by passengers of the Cairo metro. It is emphasized that high levels of body vibration of passengers can cause diseases and health problems, especially low back pain. Vibrations can also cause damage to the musculoskeletal system of the neck and back. After daily exposure for several years, these same body vibrations can lead to a number of health disorders, including damage to internal organs, muscles, joints and bone structure. The measurement data were analyzed according to ISO 2631-1 and ISO 2631-5. ISO 2631-1 (1997) uses daily exposure A(8) and VDV, while the new methodology of ISO 2631-5 (2004) uses Sed and R-factor parameters. The analysis revealed that the whole-body vibration absorbed by the human body increases with the magnitude and duration of vibration exposure experienced by passengers. It was found that subway passengers have a higher risk of exposure than bus passengers. The main conclusion of this study is that musculoskeletal symptoms and disorders of the lower back, neck and upper extremities in subway passengers may be the result of prolonged exposure to vibration, especially for passengers who sit during the trip.

The article [11] presents the results of many years of research on the relationship between vibration perceived by a passenger in a train car and pain that occurs in the lower back of a person. Based on the analysis of a large number of publications on this topic, a direct relationship between vibration exposure and back pain has not been confirmed on a mass scale. However, it was observed in a certain proportion of passengers (25%).

The impact of vibrations on humans in vehicles is most clearly manifested in the work of drivers. The article [12] examines the causes of low back pain (LBP), which is a common phenomenon among professional bus drivers. Studies have shown a relationship between the impact of whole-body vibration (WBV) and low back pain (LBP). The differences in the WBV level are considered using the example of two bus designs. An intercity bus with a high floor and a city bus with a low floor were considered. Experiments were conducted on different roads, i.e. with different excitation characteristics. As a result, it was concluded that on average the driver's seat attenuates vibrations transmitted by the floor by only 10%. This conclusion is important in studies of the vibration-protective characteristics of the floor of a passenger car and passenger seats. In particular, it indicates the need to pay attention primarily to the absorbing properties of the floor.

In [13], some problems associated with comparing measured passenger vibration levels with the standard are outlined, and the need to revise the standard format is discussed. A method for generalizing the attenuation of vehicle seat vibration is proposed. Two criteria for assessing the threshold impact of vibrations on the passenger are considered: the "limit of reduced comfort" and the "limit of qualification reduced by fatigue". It is shown that the vibration isolation of most vehicle seats is not effective enough.

In [14] it is emphasized that vibrations of the body perceived by passengers mainly occur in the low frequency range – up to 50 Hz. According to the researchers, they arise due to geometric defects of the wheels and rails. Vibrations are transmitted to passengers through the suspension stages and, finally, reach the body, floor and seats. In addition, the coupling effects of the assembled system should be properly taken into account. The dynamics of two subsystems of the car are studied, namely the floating floor and the passenger seat. The test results demonstrate a strong influence of the coupling between the floor and the seat on the frequency response of the vibrating unit. The methodology proposed in the article, which is based on both laboratory tests and numerical models, is a promising approach to the design and optimization of railway transport subsystems. The results obtained open up the prospect of improving the vibration protection of passengers based on vibration-isolating inserts between the floor and the seat.

A comprehensive model of the track-train-seat-passenger vibration system for lateral, vertical and roll vibrations is considered in [15]. The comfort characteristics of a high-speed train were studied. Ride comfort was assessed by the total equivalent acceleration determined according to ISO 2631-1. It was found that the flexibility of the rail bed has a negligible effect on floor vibrations. The flexibility of the body caused a sharp vibration of the floor in the lateral, vertical and tilt directions at frequencies above 7.5 Hz. Comfort indicators were the worst near the ends of the body. The vertical acceleration on the seats did not depend on the position of the seat.

The work [16] is devoted to the search for lightweight, laminated vibration-absorbing materials for the floors of railway cars. In particular, the possibility of using bamboo for floor elements is considered. Its important properties are emphasized: vibration-proof, noise-proof, fire resistance, strength. The developed composite material with bamboo inclusions combines the unique advantages of laminated construction and composite interface bionics. The low density (0.73 g/cm^3) of the layered composite provides a specific modulus of elasticity of $13.03 \text{ GPa cm}^3/\text{g}$, a vibration damping coefficient of 6.61% and an impact strength of 14.16 J/cm^2 . This is significantly higher than that of other wood-based composite materials used for the floors of high-speed train cars. This bamboo-wood composite material has great potential for use in the arrangement of floors of environmentally friendly railway cars.

The paper [17] presents the results of field tests of the dynamic characteristics of low-floor railway cars. The tests revealed the presence of predominant vertical vibrations at a frequency of about 8 Hz. It was proven that these vibrations are the result of the pitching motion of the cars. According to the results

of theoretical analysis, it was found that the cause of the pitching motion with a frequency of 8 Hz is the elastic characteristics of the articulated connection between the body and the bogies.

In the article [18], the results of experimental studies of the influence of viscoelastic damping materials on vibration reduction in railway cars were published. In particular, the paper emphasizes that the problem of noise and vibration has become particularly acute for high-speed train traffic. To reduce vibration and noise in railway vehicles, three types of viscoelastic damping materials were proposed: bitumen-based damping material; water-based damping coating and butyl rubber damping material. Measurements of vibration and noise levels were carried out on experimental cars, finished with new materials in various structural modifications. It was found that the effect of vibration reduction significantly depends on the speed of movement. One of the results suggests that the first two materials reduce vibration in a wider frequency range of 63–1000 Hz than the last damping material. They also reduce the level of internal noise in the car by 5–8 dBA, and the latter by 1–6 dBA.

Many studies claim that the main source of car vibrations is dynamic processes in the contacts of wheel pairs with the track. In particular, work [19] presents the results of the analysis of vibrations caused by irregularities in the railway track. The focus is on the mechanism of vibration excitation of the car body and its impact on passenger comfort. The hypothesis of the leading role of wheel pair vibrations in the vibration excitation of the car floor is confirmed based on the results of a numerical experiment on a multi-body model and experimental test data.

Works [6–10, 13, 15] contain important data on “dangerous” vibration frequencies for the human body, which are undesirable to allow in passenger cars. Therefore, before making a decision on floor modernization, in order to choose the most rational variant of its structure, it is necessary to conduct comprehensive theoretical and experimental studies. One of the directions of such studies is obtaining resonant frequency characteristics of the floor. This article is devoted to the first stage of resonant studies – on compact floor samples of different structures.

The aim and objectives of research. The aim of research is an experimental and theoretical comparative assessment of the resonant frequencies of the floor of suburban electric train cars on samples of different structural structures.

To achieve the aim, the following objectives were set:

- justification of the parameters of experimental samples of the floor of passenger cars of different structures;
- experimental studies of the resonant frequencies of the floor of different structures.

Materials and methods of research. The object of research is the resonant frequency characteristics of the floor of a suburban electric train car.

The main hypothesis of research: the introduction of rubber shock-absorbing elements into the structure of the floor of the car significantly affects its resonant frequency characteristics.

The study was carried out on experimental full-scale samples of the floor of passenger cars with different structural schemes. To obtain the frequency-amplitude characteristics (FAC) of the floor, an experimental complex was used, which consists of the following elements:

- vibration source – portable vibrator BCB -131/2 (produced by LLC NVF "Promvitech", Ukraine);
- UM 3-050 accelerometer (manufactured by the “SRDTI” branch of JSC “Ukrzaliznytsia”, Ukraine);
- equipment for recording the results of the experiment – analog-to-digital converter NI 9237 (manufactured by National instruments, USA);
- certified software for conducting research and processing results – LabVIEW (developed by National Instruments, USA).

In general, the model of the vibration protection system can be represented as three components: a source of vibrations; vibration isolation; object of vibration protection. The source of vibrations of a passenger car is the base (bottom) of the car, which is under the action of excitations from bogies and attachments. Vibrations are transmitted to the base of the car through its frame. Vibration isolation is a multi-component layered floor of a car, which includes elastic and dissipative elements, the function of which is to absorb vibration, and rigid power structural elements, the function of which is to support the

load from passengers, seats, partitions and internal equipment of the car. The object of vibration protection is passenger seats installed on the surface of the car floor.

The reaction perceived by the car floor from the vibration isolator side can be considered proportional to the deformation Δ and deformation rate $\frac{d}{dt}\Delta$ of the vibration isolator

$$R = C \cdot \Delta + \beta \cdot \frac{d}{dt}\Delta, \quad (1)$$

where C, β – respectively, the stiffness coefficient (stiffness) and the damping coefficient of the linear inertialess vibration isolator.

The stiffness coefficient of the vibration isolator C and the reduced mass of the vibration system m determine its natural frequency of oscillations ω_0

$$\omega_0 = \sqrt{\frac{C}{m}}. \quad (2)$$

The damping properties of the vibration isolator are characterized by the vibration damping coefficient δ

$$\delta = \frac{\beta}{2 \cdot m}, \quad (3)$$

According to the theory of resonance [20], the efficiency of the vibration isolator during force harmonic excitation can be estimated by the coefficient of reduction of the force amplitude k , which is transmitted to the vibration protection object

$$k = \frac{F}{F_0} = \frac{\sqrt{\omega_0^2 + 4 \cdot \delta^2 \cdot \omega^2}}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4 \cdot \delta^2 \cdot \omega^2}}, \quad (4)$$

where F_0 – the amplitude of force excitation according to the law $F_0 \cdot \sin(\omega \cdot t)$;

ω – the frequency of force excitation.

Fig. 2 shows typical amplitude-frequency characteristics of the vibration system for several values of the vibration damping coefficient δ .

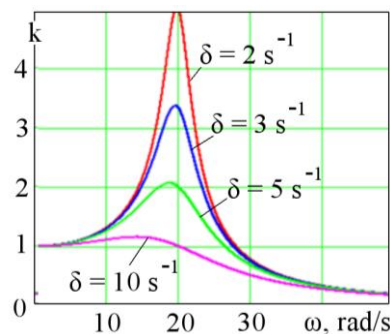


Fig. 2. Typical amplitude-frequency characteristics of an oscillatory system for different values of the oscillation damping coefficient

An experimental and computational method for determining the resonant frequency of an oscillatory system based on limited experimental data, namely the excitation frequency and the measured force

amplitude reduction coefficient λ , is proposed.

To do this, it is necessary to solve equation (4) with respect to ω_0 :

$$k(\omega_0) = \frac{\sqrt{\omega_0^2 + 4 \cdot \delta^2 \cdot \omega^2}}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4 \cdot \delta^2 \cdot \omega^2}}. \quad (5)$$

At this oscillation damping coefficient δ , cyclic excitation frequency ω and force amplitude reduction coefficient k are considered known.

This method is important for cases when the experiment has the possibility of creating external excitation only in a limited frequency range, or for fixed frequencies. It is such equipment that was used in this study. To solve equation (5), the Given-Find procedure of the MathCAD computing package (Parametric Technology Corporation – USA) was used.

Justification of the parameters of experimental samples of the floor of passenger cars of different structures. In the process of forming a project for the deep modernization of electric trains at the “KECRP” the task was set of choosing a structural floor structure that would best meet the criteria of comfort and smoothness of movement (SOU MPP 45.060-204:2007).

To conduct experimental studies of the vibration-proof properties of the floor of the modernized cars, four variants of the structure used on passenger cars and electric trains of Ukrzaliznytsia were selected. Fig. 2 shows photos and diagrams of the structural structure of the floor samples selected for the experiments.

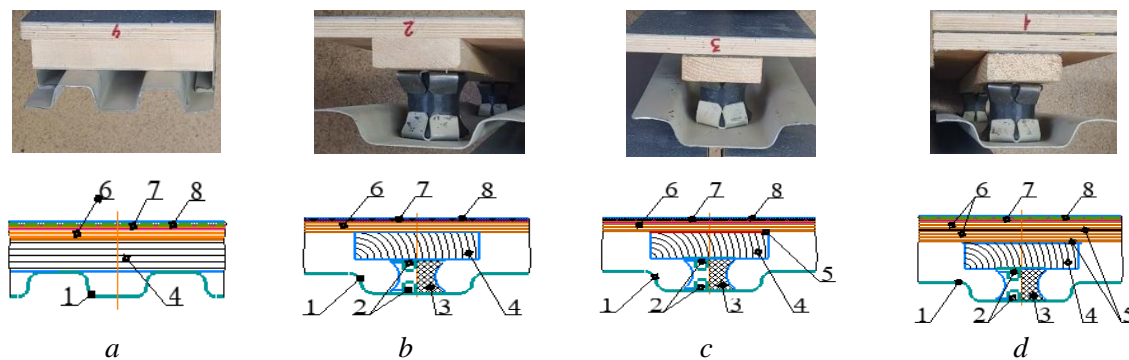


Fig. 2. Structural structure of the floor of the cars under study.

a – Ammerndorf car; b – KCBP car with rubber shock absorbers; c – modernized floor of car 61-776 with vibration-damping membrane; d – modernized floor of car 61-776 with two layers of vibration-damping membrane and plywood flooring: 1 – floor base; 2 – fasteners; 3 – rubber shock absorber; 4 – floor beam; 5 – vibration-damping membrane; 6 – floor covering; 7 – key layer; 8 – floor covering

Floor option a – Ammerndorf car – model 47-K (GDR). Ammerndorf cars have long been the most popular passenger cars on Ukrainian railways and have extensive experience in operation. Each of the other three floor samples is a certain step towards improving the vibration isolation structure: rubber shock absorbers – a layer of vibration damping membrane – an additional solid layer of vibration damping membrane. Floor option b – a car built by PJSC “Kriukiv Car Building Plant” (KCBP) (Ukraine) model 61-776 using a system of rubber shock absorbers. Floor option c – a modernized floor based on the 61-776 car model with the addition of a layer of vibration damping membrane. Floor variant d is a further modernized floor of the 61-776 model car with an additional solid layer of vibration damping membrane and a second layer of plywood flooring.

Table 1 shows the structural structure of the floor samples studied.

Table 1. Structural structure of experimental floor samples

Floor structure	Floor element material	Presence of an element on the floor option			
		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
Floor base	Profile sheet	+	+	+	+
Rubber shock absorber mount	Sheet B 1.5	-	+	+	+
Rubber shock absorber	Rubber B-14 (vulcanization)	-	+	+	+
Floor joist	Pine board – 50 mm	+	+	+	+
Vibration damping membrane-first layer	Vibrofix ML, 5kg/m ²	-	-	+	+
Floor sheet-first layer	Plywood PFA-T 20mm	+	+	+	+
Vibration damping membrane-second layer	Vibrofix ML, 5kg/m ²	-	-	-	+
Floor sheet-second layer	Plywood PFA-T 20mm	-	-	-	+
Linoleum adhesive	Ke 2000S glue	+	+	+	+
Floor covering	PVC (linoleum)	+	+	+	-
	PVC, 2TEC (Belgium)	-	-	-	+

Research objectives: to determine the impact of improving the structural structure of the car floor on its vibration-protective properties, for example, a vibration-damping membrane; rubber shock absorbers; the presence of a second layer of plywood flooring, etc.

Experimental studies of vibration isolation of floor options of different designs. The main element of the experimental complex for studying the vibration isolation of the floor of experimental cars is the source of exciting vibration – the BCB-131/2 vibrator ("Promvitech", Ukraine). The vibrator has the following characteristics:

- the direction of vibration creation – horizontal;
- the range of acceleration values – 1..20 m/s²;
- the range of vibration velocity values – 0.5..70.7 mm/s;
- vibration frequencies – fixed – three options – 45; 64; 79.6 Hz;
- the limit of permissible amplitude error – 3%;
- the limit of permissible frequency error – 0.2%.

Vibration sensors – UM 3-050 accelerometers (manufactured by the branch of "SRDTI" of JSC "Ukrzaliznytsia", Ukraine). The accelerometer is built on the ADXL 278 Analog Devices chip (USA). The collection and initial processing of experimental data is carried out by the CompactRIO controller of National Instruments (USA).

To measure the vibration parameters, convert signals and record the experimental results, a system of control running tests of rolling stock units (CRT) was used. CRT was developed at the Regional Branch of JSC "Ukrzaliznytsia" "Scientific Research and Design and Technological Institute of Railway Transport" ("SRDTIUZ").

Processing of measurement signals and recording of results - analog-to-digital converter NI 9237 (manufactured by National Instruments, USA) based on the LabVIEW software of the National Instruments company.

The equivalent loading scheme allows for the creation of artificial vibrations of experimental samples and their registration. Fig. 3 shows the loading scheme and the experimental complex.

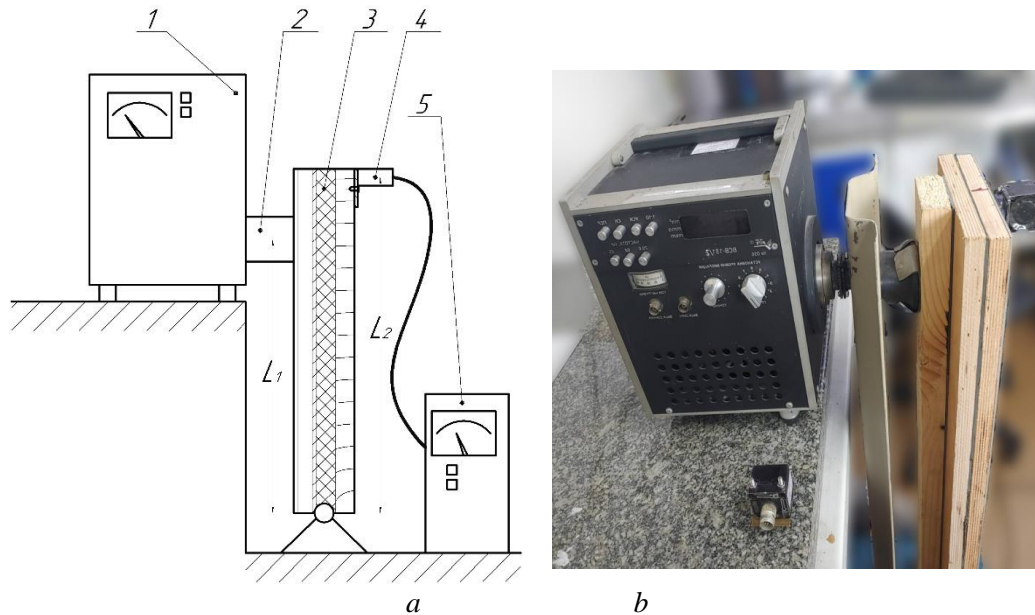


Fig. 3. Equivalent load scheme (a) and experimental complex for studying the parameters of floor vibration isolation (b):

1 – vibrator; 2 – movable vibrator rod; 3 – floor test sample; 4 – accelerometer; 5 – equipment for recording results

Research results. In accordance with the technical capabilities of the BCB-131/2 vibrator, the test was carried out at three fixed excitation frequencies – 45; 64; 79.6 Hz, with three amplitudes of vibrator excitation accelerations: 1.0; 1.5; 2.5 m/s².

As a result of the tests, the frequency characteristics of the relative change in the amplitude of accelerations on the floor surface of different structures were obtained. Relative amplitudes are presented as the acceleration amplitude growth factor k , as the ratio of the amplitude at a certain frequency to the amplitude at a frequency of 45 Hz, which was taken as the base (Fig. 4).

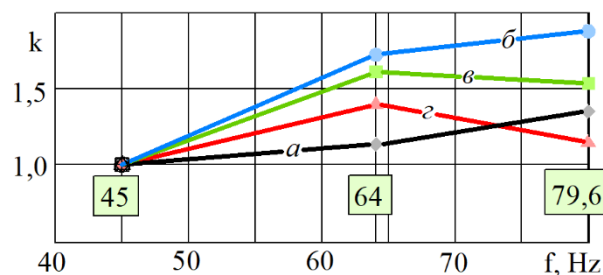


Fig 4. Frequency characteristics of the relative amplitude of accelerations on the floor surface k for different structures: a, b, c, d – variants of the structural structure of the floor

In addition, the following results were obtained.

For all investigated variants of the structural structure of the floor, the coefficient of growth of the acceleration amplitude (k) does not depend on the excitation amplitude. For all variants of the excitation amplitude k has close values and depends only on the frequency.

To calculate the resonant frequencies of the floor of the car f_r , the proposed experimental and computational method for determining the resonant frequency based on limited experimental data was used, namely, by the excitation frequency and the measured coefficient of reduction of the excitation force amplitude (5). The results obtained are presented in Fig. 5.

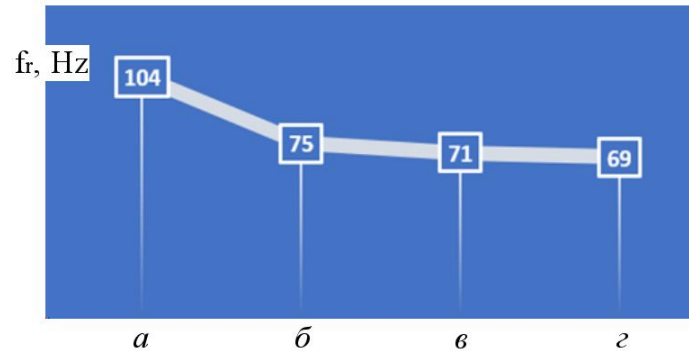


Fig 5. Calculated values of the resonant frequency for floor samples of different structures: a, b, c, d – variants of the structural floor structure

The frequency characteristics of the floor design variants with rubber shock absorbers – variants b, c, d – differ significantly from the basic variant a without rubber shock absorbers. In this case, the influence of rubber shock absorbers is manifested in a decrease in resonant frequencies from 104 Hz (floor without rubber shock absorbers) to 69–75 Hz (floor with rubber shock absorbers). The influence of the vibration damping membrane also manifested itself, namely, a shift of the resonant frequency towards low frequencies is observed. Thus, for variant b (without vibration damping membrane), the resonant frequency is 75 Hz, and for variants c and d – 71 and 69 Hz, respectively. The introduction of an additional solid layer of the anti-vibration membrane (variant d) slightly shifts the resonant frequency towards low frequencies compared to variant c.

Conclusions.

1. The parameters of experimental samples of the floors of passenger cars of different structural structures were substantiated for the experimental assessment of their vibration-protective properties. Four floor options were selected. The Ammerndorf (47-K) car was chosen as the basis for comparison, as it was the most popular passenger car on the railways of Ukraine for a long time and has extensive operating experience. Each of the other three cars is a certain step, a significant expansion of the means of improving vibration insulation: rubber shock absorbers – a layer of vibration-damping membrane – an additional solid layer of vibration-damping membrane.

2. An assessment of resonance zones for floors of different structural structures was carried out. The frequency characteristics of the relative change in the amplitude of accelerations on the surface of the floor of different structures were obtained. The relative amplitudes are presented in the form of a coefficient of growth of the acceleration amplitudes k , as the ratio of the amplitude at a certain frequency to the amplitude at a frequency of 45 Hz, which was taken as the base. It was found that the coefficient of increase in the amplitude of floor accelerations does not depend on the excitation amplitude and depends only on the frequency.

3. An experimental and computational method for determining the resonant frequency of the oscillatory system is proposed based on limited experimental data, namely the excitation frequency and the measured coefficient of reduction of the excitation force amplitude.

The frequency characteristics of the floor design options with rubber shock absorbers differ significantly from the basic version in terms of resonant frequency – 104 Hz versus 69–75 Hz.

The introduction of layers of a vibration damping membrane into the design scheme has a negligible effect on the resonant frequency of the floor: 75–71–69 Hz.

General conclusion: experimental studies are necessary on a full-scale car sample in a wide range of excitation frequencies to obtain more reliable characteristics of the influence of the passenger car floor structure on its resonant frequencies.

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Порівняльна оцінка резонансних частот підлоги вагонів приміських електропоїздів

Робота присвячена дослідженню віброізоляційних властивостей підлоги пасажирських вагонів з метою вибору конструктивної структури при модернізації електропоїздів приміської залізниці серій EP2, EP9, ЕПЛ2, ЕПЛ9, ЕД9, яку проводить ПрАТ «Київський електровагоноремонтний завод». На основі аналізу відомих досліджень вібрацій підлоги вагонів вибрано характеристики вібратора збудження механічних коливань – частоти і амплітуди прискорень. Для проведення експериментів прийнято горизонтальну схему навантаження. Метою дослідження є експериментальна порівняльна оцінка віброзахисних властивостей підлоги вагона з різними варіантами конструктивної структури. Були поставлені задачі дослідження: обґрунтування параметрів експериментальних зразків підлоги пасажирських вагонів різної конструктивної структури; проведення експериментальної оцінки резонансних зон підлоги пасажирського вагона різної конструктивної структури. Запропоновано експериментально-розрахунковий метод визначення резонансної частоти коливальної системи на основі обмежених експериментальних даних, а саме частоти збудження і виміряного коефіцієнта зменшення амплітуди сили. На основі випробувань отримано частотні характеристики відносної зміни амплітуди прискорень на поверхні підлоги різної структури. Відносні амплітуди представлено у вигляді коефіцієнта зростання амплітуд прискорень k , як відношення амплітуди на певній частоті до амплітуди на частоті 45 Hz, яку було прийнято як базову. З'ясовано, що коефіцієнт зростання амплітуди прискорень підлоги не залежить від амплітуди збудження і залежить тільки від частоти. Частотні характеристики варіантів конструкції підлоги, що мають гумові амортизатори суттєво відрізняються від базового варіанту і сприяють появі ознак резонансу у зоні відносно низьких частот в діапазоні 55–70 Hz. Ведення в конструктивну схему шарів вібродемпферної мембрани також сприяє зсуву максимальних коефіцієнтів зростання амплітуд у бік низьких частот. Але цей вплив є вкрай незначним.

Ключові слова: залізничний вагон, комфорт пасажирів, віброізоляція підлоги, рівні вібрацій, експериментальні дослідження.

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Migration and evolutionary analysis of trends in the transformation of maritime education in wartime conditions

The research focuses on analyzing fundamental changes in Ukraine's higher education system occurring under the influence of unprecedented geopolitical events and demographic shifts, with particular emphasis on the maritime education sector. The study examines the period of 2020-2023, characterized by large-scale challenges caused by Russian military aggression and its consequences for the educational sector. Based on the analysis of institutional reports and statistical data, significant changes have been identified in student contingent dynamics, redistribution of educational flows, and transformation of educational practices. The research results demonstrate that despite considerable adaptability and successful implementation of European educational standards, Ukraine's higher education system has faced serious challenges related to forced youth migration and demographic decline. This problem is particularly acute in the maritime education sector, where there is a persistent trend toward decreasing numbers of students. The paper substantiates the necessity of systematic state measures for developing maritime education in Ukraine. The research reveals the complex interaction between demographic trends, educational transformation, and sectoral development under wartime conditions.

Keywords: adult higher education; Education during the war, Maritime Education and Training, competitiveness of education, educational migration, MET.

Introduction. With the onset of the armed conflict in Ukraine, more than two million children were forced to leave their homes, becoming internally or externally displaced persons, which triggered a large-scale humanitarian crisis and affected the sustainability of the educational process. Military actions not only exacerbated the existing challenges caused by the COVID-19 pandemic but also led to reduced government spending on higher education, fewer state-funded positions in universities, and decreased household income levels. These factors significantly impacted the accessibility and competitiveness of domestic education.

Against the backdrop of these circumstances, students and faculty members found themselves in various situations: some students left the country, others remained in temporarily occupied territories or were subjected to shelling, some became internally displaced persons, while others experienced virtually unchanged living and learning conditions. University teaching staff also face significant challenges, including forced remote teaching and decreased stability in working conditions. The combination of these factors may lead to a substantial decrease in demand for national higher education, particularly among youth oriented toward international opportunities.

However, despite the negative consequences, the war has become a catalyst for long-awaited transformations in the education system, including the active development of digital and distance learning. The transition to digital formats, which began with the pandemic, has now become the primary

means of ensuring educational continuity. Furthermore, under these conditions, the importance of integrating Ukrainian universities into the international educational community and creating joint programs with foreign universities has increased, contributing to the enhanced competitiveness of Ukraine's higher education.

The prospects for transforming Ukrainian higher education extend beyond digitalization and distance learning. It is important to consider directions for strengthening international partnerships, implementing hybrid educational models, and developing educational programs adapted to changing socio-economic conditions.

Analysis of recent research and problem statement. Education has always been an important instrument for society's development, the foundation of cultural and economic progress, and a crucial factor in unlocking human potential. However, today Ukraine's educational system is affected by a range of negative factors, among which the consequences of the war, which has directly impacted every sphere of the country's life, should be primarily highlighted. Large-scale forced population displacement, destruction and damage to educational institutions, as well as limited access to educational resources are just some of the problems that have resulted from military actions.

The full-scale invasion of Russian forces into Ukrainian territory on February 24, 2022, not only directly impacted Ukraine's higher education system but also caused significant changes in the national systems of the EU and other civilized countries. From the first days of the war, Ukrainian universities found themselves under attack by Russian forces. By the summer of 2022, analysts from the Kyiv School of Economics reported that Russian troops had completely destroyed four higher education institutions, while nearly fifty others had been damaged. While these figures may seem less significant compared to the destruction of schools and kindergartens, in percentage terms, almost 20% of universities and institutions of professional pre-higher education were either destroyed or severely damaged.

According to data from the State Statistics Service of Ukraine, in 2021 there were 281 higher education institutions in the country, including universities, institutes, and academies, as well as 234 state-owned colleges. A total of 964,500 students were enrolled in universities, the majority of whom were pursuing bachelor's and master's degrees. Additionally, 25,600 individuals were pursuing doctoral degrees. Ukrainian higher education institutions employed 135,200 staff members, and 67,300 international students were enrolled.

According to the United Nations, as of October 2022, 7.6 million Ukrainian refugees were in other European countries, with 4.2 million registering for temporary shelter or participating in national assistance programs for Ukrainians. As a result of the Russian invasion, Ukraine experienced one of the largest displacements of people in history, with nearly 14 million people forced to leave their homes due to the ongoing conflict.

To date, over 10 million Ukrainian citizens have been forced to leave their homes due to shelling and the threat to their lives, causing a humanitarian crisis both within the country and beyond its borders. Approximately 2,000 educational institutions have been damaged due to bombings, a significant portion of which are beyond repair. Some universities and other educational institutions have been forced to relocate their campuses to safer regions, further complicating the educational process [1].

Moreover, the war has disrupted international student mobility and educational migration, significantly hindering access to quality education for both Ukrainian citizens and international students. The loss of access to educational resources and security has become a major issue, complicating the pursuit of quality education not only for Ukrainian citizens but also for foreign students who sought to study at Ukrainian institutions. The lack of stable conditions for studying and working in wartime has led to significant changes in the educational systems of

other countries, where Ukrainian students have sought refuge and continued their studies. This has necessitated the adaptation of educational systems to new realities, including flexibility in delivering education, supporting distance learning, and developing international educational programs to restore academic mobility once the conflict is over.

During this challenging period, it is important to remember that the problem is not limited to just physical destruction of educational institutions. Significant difficulties have also arisen due to challenges that emerged even before the COVID-19 pandemic and have become more pressing under wartime conditions. Issues such as education funding, reduction in state-funded positions in higher education institutions, declining household incomes, and intensification of educational migration processes have placed additional strain on Ukraine's educational system. The demand for domestic education is decreasing, which is an alarming signal for the future.

According to the Strategy for Higher Education Development in Ukraine for 2021-2031, the main problem of the educational system is its lack of demand in Ukrainian society, which, combined with the massification of education, creates distortions in the educational process. Under these conditions, the war has become a catalyst for necessary changes, particularly in the direction of digitalization and distance education, which maintains access to learning even under physical and logistical constraints.

At the same time, despite serious difficulties, the Ukrainian state continues to follow the defined direction of higher education reform aimed at integration into the European and global educational community. Progressive legislative initiatives, such as the national "Education" program, the Law of Ukraine "On Higher Education," and the Presidential Decree "On the Main Directions of Higher Education Reform in Ukraine," should become the foundation for building next-generation education capable of withstanding modern challenges and becoming competitive at the international level.

To implement this strategic vision, united efforts of government bodies, universities, businesses, the scientific community, and the public are necessary [2]. An innovative approach to development, based on the active use of scientific knowledge, achievements, and support for innovative activities, becomes particularly important.

Given a number of global challenges, the higher education system in Ukraine requires a deep rethinking of its role and objectives. Training specialists capable of acting in conditions of rapid change, addressing sustainable development issues, and maintaining harmony between humans and nature should become a key priority.

The reform of Ukrainian higher education aligns with global trends such as standardization, focus on core disciplines, implementation of modern management, and increased university accountability for education quality. Overcoming existing problems and implementing the strategy for higher education development is a crucial task that determines Ukraine's future.

Recognized Western researchers of educational systems emphasize the necessity for deep and decisive transformations in higher education. They warn that without decisive changes, higher education may remain within a conservative approach, limited to only local innovations. Conservative models that dominated in the second half of the 20th century no longer meet modern needs.

Since independence, the Ukrainian higher education system has undergone significant changes, gradually integrating into the global educational and scientific space. The COVID-19 pandemic had a significant impact on this process, accelerating the implementation of distance learning and the transformation of teaching and examination methodologies. The pandemic effectively accelerated higher education's transition from traditional to online formats [3].

However, the connections between Ukrainian higher education and the global system remain insufficiently strong. Even leading Ukrainian universities hold limited positions in world rankings, and the level of scientific productivity and citation rates of their academic staff significantly lag behind those of foreign colleagues. For example, in 2021, only 10 Ukrainian higher education institutions entered the

World University Rankings, occupying positions in the range of 491-819 among 867 universities. The low level of internationalization in Ukrainian higher education and science negatively affects the quality of educational and scientific processes.

At the same time, the global community views higher education as the primary tool for social, cultural, and economic modernization. Therefore, all countries are currently seeking innovative approaches capable of ensuring noticeable progress, as no state is fully satisfied with the condition of its higher education system [4-5].

Given the high competition in the labor market, modern youth must be able to demonstrate necessary knowledge, skills, and competencies. This requires creating an effective mechanism for state regulation of the youth segment of the labor market. Such a mechanism should ensure close cooperation among all stakeholders (public administration bodies, higher education institutions, employers, and youth) in overcoming problems of youth unemployment and professional-qualification imbalances, as well as promote increased youth motivation for highly effective activities.

The purpose and tasks of the study. Ukraine has one of the largest maritime industries in the world, and maritime education is critically important for the country's economic growth. Training specialists in the maritime field provides employment opportunities and contributes to logistics development. The maritime education system in Ukraine represents a comprehensive structure that fully complies with international standards, particularly the STCW Convention (Standards of Training, Certification and Watchkeeping for Seafarers) and its Manila Amendments. This regulatory architecture encompasses both international protocols and national legislation, creating a reliable system for training and certification of seafarers.

The regulatory framework has a hierarchical structure, where the STCW Convention and SOLAS (International Convention for the Safety of Life at Sea) form the fundamental international level. These conventions establish basic standards of competency and safety requirements for maritime operations. Particularly important is Ukraine's full implementation of the Manila Amendments to the STCW Code, covering competency standards at both operational and management levels [9].

The national regulatory framework includes several interconnected elements, particularly the Law of Ukraine "On Higher Education" and special ministerial directives regarding maritime education. This legislative foundation is supplemented by industry standards and quality assurance mechanisms. The Ukrainian maritime education system implements a multi-level approach to quality management, including ISO 9001:2015 standards and institution-specific quality management systems.

A distinctive feature of the Ukrainian maritime education system is its comprehensive integration of theoretical learning and practical training. The system takes into account specific requirements of shipowners and recommendations of the International Maritime Organization (IMO), providing graduates with both academic knowledge and practical competencies necessary for the international maritime industry.

Ukraine holds an important position in the global market of maritime professionals, having four leading educational institutions that are members of the International Association of Maritime Universities (IAMU):

- Kherson State Maritime Academy (KSMA), Kherson;
- National University "Odessa Maritime Academy" (NUOMA), Odessa;
- Odessa National Maritime University (ONMU), Odessa;
- Kherson State Maritime Academy (KSMA), Kherson;
- State University of Infrastructure and Technologies (SUIT), Kyiv.

However, the war in Ukraine has become a serious obstacle to providing quality maritime education and cadet training. Educational institutions were forced to switch to an exclusively online learning format, without the possibility of conducting necessary practical training. More than a third of teaching staff found themselves outside Ukraine, and state funding for institutions has been reduced to a critical level.

Despite these challenges, Ukraine remains on the International Maritime Organization's "White List," demonstrating full compliance with the STCW Convention and Code requirements. Ukrainian seafarer

certificates (diplomas) are recognized by 53 IMO member states in accordance with Regulation 1/10 of the STCW Convention. Furthermore, Ukraine's system of seafarer training and certification has been approved by the European Commission following periodic inspections by the European Maritime Safety Agency (EMSA).

According to BIMCO's 2015 maritime workforce report, the number of STCW-certified seafarers available for the international merchant fleet has increased, with growth in both qualified officers and ratings. The number of STCW-certified officers is now estimated at 857,540, representing a 10.8% increase from 2015.

According to data collected from shipping companies, Ukraine ranks among the top five nationalities of STCW-certified seafarers (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) working in the global merchant fleet.

According to the Seafarer Workforce Report 2021 by BIMCO (Baltic and International Maritime Council), Ukrainian seafarers are represented in all key segments of this market (Tab. 1)

Tab. 1. Five main nationalities of STCW seafarers as indicated by shipping companies

	All seafarers	Officers	Ratings
1	Filipino	Filipino	Filipino
2	Chinese	Chinese	Chinese
3	Ukrainian	Ukrainian	Indian
4	Russian	Indian	Ukrainian
5	Indonesian	Russian	Indonesian

The maritime education system in Ukraine demonstrates significant potential for training highly qualified specialists capable of meeting the needs of the modern international shipping industry. Several key advantages of the Ukrainian model of training seafarers and cadets ensure the sustainable competitiveness of its graduates in the global labor market.

First and foremost, it is worth noting the high motivation of Ukrainian citizens to work in officer positions in international shipping. The prestige and promising nature of maritime professions in Ukraine stimulates a significant influx of applicants to specialized educational institutions. This, combined with the institutions' capacity to increase enrollment, creates broad opportunities for training a sufficient number of ship officers.

An additional advantage is the relatively low cost of education, complemented by the opportunity for the best students to receive state funding. Such accessibility of education promotes the attraction of talented youth to the maritime industry, ensuring a stable source of qualified personnel.

Ukrainian universities and academies also demonstrate flexibility and efficiency in their seafarer training and certification system. Specifically, the transition to junior officer status can be achieved within a 4-year educational cycle, accelerating graduates' professional adaptation. An important element is also the involvement of experienced practicing seafarers in teaching activities, ensuring a close connection between theoretical training and maritime practice realities.

Further evidence of the high quality of maritime education in Ukraine is the active support of educational programs by industry companies, particularly through scholarships and other forms of assistance. Such interaction allows alignment of educational program content with current and prospective needs of the shipping industry. Moreover, significant attention is paid to language training and simulator preparation of cadets, ensuring compliance with international standards.

The comprehensive combination of these advantages enables Ukraine to train competitive specialists who are in demand in the global maritime industry. Further improvement of educational standards and teaching methods, along with strengthening industry connections, will contribute to maintaining the leading position of Ukrainian maritime education at the global level [7-8].

The war unfolding in Ukraine presents a serious challenge to ensuring quality training for future maritime professionals. Government restrictions on men's travel have led to significant difficulties for cadets in completing mandatory onboard vessel training. Additionally, logistical complications hinder the timely return of already working students. These factors, along with many cadets' desire to continue

their studies abroad, create serious obstacles for the Maritime Education and Training (MET) system in Ukraine.

Continuous practice on actual vessels is a critically important component of quality maritime specialist training. The inability to complete this practice not only deprives cadets of necessary experience but also threatens the compliance of Ukrainian educational programs with international standards. Alternative forms of practical training, such as the use of simulators and virtual trainers, could help address this problem by partially compensating for the lack of actual onboard practice.

Logistical difficulties related to Ukrainian students' stays abroad also present a serious problem. Delays in returning home not only disrupt the educational process but may also cause students to lose the opportunity to continue their studies. Establishing close coordination between educational institutions, government bodies, and shipping companies to ensure unhindered student movement could serve as an effective solution.

At the same time, the desire of many cadets to continue their studies outside Ukraine is an understandable and justified step. However, excessive outflow of talented youth poses a threat to the future restoration and strengthening of the country's maritime education system. Targeted support programs and scholarships for studying in Ukraine, as well as ensuring employment opportunities for graduates, could help address this issue.

Materials and methods of research. Emigration for education is not a new phenomenon. The departure of Ukrainian youth abroad to obtain higher education is a phenomenon with a long history and stable development trends. Before the war in Ukraine, this migration was largely voluntary, massive, and sociocultural in nature, characterized by clearly defined periods of students' stay abroad and their age characteristics.

According to the results of an online survey conducted among students, faculty, and staff of Ukrainian higher education institutions who remained in the country, 97.8% of respondents reported a deterioration in their psycho-emotional state. Complaints of depression were expressed by 84.3%, exhaustion by 86.7%, loneliness by 51.8%, nervousness by 84.4%, and anger by 76.9%. Students, compared to staff, more frequently reported feelings of exhaustion, loneliness, nervousness, and anger, while women more often than men reported depression, exhaustion, loneliness, and nervousness. The authors of the study indicate that respondents who complained of a deterioration in their psycho-emotional state showed higher levels of fear, burnout, and feelings of loneliness, as well as a lower level of resilience [28].

These serious psycho-emotional challenges faced by students and faculty members of Ukrainian higher education institutions may negatively impact not only academic performance but also the overall social climate within these institutions. In such conditions, it is important to pay attention to global trends that could help preserve the intellectual potential of the country and support Ukrainian students and researchers during these difficult times.

Statistical data from the Organisation for Economic Co-operation and Development (OECD) confirm a steady global trend of increasing numbers of international students worldwide. In 1975, their number was 0.8 million, rising to 4.3 million in 2011 and 4.85 million in 2017. It was expected that by 2020 this number would reach 8 million. However, the COVID-19 pandemic introduced some adjustments, but this trend is recovering, opening new opportunities for Ukrainian students, especially those who, due to the war, were forced to seek new ways to pursue education abroad [10].

Among countries that traditionally act as "importers" of educational migrants, highly developed nations with significant scientific potential and leading positions in world university rankings predominate. The world leaders in terms of international student share include the USA, United Kingdom, Australia, France, Germany, and Canada (Tab. 2). The high demand for Ukrainian students in the global educational market is explained by their foreign language proficiency and professional competencies acquired in their homeland.

Tab. 2. Comparative Analysis of Study Conditions for Ukrainian Students in Countries with High Levels of Academic Support and Accessibility

Countries	Possibility of free education	Relatively easy-to-learn language	Prospects for obtaining prestigious employment	Affordable cost of education and living	Easy admission requirements to higher education institutions	Study at world-ranked higher education institutions
Poland	+	+	+	+	+	+
Czech Republic	+		+	+	+	
Spain			+	+		
Canada		+	+			+
Italy			+	+		
Austria			+		+	
United Kingdom		+				+
Germany	+		+			+
United States	+	+				+
France			+	+	+	+

The USA and France, along with other countries, view Ukrainian students as desirable migrants due to their language skills and professional competencies. One of the key factors attracting international students is free or affordable education at public universities. Such conditions are offered, in particular, by Poland, Germany, and partially France.

Poland is a popular choice for Ukrainian youth planning to study abroad due to its proximity to Ukraine both territorially and culturally. Poland offers quick adaptation for students, ease of language learning, affordable living and study costs, and the possibility of free education. Recently, Polish universities have intensified their activities in the Ukrainian educational services market. In the context of demographic crisis and youth migration abroad, Poland actively seeks applicants from Ukraine, focusing on geographical, linguistic, and cultural proximity between the countries. For this reason, Poland makes efforts to create attractive conditions for international students, particularly from Ukraine.

The Czech Republic is also one of the leaders among countries offering free education if programs are taught in Czech. Spain attracts students with accessible pathways to professional education and prestigious diplomas. Education in public institutions is inexpensive, and students have opportunities for internships in Spanish companies. Canada attracts youth thanks to its numerous Ukrainian diaspora, which facilitates faster student adaptation. Admission to Canadian universities is possible after completing 11th grade, without mandatory preparatory programs.

Italy is known for its programs in fashion and design. The cost of education here is moderate compared to other European countries, making Italy attractive for many students.

The United Kingdom offers an Online MBA program that allows Ukrainian citizens to study without leaving their country. These students receive textbooks by mail, attend online lectures, and take written examinations. Upon completion of their studies, they receive a British diploma.

An important factor motivating Ukrainian students to pursue higher education abroad is the prospect of obtaining quality employment and permanent residence after graduation [6]. The attractiveness of different countries for Ukrainian youth is determined by various aspects, including study and living conditions. The main motives for educational migration among Ukrainian youth include safe conditions for staying and studying abroad; high-quality education at prestigious institutions; opportunities for obtaining prestigious work and subsequent permanent residence; availability of tuition-free programs; relative ease of admission; affordable study and living costs; and better economic and social conditions

Current demographic trends in Ukraine show concerning signs of intellectual and physically developed young population outflow to other countries. This process, along with a complex of socio-economic problems, indicates a deep demographic crisis that threatens the national security of the state.

Students abroad most frequently face issues such as financial difficulties, language barriers, challenges in finding employment, unstable mobile and internet connections, limited access to medical services, problems with housing search and payment, as well as psychological issues.

In a fundamentally different situation are the students, teachers, and staff of higher education institutions who remained in Ukraine in the government-controlled territory. Their activities underwent substantial transformation, yet they managed to adapt to the new conditions of the educational process functioning.

The educational process in Ukrainian higher education institutions began to resume from mid-March in remote or blended formats. Despite challenging conditions, higher education institutions demonstrated significant flexibility and adaptability, implementing innovative approaches to organizing the educational process.

Teachers and students face psycho-emotional challenges related to the general situation in the country, yet they have the opportunity to continue the educational process in relatively safe conditions. Higher education institutions are actively implementing technological solutions to ensure quality distance learning, developing new teaching methodologies and knowledge assessment approaches [29].

An important aspect has been the support for students and teachers who were forced to relocate from occupied territories. Ukrainian higher education institutions created conditions for continuing education and work for displaced persons, providing them with necessary resources and support. Educational institutions have also developed mechanisms for recognizing learning outcomes and confirming qualifications of students who previously studied in temporarily occupied territories.

Despite wartime challenges, Ukrainian higher education institutions continue to provide high-quality educational services, maintain international connections, and develop new educational programs. Special attention is paid to preserving the academic community and supporting professional development of teaching staff in remote working conditions.

It is worth noting that higher education institutions in government-controlled territory have become important centers of support and coordination of the educational process for the entire academic community of Ukraine. They not only ensure educational continuity but also contribute to the preservation and development of Ukrainian academic culture under martial law conditions.

The unprecedented challenges facing Ukrainian higher education have catalyzed rapid transformation and adaptation of educational processes, demonstrating the resilience and commitment of the academic community. This transformation encompasses not only technological adaptation but also fundamental changes in educational methodology and institutional support systems, reflecting the sector's capacity for innovation under extreme circumstances.

At least several issues can be identified related to the organization of the educational process in Ukrainian higher education institutions. Firstly, the completion of the 2021/2022 academic year took place under challenging conditions. Although continuity in the educational process was maintained, it required significant effort. The academic year concluded in an accelerated format, particularly for universities that had been relocated or damaged, which imposed additional demands on students, faculty, and administration - especially on graduating students who needed to complete qualification exams and defend their theses.

Secondly, the motivation to teach and learn was significantly affected by the constant state of uncertainty, unstable psycho-emotional environment, and frequent air-raid alerts, with some participants in the educational process facing shelling in active conflict zones. Most surveyed students indicated that it became more difficult to concentrate on their studies; however, the majority also confirmed that they had not lost interest in learning. For faculty and HEI staff, key motivational factors remained their students, a sense of duty and responsibility, and belief in Ukraine's victory.

Third, potential losses in the quality of the educational process should be noted. The period of quarantine restrictions demonstrated that not all institutions managed to implement high-quality distance

learning. This challenge required both technical and pedagogical improvement, and in wartime conditions, this issue has become even more acute.

The situation in Ukraine's maritime education system causes particular concern. Analysis of reporting documentation from heads of specialized higher education institutions indicates a steady trend of decreasing student enrollment during 2020-2023. This phenomenon takes on critical significance considering the strategic importance of the maritime sector for the country's economy and its position in the global maritime services market.

Analysis of annual reports [12-27] from maritime higher education institution rectors demonstrates a gradual reduction in the total number of students (Fig. 1).

The data demonstrates a clear downward trajectory in student enrollment from 2020 to 2023, with some recovery in the final year. In 2020, the total student population stood at 21,936, establishing a baseline for comparison. The following year witnessed a modest decline of 3.2%, bringing the total to 21,232 students. This initial decrease, while concerning, remained within manageable parameters.

In 2022, the Ministry of Education and Science of Ukraine attempted to support maritime specialties amid wartime challenges by simplifying the admission process. For certain specialties within maritime higher education institutions, admission to the contract-based form of study was permitted solely based on a motivation letter, aiming to ease access to education. However, despite these efforts, 2022 saw a sharp decline in student numbers, dropping to 19,137 individuals—a significant decrease of 9.9% compared to the previous year. This downturn marked the most pronounced change within the study period and highlights a critical juncture in the demographics of maritime education, one that proved unavoidable despite the measures taken.

Therefore, while policy adjustments such as simplified admissions reflect efforts to mitigate enrollment losses, more comprehensive strategies are required to support the sustainability of maritime education in Ukraine. These might include increased financial aid, mental health support, enhanced digital infrastructure for remote learning, and strong industry partnerships to provide career opportunities for graduates.

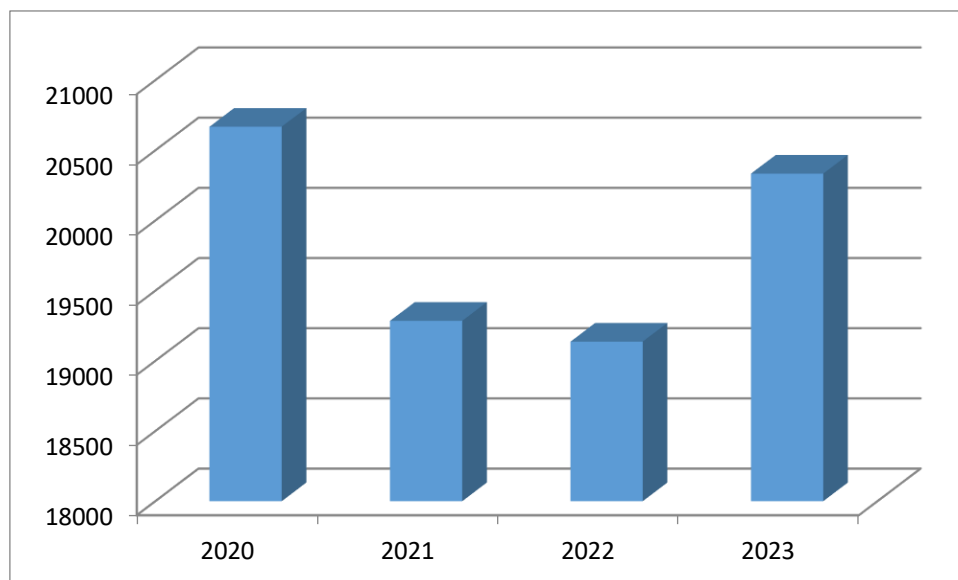


Fig. 1. The dynamics of student enrollment in Ukrainian maritime higher education institutions (2020–2023)

The most recent data from 2023 shows signs of recovery, with numbers rising to 20,334 students, representing a 6.3% increase from the 2022 low. While this uptick is encouraging, it's important to note that enrollment remains 7.3% below the 2020 baseline, indicating persistent challenges in student retention and recruitment.

At the same time, 47% of surveyed students indicated that the quality of education in their program had not changed, while 38% reported a slight decline. This suggests that the losses accumulated during the pandemic have only intensified with the onset of the war. Another significant aspect impacting the quality of higher education in Ukraine is full access to learning. A distinction should be made between the end of the 2021/2022 academic year and the beginning of the 2022/2023 academic year. While ensuring safe conditions for students and faculty was the main challenge in the spring, the situation worsened in the fall due to power outages, unstable internet access, and heating issues, which further deepened the crisis in organizing distance learning [30].

In the new academic semester, students, faculty, and staff in Ukrainian universities were forced to work as efficiently as possible within limited time periods when electricity and internet access were available in their homes or university facilities. Additionally, as during the pandemic, most Ukrainian higher education institutions only partially adapted their educational processes to the distance format. Changes in the formats of classes, assessment, scheduling, and so forth were not fully implemented. Despite faculty members' interest in teaching, students noted that most of them had not altered assessment criteria, adapted course content, or modified assignment types to suit the new learning conditions.

Between 2020 and 2023, several Ukrainian maritime and transport institutions, including saw varying trends in their enrollment numbers. The study aimed to analyze the enrollment campaigns at these universities and their structural subdivisions to understand student preferences, the impact of external factors such as economic and social changes, and the overall growth or decline in student interest in maritime and transport education (Fig. 2).

One of the most notable changes is the significant increase in the student body at the Kyiv institution, specifically in the State University of Infrastructure and Technologies (SUIT) in Kyiv. While in 2021 the number of students was 3,495, by 2023 this figure had risen to 4,851, representing an increase of approximately 38.8%. This growth can be explained by the mass relocation of students from occupied territories to the capital. Kyiv has become one of the main centers attracting students, as many universities in the capital offered the possibility of studying in safer conditions. Student mobility from dangerous regions significantly increased the student population in these institutions.

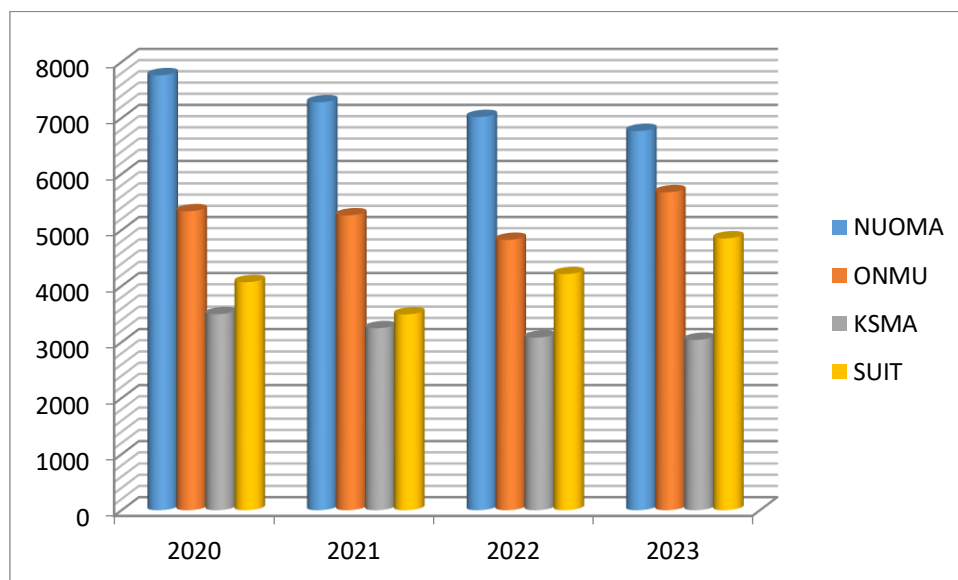


Fig. 2. The dynamics of student enrollment in Ukrainian maritime higher education institutions (2020–2023)

In contrast, Kherson State Maritime Academy (KSMA) has shown a significant decrease in enrollment. The number of students dropped from 3,499 in 2020 to 3,040 in 2023, reflecting a decline

of about 13.1%. This decrease is directly related to the prolonged occupation of Kherson, which has led to considerable difficulties in restoring the educational process. After the de-occupation of the city, the university faced numerous challenges, including infrastructure damage and staff shortages. Ongoing hostilities also contributed to the emigration of students, many of whom were unable to return to their studies.

The National University "Odesa Maritime Academy" (NUOMA) shows the most substantial decline in student enrollment over the period from 2020 to 2023 — from 7,763 to 6,769 students, a decrease of approximately 12.8%. This decline may be explained by the loss of its branch in Mariupol, which was captured by occupying forces. As some students were unable to evacuate, and a significant number who did relocate opted to continue their studies abroad, the total student population of the university decreased. The loss of this branch, which traditionally enrolled a significant number of students, had a substantial impact on the university's overall enrollment.

The Odesa National Maritime University (ONMU) demonstrates relative stability with a trend toward growth in recent years. This may reflect the institution's adaptation to new conditions, particularly through the transition to online learning formats, preservation of infrastructure, and the opportunity for students to continue their education amid wartime conditions.

The decline in student enrollment in these institutions reflects a combination of internal and external factors that hinder stable growth and development. Although there was some recovery in 2023, the overall situation remains challenging:

- The general trend shows a decline in enrollment from 2020 to 2022, likely due to economic and social factors, including the impact of the COVID-19 pandemic and the war. The instability of regions where maritime educational institutions are located, along with difficulties in restoring the educational process after lockdowns and occupation, has led to student outflows and a decrease in applicant numbers.

- In 2023, certain institutions, such as The Odesa National Maritime University (ONMU) and the the State University of Infrastructure and Technologies (SUIT), saw an increase in student numbers, which may indicate a degree of stabilization or enhanced recruitment efforts. Measures introduced by these institutions, such as tuition discounts, program enhancements, and recruitment campaigns, have contributed to this positive trend.

- However, the total number of students in 2023 remains below the 2020 level, indicating that the downward trend in higher education in Ukraine's maritime institutions persists. Despite some progress, challenges related to security, economic pressures, and competition with other educational institutions continue to affect the overall state of the sector.

Although a slight recovery was observed in 2023, the situation remains challenging. To stabilize and further develop maritime institutions, comprehensive measures are necessary, including improved security, reduced tuition costs, increased international support, and modernization of educational programs to enhance their competitiveness.

Conclusions. The higher education system of Ukraine is experiencing an unprecedented period of changes driven by a complex interweaving of geopolitical and epidemiological factors. Despite the complexity of the situation, the educational sector demonstrates significant adaptive potential and the ability to rapidly transform established paradigms.

Analysis of the current state of affairs indicates a substantial modification of approaches to organizing the educational process in higher education institutions. Despite the territorial dispersion of educational process participants, higher education institutions have managed to ensure the continuity of learning. This became possible due to flexibility and prompt response to new challenges.

It is worth emphasizing that this adaptation occurred against the backdrop of existing systemic transformations related to the implementation of European educational standards and modernization of the quality assurance system. These processes created additional foundations for implementing innovative approaches in teaching and management.

Undoubtedly, the extreme conditions faced by higher education threatened the stability of the educational landscape. However, the presence of an established regulatory framework, accumulated

experience of institutional changes, and high qualification of academic staff allowed Ukraine's higher education system to demonstrate flexibility and resilience to external influences.

Having passed this stress test, domestic higher education gained unique experience in reconfiguring educational practices. This potential for adaptation and transformation became key to maintaining educational quality and competitiveness of Ukrainian universities even under conditions of global upheaval. Further improvement of regulatory framework, digitalization of educational space, and strengthening of international cooperation will allow Ukraine's higher education system to fully unlock its modernization potential.

However, current demographic trends in Ukraine show concerning signs of outflow of intellectually and physically developed young population to other countries. This process, along with a complex of socio-economic problems, indicates a deep demographic crisis that threatens the national security of the state.

The situation in Ukraine's maritime education system causes particular concern. Analysis of reporting documentation from heads of specialized higher education institutions indicates a persistent trend of decreasing student contingent over recent years. This phenomenon becomes critical considering the strategic importance of the maritime sector for the country's economy and its position in the global maritime services market.

The roots of this problem should be sought in a complex of economic, social, and geopolitical factors that motivate Ukrainian youth to emigrate. Lack of prospects for decent employment, low income levels, and deteriorating quality of life in Ukraine become significant incentives for moving abroad. Moreover, the war initiated by Russia exacerbates these trends, complicating access to maritime education and career prospects in the field.

Negative demographic trends in Ukraine's maritime education system pose a threat to maintaining the competitiveness of domestic specialists in the international labor market. The decrease in the contingent of cadets and students in maritime specialties narrows the possibilities for sector staffing, threatening the future development of the national maritime sector.

Solving this problem requires comprehensive efforts at the state level. Key directions should include creating favorable socio-economic conditions for youth, ensuring a decent standard of living and career growth prospects. Simultaneously, it is necessary to implement targeted programs to popularize maritime professions and increase the prestige and attractiveness of sectoral education. Only a systematic approach can neutralize destructive demographic trends and preserve the human resource potential of Ukraine's maritime education.

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Міграційно-еволюційні аналіз тенденцій розвитку морської освіти в умовах війни

Дослідження присвячене аналізу фундаментальних змін у системі вищої освіти України, що відбуваються під впливом безпрецедентних геополітичних подій та демографічних зрушень, з особливим фокусом на секторі морської освіти. У роботі досліджується період 2020-2023 років, що характеризується масштабними викликами, спричиненими російською військовою агресією та її наслідками для освітньої галузі. На основі аналізу інституційних звітів та статистичних даних виявлено суттєві зміни у динаміці студентського контингенту, перерозподілі освітніх потоків та трансформації освітніх практик. Результати дослідження демонструють, що попри значну адаптивність та успішне впровадження європейських освітніх стандартів, система вищої освіти України зіткнулася з серйозними викликами, пов'язаними з вимушеною міграцією молоді та демографічним спадом. Особливо гострою ця проблема постає у секторі морської освіти, де спостерігається стійка тенденція до зменшення кількості здобувачів освіти. У статті обґрунтовується необхідність системних державних заходів щодо розвитку морської освіти в Україні. Дослідження розкриває складну взаємодію між демографічними тенденціями, освітньою трансформацією та галузевим розвитком в умовах воєнного часу.

Ключові слова: вища освіта дорослих; освіта під час війни, морська освіта та навчання, конкурентоспроможність освіти, освітня міграція, MET.

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Analysis of the effectiveness of the regulatory act "Regulations on the Railway Transport Safety Management System"

The article is devoted to a study that is quite rare in the scientific and technical literature. It is about analysing the impact of the regulatory document "Regulations on the Railway Transport Safety Management System" on the population groups and enterprises of Ukraine and its effectiveness after its approval. These two analyses are carried out before and after the approval of regulatory documents by state authorities (ministries, the Cabinet of Ministers, etc.). The relevance of this Regulation is explained by the need to implement European-type regulations in the activities of Ukrainian railways. The implementation is in line with the EU-Ukraine Association Agreement. The peculiarity of the Regulation in comparison with the existing one is explained by the fact that it becomes mandatory not only for JSC "Ukrainian Railways", but also for enterprises that use railway rolling stock and railway infrastructure in their activities. It was found that the railway transport sector includes 1517 enterprises. Based on the analysis of the impact of the Regulation on the Railway Traffic Management System on the interests of citizens, the state and business entities, a conclusion was made on the most rational option for achieving the goal of improving the level of railway traffic safety. The Regulation was approved by the Ministry of Infrastructure in 2021.

Keywords: *traffic safety, railway transport, analysis, assessment, management, regulation, risk*

Introduction. The relevance of adopting a new Regulation on the Traffic Safety Management System (hereinafter - the Regulation on the SMS) in Ukraine is explained by two aspects: the seriousness of the consequences of traffic safety violations in transport and the need to develop regulatory documents in line with European analogues.

Violations of train safety requirements and shunting operations in railway transport pose a threat to the lives and health of Ukrainian citizens, as well as increase damage to property owned by both the state and business entities. JSC Ukrzaliznytsia annually compiles a report on the state of train safety, and this document describes the violations. In 2021, 869 transport accidents occurred on Ukrainian railways, in which 182 people died and 134 people were injured. Of these, there was one catastrophe (no casualties); 480 accidents, including (a) 316 accidents with people caused by rolling stock in motion (182 people died and 134 were injured); (b) 64 accidents involving railway vehicles - collisions, derailments, etc. (no casualties) and 388 incidents (no casualties).

Of particular concern is the state of traffic safety during shunting operations and on sidings - more than 80% of rolling stock derailments occurred during shunting operations, many derailments occurred on sidings, and business entities neglect to report accidents to the competent state authority. Therefore, the number of derailments on sidings is actually higher.

Any railway accident has potentially disastrous consequences for the economy and society: damage to Ukrzaliznytsia's infrastructure, fire of locomotives and wagons, formation of a cloud of combustion

products over tens of square kilometres around the scene, and damage to personnel and ordinary citizens.

At the same time, it should be noted that business entities have significantly increased the number of rolling stock that is used on public tracks, which directly affects traffic safety. For example, JSC Ukrzaliznytsia owns 83.5 thousand freight cars, while the five largest railway operators own approximately 33 thousand freight cars. Projects are also being implemented to increase railway speeds and allow private traction to run on public tracks. Particular attention is drawn to railway operators that own their own private traction, which inevitably affects the overall traffic and transportation safety in Ukraine.

Therefore, the issues of traffic safety management are currently relevant not only and not so much to JSC Ukrzaliznytsia, but also to railway transport companies: those that have rolling stock and infrastructure on their balance sheets, or use rolling stock to transport products, etc.

A consistent cause of most transport accidents is the human factor: inattention, carelessness, lack of knowledge and skills.

The Regulation on the RMS is designed to implement a train safety and shunting management system that will allow efficient planning and use of funds for rolling stock modernisation and personnel training. In particular, ongoing comprehensive risk analysis will allow funds to be allocated to areas that are beyond the critical risk limit (repairs or staff training). At the same time, the potential damage to business entities will be analysed, which will help prevent accidents more effectively. Implementation of the SMS will allow business entities to save costs for rolling stock repairs, compensation for environmental damage and lost cargo, improve the quality of services and be competitive in both the domestic and European markets.

Analysis of recent research and problem statement. The Regulation on the SMS establishes the obligation of the railway transport enterprise to implement a procedure for identifying hazards or threats, risk assessment, and risk management. This issue is described in the works of other researchers.

Paper [1] states that the existing methodology for assessing the level of safety in the railway transport of Ukraine does not reflect the real and adequate state of railway safety. According to the authors, the solution to this problem may be the development of a risk management system. The paper presents the a posteriori and a priori values of risk, which allow to characterise the actual safety - the real state of railway traffic safety for the period under study, and the predicted railway traffic safety. However, the risk system proposed in this paper is of a generalised nature, where the analysed risks are combined into the following groups: general, local, technological and technical risks, which makes it difficult to determine the causes of traffic safety violations.

Paper [2] identifies the risk of adverse events as one of the main problems of modern production and the main criterion for the realisation of danger. The authors propose the use of risk management as a promising direction in the development of transport systems, which will allow stabilising and increasing the efficiency of their activities. The starting point of effective risk management in the management of transport processes at an enterprise is the construction of an effective risk management system. However, at present, there is almost no information on risk management in railway transport.

Paper [3] identifies the most problematic areas in the technological process of maintenance and offers an example of a management solution to prevent them. The problem is defined as the search for an effective way to manage the process of maintaining alarm systems in the required technical condition. It is proposed to use the method of searching for hidden bottlenecks based on the analysis of failure statistics as risks and mitigation. The carried out research has identified a disadvantage of the methodology in the form of the need to accumulate failure statistics and continuous monitoring of the risk management programme. Also, the identified advantages of the methodology allow us to assert that the proposed approach will be able to solve the problem of substantiating the most significant problem areas of the process of ensuring the operability of railway automation systems. In order to eliminate the identified shortcoming of the methodology, it is proposed to develop appropriate software with the help of which the statistical base will be accumulated automatically. The solution to the problem is proposed in the form of time planning for monitoring the most dangerous causes of failures.

Thus, statistical methods are the most effective in the management of organisational structures. It is proposed to adapt the obtained results into a form familiar to managers for widespread use in practice.

Untimely update of the Order of the Ministry of Infrastructure "On Approval of the Unified Form of the Act Drawn Up on the Results of a Scheduled (Unscheduled) State Supervision (Control) Measure on Compliance by a Business Entity with the Requirements of Legislation, Norms and Standards in the Field of Railway Transport, and the Form of the Order to Eliminate Violations Identified During a Scheduled (Unscheduled) State Supervision (Control) Measure on Compliance by a Business Entity with the Requirements of Legislation, Norms and Standards in the Field of Railway Transport".

The lack of an effective mechanism for bringing to justice officials responsible for traffic safety at railway transport enterprises and, as a result, their failure to fulfil the obligation established by the Order of the Ministry of Infrastructure of Ukraine No. 842 "On Approval of the Regulation on the Traffic Safety Management System in Railway Transport" of 24 December 2020 [5] to implement a traffic safety management system at the enterprise.

Thus, the problem of qualitative assessment of the impact of the regulatory act "Regulation on the Railway Transport Safety Management System" and assessment of the results of the implementation of the regulatory act and the degree of its implementation remains quite relevant due to the slow pace of implementation of the safety management system by railway transport enterprises.

The purpose and objectives of the study. The purpose of the article is to demonstrate in practice such an important aspect of the implementation of state-level regulatory documents as regulatory analysis of a document before its submission for approval and assessment of the results of implementation of a regulatory act and the degree of achievement of certain goals. Objectives of the article: 1 - to analyse the scope and number of Ukrainian enterprises which are subject to the Regulation on the Railway Transport Safety Management System; 2 - to determine the most rational of the alternative ways to achieve the objectives of state regulation; 3 - to determine the performance indicators of the regulatory act; 4 - to assess the result of implementation of the regulatory act and the degree of achievement of the defined objectives using the statistical method.

Materials and methods of research.

1. Analysis of the scope and number of Ukrainian enterprises that are subject to the Regulation on the Railway Safety Management System.

The following factors have a direct impact on the level of railway safety:

- technical condition of the rolling stock;
- interaction of the carrier with other business entities that have their own rolling stock (mutual coordination of actions).

Personnel involved in the departure of rolling stock (wagons, tanks, etc.) owned by the business entity on public tracks must responsibly and systematically maintain a high level of safety at the enterprise, and the business entity must ensure that the requirements for personnel, rolling stock, shunting operations and other components of traffic safety are met in accordance with the law.

Table 1 provides information on the Ukrainian enterprises that fall within the scope of the RRMS Regulation. It should be noted that this analysis was carried out before the full-scale invasion of Ukraine by the Russian Federation.

Table 1. Characteristics of railway transport enterprises to be covered by the Regulation on the RMS

Indicator.	Large	Medium	Small	Micro	Together
Number of business entities subject to regulation	9	1438	-	-	1517
Share of the group in the total number, %.	5,2	94,8	-	-	100

The problem of railway traffic safety is exacerbated by the lack of a single regulatory act that would regulate a unified approach of business entities to ensuring the safety of train traffic on railway transport, as well as the lack of a definition of what constitutes a railway traffic safety management system at the level of the Law of Ukraine "On Railway Transport".

However, during 2021-2023, several draft laws were registered in the Verkhovna Rada of Ukraine that raise the issue of a unified approach to ensuring train safety on rail transport through an effective safety management system:

- Draft Law on Amendments to the Code of Ukraine on Administrative Offences to Strengthen Administrative Liability for Violation of Legislation on Road, Urban Electric and Railway Transport [6], the adoption of which will resolve the issue of expanding the circle of persons subject to liability, which will ensure compliance with the law by all business entities in the field of road, urban electric and railway transport and the filling of the State Budget of Ukraine.

- The Draft Law on Amendments to the Law of Ukraine "On Railway Transport" on Certain Issues of Railway Safety Management [7], which was developed to create legal certainty regarding the term "traffic safety management system", define the content and the central executive body responsible for developing the regulation on the SMS, as well as establish exhaustive grounds for prohibiting the operation of railway rolling stock and railway transport infrastructure;

- Draft Law on Amendments to Certain Laws of Ukraine on Improving Safety in Railway Transport [8] aims to regulate the issues of stable annual funding allocated by railway transport enterprises for traffic safety in the amount of at least 1% of gross income for the previous year (analogous to the article on labour protection, where the employer is obliged to spend 1% of the gross income on labour protection), as well as to introduce provisions that will make it impossible to accept railway infrastructure elements for scrap.

It should be noted that currently, the requirements for rolling stock and personnel training are already enshrined in legislation and regulations, for example [10-15], etc., but their distinction and lack of systematic control at enterprises leads to accidents and material losses for both the carrier and business entities.

The Regulation on the train safety management system at the State Administration of Railway Transport of Ukraine [16] was outdated, its content, terms and requirements did not meet the requirements of national and European legislation.

The first step to improve the level of traffic and shunting safety in railway transport was the introduction of a European-style traffic and shunting safety management system for railway transport by adopting the Regulation on the Traffic Safety Management System for Railway Transport, which in turn will make it possible to develop effective preventive measures to prevent similar events in the future, prevent human casualties, and monitor the state of traffic safety in railway transport.

Based on the above, it can be concluded that the RDRS Regulation affects individuals, the state and business entities in Ukraine.

The objectives of state regulation are:

- Improving the procedures for hazard identification, risk assessment, and determining traffic safety measures at railway transport enterprises;

- Improving programmes to train staff (employees and managers) in traffic safety;

- improving the procedures for documenting information on traffic safety and shunting operations;

- Improving the procedures for reporting, recording and official investigation of transport accidents at railway transport enterprises;

- improving internal audit procedures for traffic safety and shunting operations at railway transport enterprises;

- implementation of the state policy on railway safety.

These goals and objectives are achieved by adopting a regulatory act.

2. Determining the most rational of alternative ways to achieve the goals of state regulation.

There are different ways to achieve improvements in road safety and its management. Table 2 summarises these alternative ways.

Table 2. Identification of alternative ways to achieve the goal of improving road safety management

Type of alternative	Description of the alternative
Alternative 1	<i>Preservation of the situation that existed at the time of the preparation of the Regulation on the SBRs.</i> This has led to a further gap in the railway safety legislation.
Alternative 2	<i>The adoption of a regulatory act</i> meets the objectives of state regulation, as well as the needs to address certain problems, and is a reasonable and effective way to achieve the objectives. This method is the most acceptable as it will achieve the goals of state regulation. This will improve the level of safety and management of train traffic safety, which will help reduce accidents, save lives and health of citizens, and the integrity of cargo .

Other methods that do not involve the adoption of a regulatory act are unacceptable, as the solution to the problem lies primarily in the legal sphere.

Tables 3 - 5 provide an assessment of the impact of the alternative ways of achieving improved road safety management from Table 2.

Table 3: Assessment of the impact of alternatives for improving train safety management on the sphere of state interests

Type of alternative	Benefits.	Costs.
Alternative 1	-	Reduction in state budget revenues due to increased accidents on the railway transport, which will lead to a deterioration in the economic situation in the field of passenger and cargo transportation
Alternative 2.	a) formation and implementation of the state policy on improving traffic safety, b) growth of foreign investment as a result of harmonisation of the requirements of the legislation in this area with the European one, c) increase in the number of business entities, d) fulfilment of Ukraine's international obligations, e) sustainable revenues to the State Budget of Ukraine, f) availability of jobs, g) satisfaction of the needs of society and the economy	-

Table 4. Assessment of the impact of railway safety improvement alternatives on the sphere of public interest

Type of alternative	Benefits.	Costs.
Alternative 1	-	a) increased risk to the life and health of citizens due to increased risks of transport accidents; b) increased risks of property loss; c) increased environmental damage.
Alternative 2	For citizens-passengers: a) use of railway transport services, b) the possibility of obtaining higher quality and safer services by reducing the risk to life and health due to the reduction of transport accidents. For citizens transporting goods and those living near railway tracks: a) reducing the risk of property loss; b) reducing environmental damage as a result of transport accidents	-

Table 5. Assessment of the impact of alternatives for improving railway transport management on the sphere of interests of business entities

Type of alternative	Benefits.	Costs.
Alternative 1	-	Increase in expenses due to emergency events: loss of cargo, rolling stock repairs, compensation for late and poor quality services.
Alternative 2	Improving the level of traffic safety during the transportation of passengers and goods will contribute to: a) improving the quality of services provided; b) creating favourable conditions for development, including the possibility of opening a new or expanding an existing business; c) reducing costs due to accidents: compensation for damage to human health, property, rolling stock.	Large and medium-sized businesses will bear the costs of implementing the SMS only to create a traffic safety service in case of its absence, or to entrust its functions on a contractual basis to the traffic safety service of the enterprise whose infrastructure they use or interact with (about UAH 300 thousand per year for two employees).

We will evaluate the preferences of alternative options for improving the situation with railway safety management by scoring on a scale:

- 1 point - the situation does not change;
- 2 points - minimal improvement;
- 3 points is an average improvement;
- 4 points - the situation has changed significantly for the better.

Table 6 presents the results of the assessment of alternatives to the traffic safety situation presented in Table 1.

Table 6. Performance rating - achievement of goals in solving the problem of railway transportation safety management

Name of the alternative	Performance score	Comments on the assignment of the corresponding score
Alternative 1	1	The absence of an effective mechanism for improving the safety of freight and passenger transportation at railway transport enterprises will lead to a deterioration in the state of safety of railway transport, and therefore to: damage to rolling stock, increased property losses of shippers and consignees, increased harmful impact of transport on the environment.
Alternative 2	4	a) introducing an effective mechanism to ensure traffic safety at railway transport enterprises; b) as a result of streamlining traffic safety procedures at railway transport enterprises, the level of traffic safety in the transportation of passengers and goods will increase, and therefore property losses will decrease: <ul style="list-style-type: none"> - from the repair of rolling stock and infrastructure, - shippers and consignees; c) harmonisation of Ukrainian legislation with the European one in the area of introducing safety management systems at railway transport enterprises will simplify the procedure for Ukrainian railway transport enterprises to enter the European market.

Table 7 shows the integrated result of the selection of alternative options for the development of the traffic safety management system.

3. Determination of performance indicators of the regulatory act.

First, let us identify the mechanism and measures that will ensure the solution of the problem. The mechanism that will ensure the resolution of the problem is the adoption of a regulatory act. The draft Regulation on the RMS proposes:

- Improving the procedures for hazard identification, risk assessment, and determining traffic safety measures at railway transport enterprises;
- Approval of methodological recommendations for building an enterprise's RMS;
- Improving programmes to train personnel (employees and managers) in traffic safety for mainline and shunting operations;
- Improving the procedures for documenting traffic safety information for mainline and shunting traffic;
- Improving the procedures for reporting, accounting and internal investigation of transport accidents;
- improving internal audit procedures for traffic safety;
- implementation of the state policy on railway safety.

Table 7. Rating of the effectiveness of applying alternative options for the development of the situation with the traffic safety management system in the railway transport sector

Name of the indicator	Alternative	
	1	2
Benefits (summary)	-	<p><u>For the state sector:</u></p> <ul style="list-style-type: none"> a) formulation and implementation of the state policy on improving the level of railway transport safety, b) growth of foreign investment as a result of harmonisation of legislation in this area with the European one, c) an increase in the number of business entities, d) Ukraine's fulfilment of its international obligations, e) sustainable revenues to the State Budget of Ukraine, f) availability of jobs, g) meeting the needs of society and the economy. <p><u>For the sphere of citizens:</u></p> <ul style="list-style-type: none"> a) ensuring the use of railway transport services as passengers; b) the possibility of receiving better and safer services by reducing the risk to life and health; c) for freight carriers and those living near railway tracks - reducing the risk of property loss and environmental damage; <p><u>For business entities:</u></p> <ul style="list-style-type: none"> a) creation of favourable conditions for development, in particular, starting a new business or expanding an existing one; b) prevention of expenses resulting from emergency events: compensation for damage to human health, property, and rolling stock.
Expenses (total)	<ul style="list-style-type: none"> a) a possible decrease in revenues to the state budget due to an increase in railway accidents; b) deterioration of the economic situation; c) increased risk to the life and health of citizens as a result of increased risks of transport accidents; d) an increase in property losses and environmental damage as a result of transport accidents on the railway; д) Increase in expenses due to emergency events: loss of cargo, rolling stock repairs, compensation for untimely and poor quality services. 	<p>Large and medium-sized businesses will bear the costs of implementing traffic safety management systems only for the establishment of a traffic safety service, in case of its absence, or for contracting the traffic safety service of the enterprise whose infrastructure is used or with which the enterprise interacts (up to UAH 300 thousand per year).</p>
Overall rating result	Does not achieve the goals of state regulation	The adoption of the regulatory act will ensure the achievement of the set goals

Measures proposed to be taken by the executive authority to resolve the problem:

- methodological recommendations for conducting internal investigations at enterprises;
- methodological recommendations on the implementation of internal audit at enterprises;
- methodological recommendations for the development of quality indicators (standards) of traffic safety at enterprises;
- to ensure that business entities and the public are informed of the requirements established by the regulatory act by publishing them.

Measures proposed by business entities to address the problem:

- to get acquainted with the requirements of the regulatory act;
- in the absence of a traffic safety service at the enterprise, or to entrust the performance of its functions on a contractual basis to the traffic safety service of the enterprise whose infrastructure is used or with which the enterprise interacts;
- develop a traffic safety management system and coordinate it in terms of procedures for interaction with other companies whose infrastructure or rolling stock it uses.

There are no risks of external factors affecting the effect of the regulatory act.

No possible damage is predicted in the event of the expected consequences of the regulatory act.

The adoption of the regulatory act will help to preserve the ability of business entities to conduct competitive business, sustainable revenues to the state budget, the availability of jobs and meet the needs of society and the economy.

The implementation of the regulatory act will not require additional costs and resources of the executive authorities.

The regulatory act is expected to enter into force six months after its official publication. It is proposed that the term of the regulatory act should not be limited in time.

Let's define the performance indicators of the regulatory act.

1. The number of business entities engaged in economic activity in the field of railway transport to which the act applies.

The regulatory act will apply to railway transport enterprises engaged in the carriage of passengers and/or loading, transshipment, unloading of cargo by rail. The estimated number of such business entities is 1517.

The number of business entities may increase due to the harmonisation of Ukrainian legislation with EU legislation and the introduction of a European approach to regulating the procedures for ensuring the safety of railway transport. The introduction of European-style traffic safety management systems by railway transport companies may encourage businesses from the EU, the US, and other countries to open businesses related to the transportation of passengers or goods by rail in Ukraine.

2. The emergence of European railway transport operators on the Ukrainian market.

3. A relative decrease in the number of transport accidents at railway transport enterprises.

4. The amount of revenues to state and local budgets and state trust funds related to the regulatory act will not change.

5. The level of awareness of business entities is average. The draft act and the relevant regulatory impact analysis are published on the official website of the Ministry of Infrastructure of Ukraine in the section "Activities" - "Regulatory Activities".

Define the measures that will be used to track the effectiveness of the regulatory act.

The Ministry of Infrastructure of Ukraine will monitor the effectiveness of the regulatory act.

The baseline performance tracking of the regulatory act will be carried out after the regulatory act enters into force, but no later than the day on which the repeated performance tracking begins.

The effectiveness of the regulatory act will be monitored again one year after its entry into force, but no later than two years after the date of entry into force of this act.

Periodic monitoring of the effectiveness of the regulatory act will be carried out once every three years, starting from the date of completion of the re-monitoring of the results of this act.

4. Evaluation of the results of the regulatory act implementation and the degree of achievement of the set goals.

The criterion for assessing the effectiveness of the implementation of the act is to reduce the number of transport accidents at railway transport enterprises. Since tracking the effectiveness of the Order, namely from 09 October 2021, based on the statistical method, according to information from official sources, the number of transport accidents in comparison with 2022 to 2021 has almost halved in 9 months - 408 against 869. However, to claim that the dynamics are positive, we need to study not only quantitative indicators, but also qualitative ones.

It should also be noted that official sources do not contain information on the number of railway transport enterprises that have implemented a traffic safety management system. In the author's opinion, only 5% of enterprises have implemented the SMS and less than 1% of enterprises have mutually agreed the SMS with JSC Ukrzaliznytsia.

The Ministry of Infrastructure of Ukraine assesses the results of the implementation of the regulatory act and the degree of achievement of the set goals positively.

Conclusions. Based on the analysis of the activities of railway transport enterprises, 1517 enterprises were identified that are subject to the Regulations of the Railway Safety Management System. These are companies that own or use railway rolling stock or railway infrastructure.

Out of two alternative options for solving the problem of improving the level of train safety through a comparative analysis of the impact on the interests of citizens, the state and business in Ukraine, the draft Regulation on the SBS was selected.

The regulatory act's performance indicators are defined, such as improving hazard identification procedures, risk assessment, developing training programmes on traffic safety for three categories of employees, improving procedures for documenting traffic safety information, introducing an internal audit on traffic safety, and implementing the state policy on traffic safety in railway transport.

The results of the implementation of the regulatory act and the degree of achievement of the set goals were assessed. The number of transport accidents in the first nine months of 2022 decreased by almost 2 times compared to 2021, but not only quantitative but also qualitative indicators should be analysed. The level of traffic and transportation safety is increasing as a result of the introduction of the SMS at railway transport enterprises, which means that the risk of deaths and injuries in railway transport is decreasing. However, the growth rate is slow, with only 5% of railways having developed and implemented an SMS.

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Аналіз регуляторного впливу Положення про систему управління безпекою руху на залізничному транспорті

Стаття присвячена дослідженню, яке досить рідко зустрічається у науковій технічній літературі. Мова йде про аналіз впливу нормативно-правового документу «Положення про систему управління безпекою руху на залізничному транспорті» на групи населення та підприємства України та його результативність після затвердження. Ці два аналізи проводяться до і після затвердження нормативних документів у державних органах влади (міністерствах, Кабінеті Міністрів, тощо). Актуальність такого Положення пояснюється необхідністю імплементації нормативних документів європейського типу у діяльність українських залізниць. Імплементація відповідає Угоді про асоціацію між Україною та ЄС. Особливість Положення відповідно до існуючого досі пояснюється тим, що воно стає обов'язковим не тільки для АТ «Українська залізниця», але також для підприємств, які у своїй діяльності використовують залізничний рухомий склад та залізничну інфраструктуру. Виявлено що до сфери залізничного транспорту підпадають 1517 підприємств. На основі аналізу впливу Положення про систему управління рухом на залізничному транспорті на інтереси громадян, держави та суб'єктів господарювання було прийнято висновок щодо найбільш раціонального варіанта досягнення мети з підвищення рівня безпеки руху залізничного транспорту. Таке Положення було затверджено Міністерством інфраструктури у 2021 році.

Ключові слова: безпека руху, залізничний транспорт, регулювання, аналіз, оцінка, управління, ризик

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Determining the Switching Frequency of a Transistor Converter for a Traction Collector Motor

The purpose of this work is to determine the switching frequency of a transistor converter for a traction collector motor of a locomotive based on the criterion of permissible current ripple. The stated goal is achieved by solving the following problem: a methodology for determining the consideration of changes in motor parameters when calculating the switching frequency of the transistor converter is proposed. The peculiarity of the proposed approach is that it takes into account the degree of saturation of individual parts of the magnetic system of the electric motor. The most significant result is an increase in the accuracy of calculating the switching frequency by taking into account the change in the inductance of the commutator motor windings when the degree of saturation of the magnetic system changes. The switching frequency for a DC traction motor with a pulse converter is calculated. Two main operating modes of the electric motor are considered: with full magnetic flux and with weakened magnetic flux. As a result of calculations, it was established that the dependence of switching frequency on currents is nonlinear. For the operating mode of the electric motor with full magnetic flux, the switching frequency is determined taking into account the processes in the field winding circuits and in the armature circuit windings. The most important results are the determination of the switching frequency of the pulse converter for powering and regulating the traction motor in all operating modes. The proposed methodology allows the selection of transistor devices for the converter according to the switching frequency.

Keywords: energy efficiency, rolling stock, traction electric motor, traction system, semiconductor converter, switching frequency.

Introduction. Stable operation of the railways requires the introduction of energy-saving technologies in all types of its activities. The locomotive fleet of railways is the most energy-intensive, as it consumes fuel and energy resources for train traction [1]. Therefore, in the context of a constant increase in the cost of fuel and energy resources, reducing their consumption is a priority. Taking into consideration that a large part of the traction rolling stock is equipped with outdated equipment with insufficient energy efficiency by modern standards, improving the energy efficiency of traction rolling stock is an urgent task.

Shunting operations are an integral part of the freight and passenger rail transport business.

A key area of modernisation of shunting locomotives is to improve their fuel efficiency. For this purpose, multi-diesel and hybrid power plants can be used [2, 3]. The first method is common on shunting locomotives manufactured or modernised by American companies [4]. Both approaches, as expected, reduce fuel consumption.

In the case of a hybrid power plant, as well as in some cases with a multi-diesel power plant, the use of pulse regulators is necessary to power and regulate traction collector motors [5]. Therefore, research that will form the basis for their modernisation is relevant.

Traction systems with collector motors and pulse converters are most common in the rolling stock of urban electric transport [6, 7]. On the rolling stock of mainline railways, switching regulators are used to control the excitation current. The use of switching regulators in traction systems of motor-car electric rolling stock is also known [8]. When collector motors are powered by a pulse converter, pulsating currents flow through its windings. The presence of pulsations in the currents of a traction motor leads to a change in the quality of switching, an increase in losses in the motor, and the appearance of electromagnetic torque pulsations.

For direct current traction electric motors, operation with current pulsations that do not exceed 10% is allowed. Therefore, to fulfil this condition, it is necessary to determine the switching frequency of the pulse converter, which depends on both the parameters of the electric motor and the structure of the semiconductor converter. In [9], a scheme of the traction system of the modernised diesel locomotive with a hybrid power plant is proposed. It provides individual power supply and regulation of traction motors. This solution makes it possible to adapt the traction parameters of the locomotive to the conditions of a specific train task, which helps to reduce the consumption of fuel and energy resources [10]. Currently, pulse regulators have been developed and implemented in which the armature and excitation circuits are powered exclusively by switching IGBT transistors. Such converters are most widely used in the traction systems of urban electric vehicles [11, 12]. Studies on the use of switching regulators to power and regulate traction collector motors of railway rolling stock are presented in [13-15].

The analysis of the considered sources shows that the scheme shown in Fig. 1 can be used for a DC traction motor [11]. The converter provides pulse-width control of the motor current with a series connection of the armature and field windings in the full excitation mode and pulse-width control of the excitation current in the magnetic flux attenuation mode.

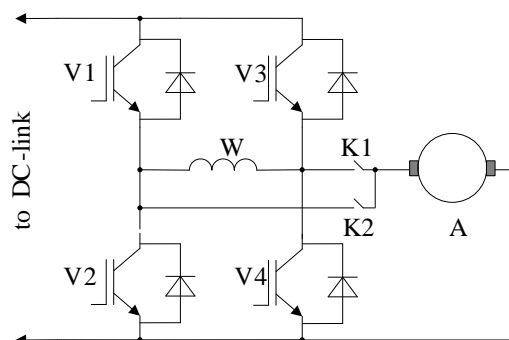


Fig. 1. Power supply and control circuit for the traction motor: A – armature, W – excitation winding, V1...V4 – semiconductor keys, K1...K2 – contactors.

General recommendations for determining the switching frequency are given in [16]. In [17], it is shown that when determining the switching frequency, it is necessary to take into account the additional losses that occur when a pulsating current flows through the motor windings, as well as losses in the traction converter. Refined models of the collector motor are presented in [18], considering the additional magnetic losses that occur when a pulsating current flows. The models can be used to calculate the switching frequency. At the same time, it can be noted that existing approaches use either simplified models or require detailed modelling. This work differs from the known ones in that it takes

into account the change in the parameters of the electric motor when the modes of its operation are changed when determining the switching frequency of the pulse converter. This approach corresponds to the physical processes that occur in the traction electric motor and will allow to increase the accuracy of calculations, which ultimately determines the quality of electromechanical energy conversion and the reliability of the system.

The aim of the study is to determine the switching frequency of a pulse converter for a locomotive traction collector motor by the criterion of permissible current ripple. This approach makes it possible to provide the motor operating modes with an acceptable degree of switching.

Research material. The magnitude of the ripples is usually estimated by the current ripple coefficient, which is determined by the expression [6,19]

$$k_i = \frac{\Delta I}{I_0} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (1)$$

where $\Delta I = \frac{I_{\max} - I_{\min}}{2}$ – half the current ripple;

$I_0 = \frac{I_{\max} + I_{\min}}{2}$ – is the average current value;

I_{\max}, I_{\min} – the highest and lowest current values, respectively (Fig. 2).

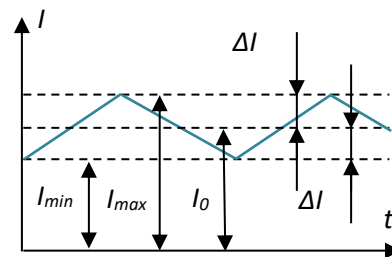


Fig. 2. Determination the current ripple factor

As noted above, when a DC traction motor is powered, pulsating current will flow through its windings. This can cause a commutation malfunction (sparking at the collector). Since it is not possible to make changes in the design of existing traction motors that would reduce the negative impact of the pulsating component on the commutation processes, it is necessary to limit the magnitude of this current pulsation. However, the standard for traction electric machines stipulates that for DC motors, the ripple factor cannot exceed 10 % (although the actual determination of the value of the ripple factor at which there is no commutation disturbance requires experimental determination and confirmation). In view of the standard, it is advisable to determine the switching frequency, provided that at 10 % current ripple the switching will be satisfactory.

Figure 3 shows the design scheme of the traction circuits, which corresponds to the scheme in Figure 2.

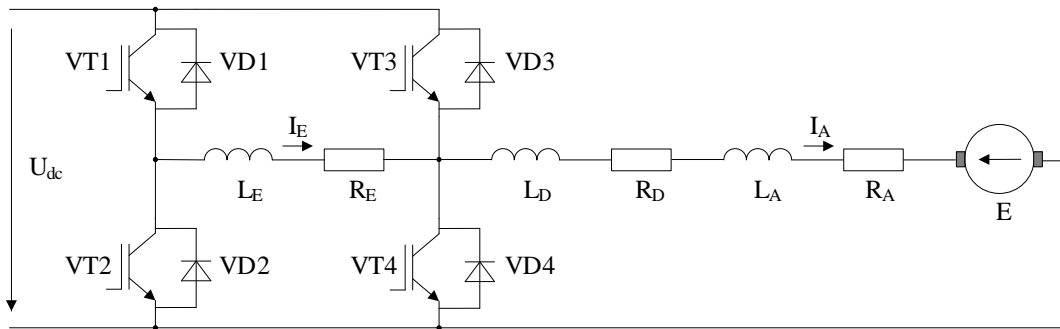


Fig. 3. Electrical circuit diagram of the traction system

In Fig. 3 the following designations are introduced: U_{dc} - DC link voltage, E - electromotive force of electric motor, I_E - excitation current, I_A - armature current, VT1..VT4 - IGBT transistors, VD1..VD4 - diodes, L_E - excitation winding inductance, R_E - excitation winding resistance, L_D - additional pole winding inductance, R_D - additional pole winding resistance, L_A - armature winding inductance, R_A - armature winding resistance.

As it is known, the traction electric drive of a vehicle operates in two zones: with a constant magnetic flux and with a weakened magnetic flux.

In the first zone, the traction motor is controlled by changing the voltage by pulse width modulation of the transistor VT1. The dependence of the current ripple value on the pulse filling factor is as follows [20]

$$k_i = \frac{\lambda(1-\lambda)U_{dc}}{2I_{0M}fL_{\Sigma}} \quad (2)$$

where f – switching frequency;

λ – the occupancy rate;

U_{dc} – power supply voltage;

L_{Σ} – total inductance of the motor circuit, which includes the armature winding, the additional pole winding and the excitation winding.

The largest pulsation occurs at a filling factor of 0.5 [20]. From this condition, the switching frequency is defined as

$$f_{VT1} = \frac{U_{dc}}{8I_{0M}L_{\Sigma}k_{i\max}} \quad (3)$$

where $k_{i\max}$ – the permissible value of current ripple, specified by 10%;

I_{0M} – average current of the electric motor.

When operating in the second zone, the field attenuation is provided by the pulse width modulation of transistor VT3. For this case, the current ripple in the field and armature windings is also determined by expression (2). However, for the excitation winding, it is necessary to take into account only its inductance, and for the armature circuit - the inductance of the armature and additional poles. Then the switching frequency for the field winding will be determined as follows

$$f_{swE} = \frac{U_{DC}}{8I_{0E}L_Ek_{iE\max}} \quad (4)$$

where $k_{iE\max}$ – permissible current ripple coefficient of the excitation winding;

I_{0E} – is the average current of the excitation winding;

L_E – inductance of the excitation winding.

The switching frequency for the armature winding is determined by the expression

$$f_{swA} = \frac{U_{dc}}{8I_{0A}L_A k_{iAmax}} \quad (5)$$

where k_{iAmax} – permissible current ripple coefficient of the armature winding;

I_{0A} – is the average current of the armature winding;

L_A – the total inductance of the armature winding and the windings of the additional poles.

Since switching of the field winding and the armature circuit is carried out simultaneously by transistor VT3, the switching frequency of transistor VT3 must be calculated taking into account the current ripple in both the armature circuit and the field winding circuit. Since the inductance of these circuits is different, the switching frequency can be determined as follows. For each of the circuits, the switching frequency at which the current ripple is 10% is determined. The largest of the two calculated values is selected.

$$f_{VT3} = \max(f_{swA}, f_{swE}). \quad (6)$$

A higher switching frequency corresponds to a circuit with a lower inductance. Therefore, for a circuit with a higher inductance, the current ripple will be less than 10%.

From the analysis of expressions (2) and (3), it follows that the switching frequency depends on the current and inductance of the windings. In turn, the winding inductances vary depending on the degree of saturation of the magnetic system, which is determined by the excitation current. In other words, there is a nonlinear dependence of the switching frequency on the currents. The switching frequency is directly proportional to the intermediate circuit voltage and inversely proportional to the current ripple factor.

Thus, to determine the switching frequency, it is necessary to know the inductances of the windings, which vary depending on the magnetic flux of the motor. In turn, the magnetic flux is determined by the field winding current. Therefore, it is convenient to determine the winding inductances depending on the current flowing through the field winding.

The winding inductances can be determined on the basis of analytical dependencies, by numerical analysis and experimentally. This paper uses an analytical approach that does not require lengthy calculations or expensive experiments, but provides acceptable accuracy of calculations.

The inductance of the excitation winding when all coils are connected in series is determined by expression [19]

$$L_e = \left(2p\sigma_e w_e \frac{d\Phi}{dI_e} \right) (1 + k_A), \quad (7)$$

where $2p$ – number of electric motor poles;

σ_e – is the scattering coefficient of the main pole;

k_A – the coefficient that takes into account the effect of eddy currents in magnetic circuits is in the range from 0.15 to 0.3;

w_e – number of turns of the excitation coil;

Φ – magnetic flux;

I_e – excitation current.

The motor magnetisation curve is used to calculate the derivative $d\Phi/dI_e$.

When calculating the winding inductance of auxiliary poles, the saturation of their magnetic circuit is usually neglected. Therefore, the inductance can be determined through the geometrical dimensions of the additional pole by the expression

$$L_d = 2p\sigma_d w_d^2 \Lambda_d \quad (8)$$

where w_d – number of turns of the additional pole;

σ_d – is the scattering coefficient of the additional pole;

Λ_d – magnetic conductivity of air gaps in the magnetic circuit of additional poles.

The magnetic conductivity is determined by the expression

$$\Lambda_d = \frac{1}{\frac{\delta_d k_{\delta_d}}{\mu_0 l_a (b_d + 3\delta_d)} + \frac{\delta_s}{\mu_0 l_d (b_d + 3\delta_s)}} \quad (9)$$

where δ_d – the air gap between the anchor and the additional pole;

k_{δ_d} – air gap coefficient under the additional pole;

l_a – length of the armature core;

b_d – width of the core of the additional pole;

δ_s – the air gap between the main body and the additional pole;

l_d – length of the core of the additional pole;

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

The armature winding inductance is mainly generated by the armature reaction flux. According to [19], the inductance value is affected by the saturation of the tooth layer. The armature inductance is determined by the expression

$$L_a = L'_a k_\mu \quad (10)$$

where L'_a – winding inductance excluding saturation,

k_μ – is a coefficient that takes into account saturation.

The inductance of the winding without considering saturation is determined by expression [19]

$$L'_a = \frac{\mu_0 \pi}{3} \frac{w'_a \alpha_\delta^3 l_a D_a}{\delta k_\delta} \quad (11)$$

where $w'_a = \frac{N}{8ap}$ – number of armatures turns per pole (N - number of armatures winding conductors;

$2a$ - number of parallel branches of the armature winding);

α_δ – pole overlap coefficient;

D_a – outer diameter of the armature;

δ – the air gap between the anchor and the main pole;

k_δ – air gap coefficient.

The coefficient that takes into account saturation is determined through the induction in the armature teeth, calculated for a section at a height of 1/3 from the base of the tooth (Table 1) [19].

Saturation coefficient takes into account the change in magnetic conductivity of the armature tooth layer depending on magnetic flux density.

Table 1. Dependence of saturation coefficient on induction in armature teeth [19]

Parameter	Value					
	Magnetic flux density, T	0.4	0.8	1.2	1.6	2.0
Saturation coefficient, f.u.	1.0	0.95	0.79	0.52	0.28	0.12

Thus, expressions (7)-(11) form a model for determining the inductances of the motor windings. Its use increases the accuracy of determining the switching frequency.

Research results. The calculations were carried out for the TE-006 traction motor when it is powered by a pulse converter according to the scheme in Fig. 1. The data from the technical documentation for the electric motor were used for the calculations.

Calculation of inductances. To determine the dependence of inductance on current, we used the magnetisation curve of the TE-006 electric motor, calculated according to [19]. Technical parameters of the electric motor are given in Table 2. The motor magnetisation curve is shown in Fig. 4.

Table 2. Technical parameters of the traction electric motor TE006

Parameter	Value
Power, kW	123/134
Voltage, V	197/283
Nominal current, A	750/522
Current at start-up conditions, A	1000
Rotation frequency, r.p.m.	295/2420
Excitation	series
Minimal field weakening, %	18
Weight, kg	2635

As can be seen from Fig. 5, due to the saturation of the magnetic system, the inductance of the excitation winding decreases significantly with increasing current.

The inductance of the additional pole winding, calculated by (8), is 0.0053 H.

Fig. 5 shows the inductance of the excitation winding without considering eddy currents (in formula (7), the coefficient is zero).

Fig. 6 shows the dependence of the armature inductance on the excitation current. The calculations were performed according to (10) and (11).

Fig. 7 shows the dependence of the total inductance of the motor windings on the current. In the calculations, it is assumed that the eddy current coefficient is 1.25.

From the analysis of the dependencies shown in Figures 5-7, the field winding inductance is significantly higher than the armature inductance. The inductance of the auxiliary poles is higher than the armature inductance. A comparison of the inductance of the field winding and the auxiliary pole winding shows that they are similar at excitation currents above 500 A. At excitation currents below 500 A, the inductance of the excitation winding increases and exceeds the inductance of the auxiliary pole winding.

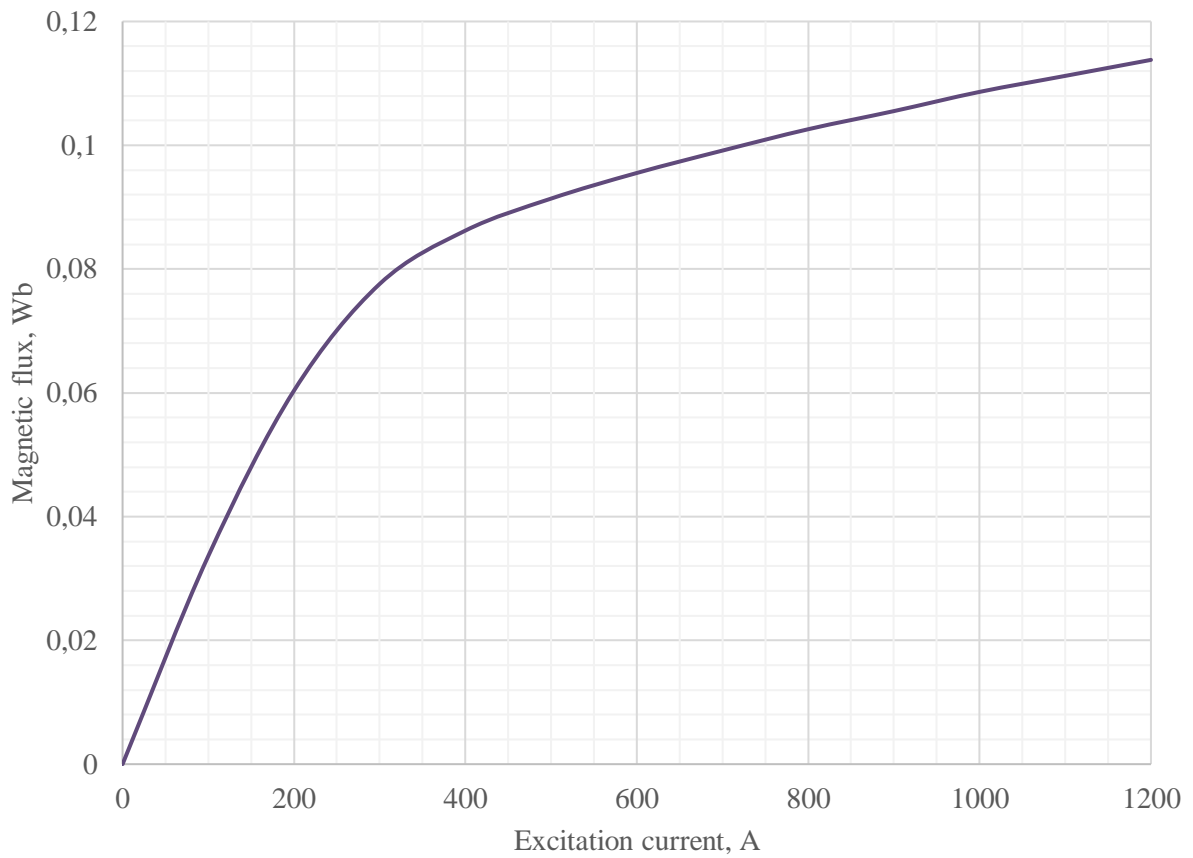


Fig. 4. Magnetisation curve of the TE-006 electric motor (calculated by the authors)

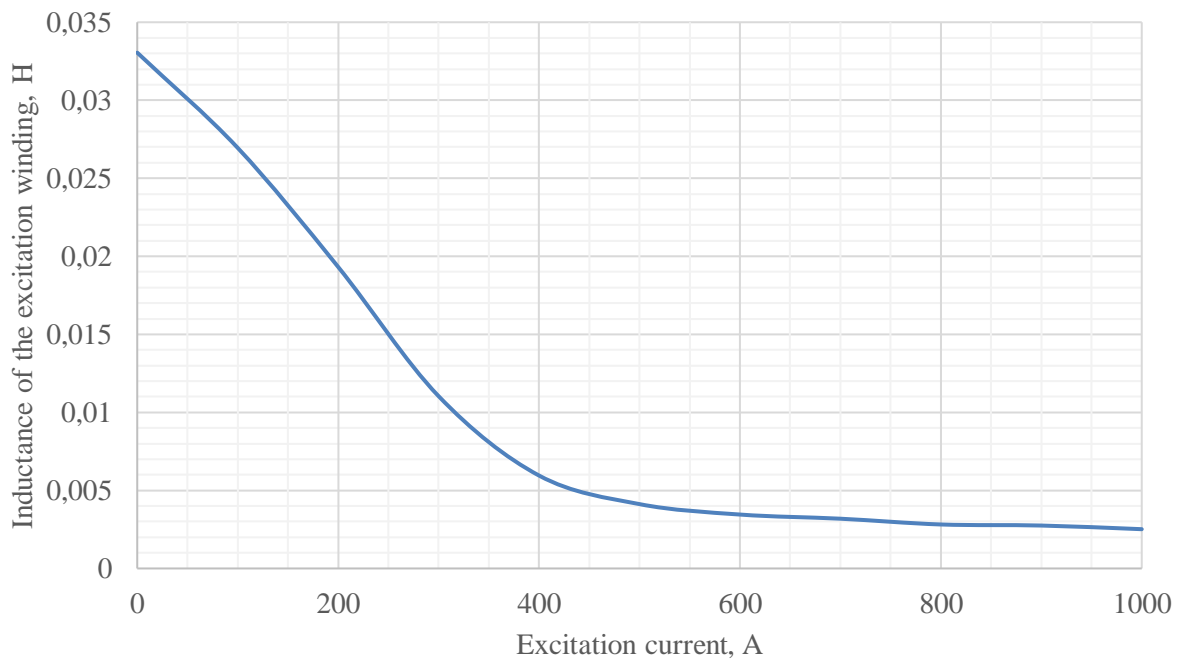


Fig. 5. Dependence of field winding inductance on current

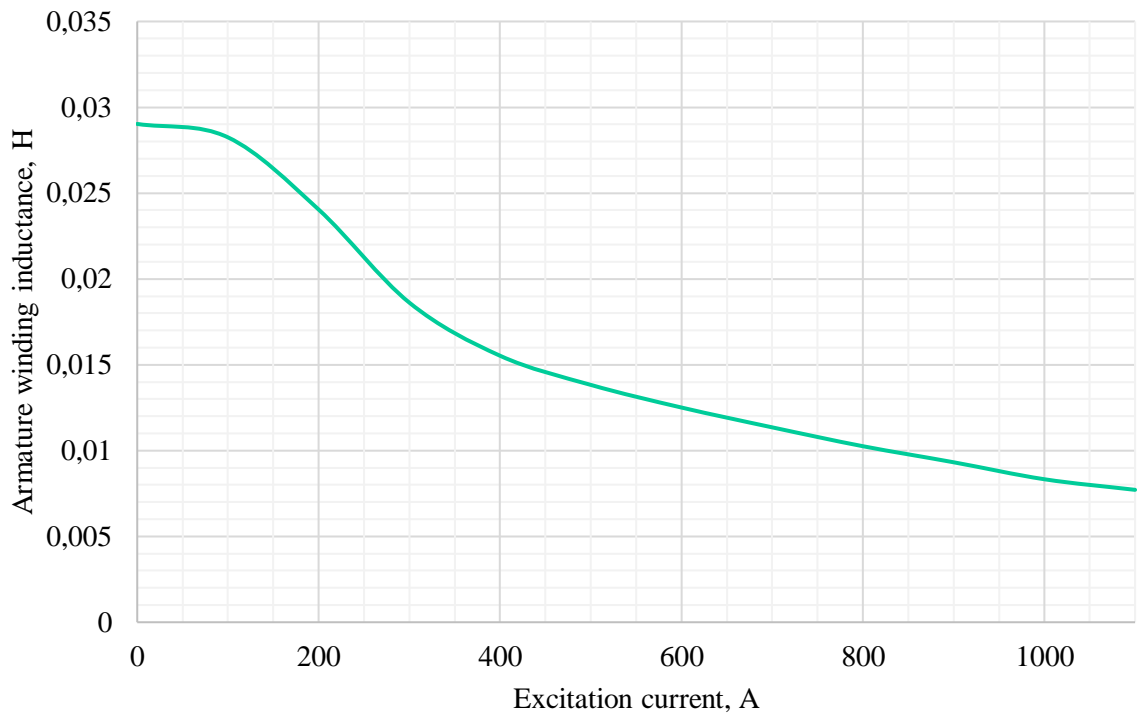


Fig. 6. Dependence of armature inductance on excitation current

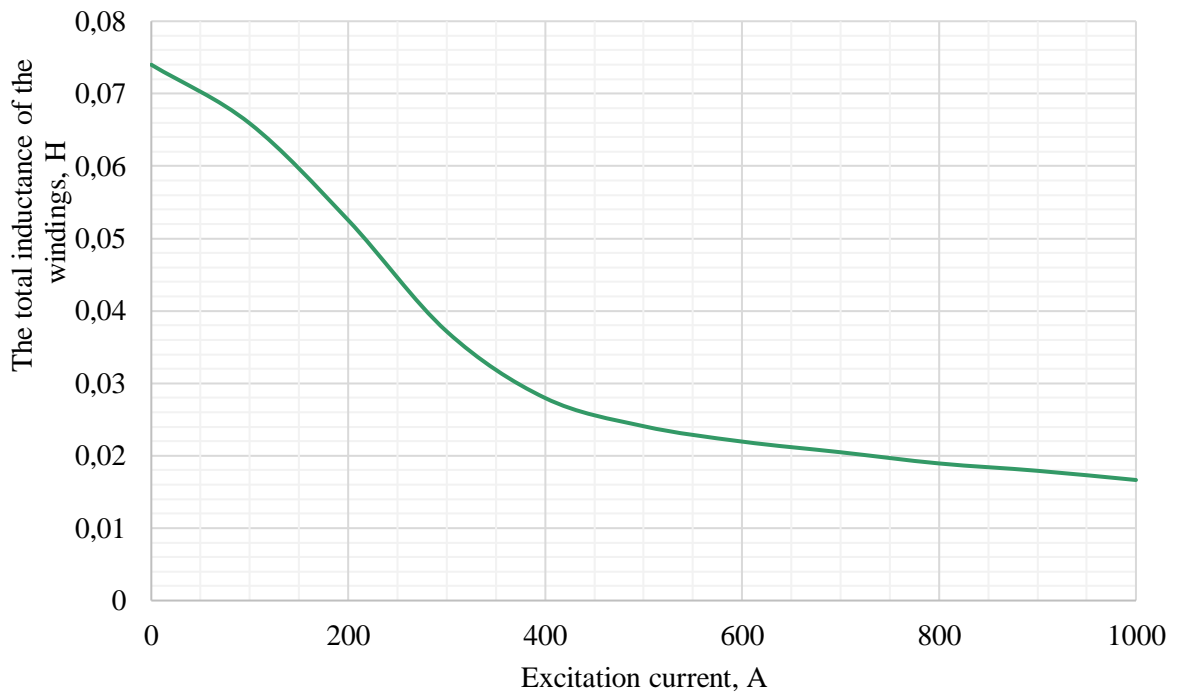


Fig. 7. Dependence of the total inductance of the motor windings (armature winding, the additional pole winding and the excitation winding) on the excitation current

Calculation of the switching frequency when operating with full magnetic flux. It follows from (2) that the switching frequency depends on the current. Since the traction motor operates with different currents, the frequency for each current must be determined.

Fig. 8 shows the dependence of the switching frequency on the current in the range from 100 A to 1000 A for the motor operation mode. In the calculations, it is assumed that the current ripple coefficient is 10% and the intermediate circuit voltage is 600 V.

The analysis of Fig. 6 shows that the switching frequency varies depending on the motor current. The switching frequency decreases as the motor current increases. At a motor current of 100 A, the frequency is 114 Hz. At a current of 1000 A, the frequency is 45 Hz.

Calculation of the switching frequency when operating with magnetic flux attenuation. The calculation of the switching frequency for the excitation winding is performed according to (5), and for the armature circuit - according to (6).

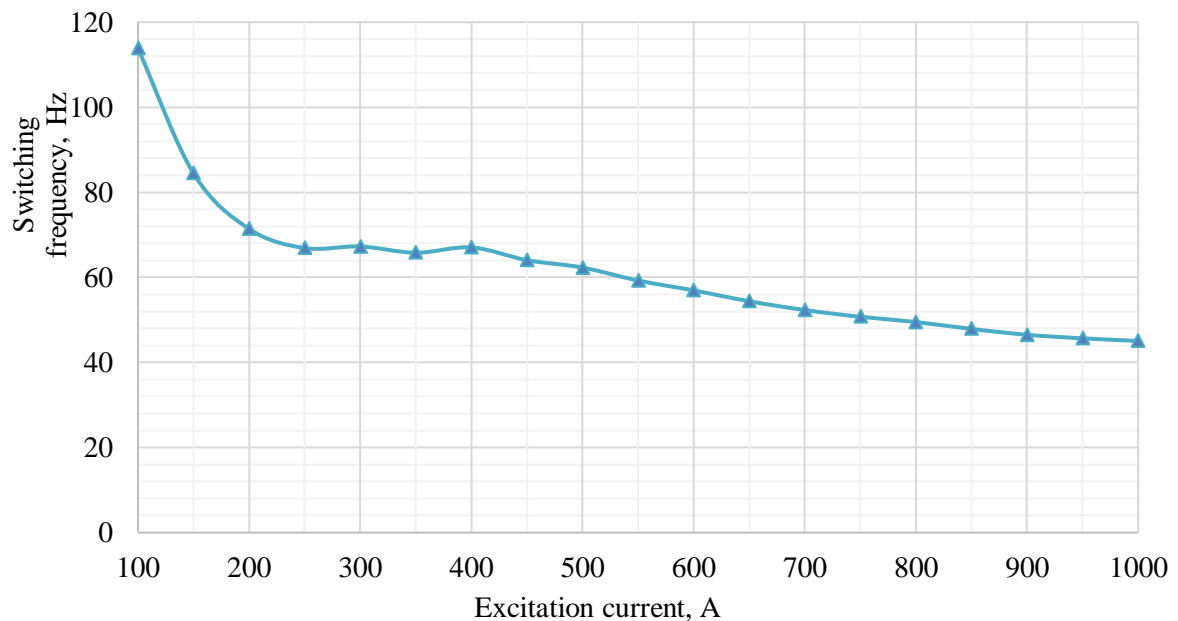


Fig. 8. Dependence of the switching frequency of the transistor VT1 on the motor current in the full magnetic flux mode

The analysis of Fig. 9 shows that the switching frequency varies depending on the motor current. The highest values of the switching frequency (about 290 Hz) are for currents from 500 A to 600 A. The lowest switching frequency (about 150 Hz) is for a current of 200 A.

Fig. 10 shows the dependence of the switching frequency of the transistor VT3 on the excitation current in the field weakening mode under the condition of 10% armature current ripple.

Analysis of dependencies in fig. 10 shows that a change in the degree of saturation of the magnetic system at a given armature current affects the switching frequency.

From fig. 10 shows that the switching frequency varies from approximately 22 Hz at 1000 A armature current to 225 Hz at 100 A armature current.

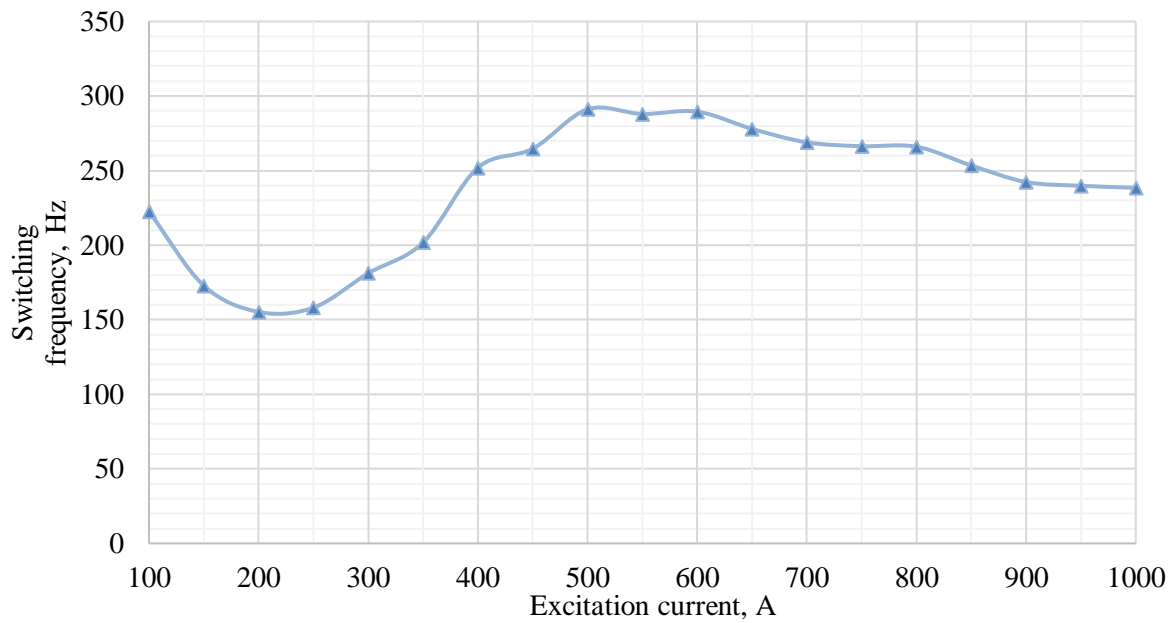


Fig. 9. Dependence of the switching frequency of the transistor VT3 on the excitation current in the field weakening mode with a 10% excitation current ripple

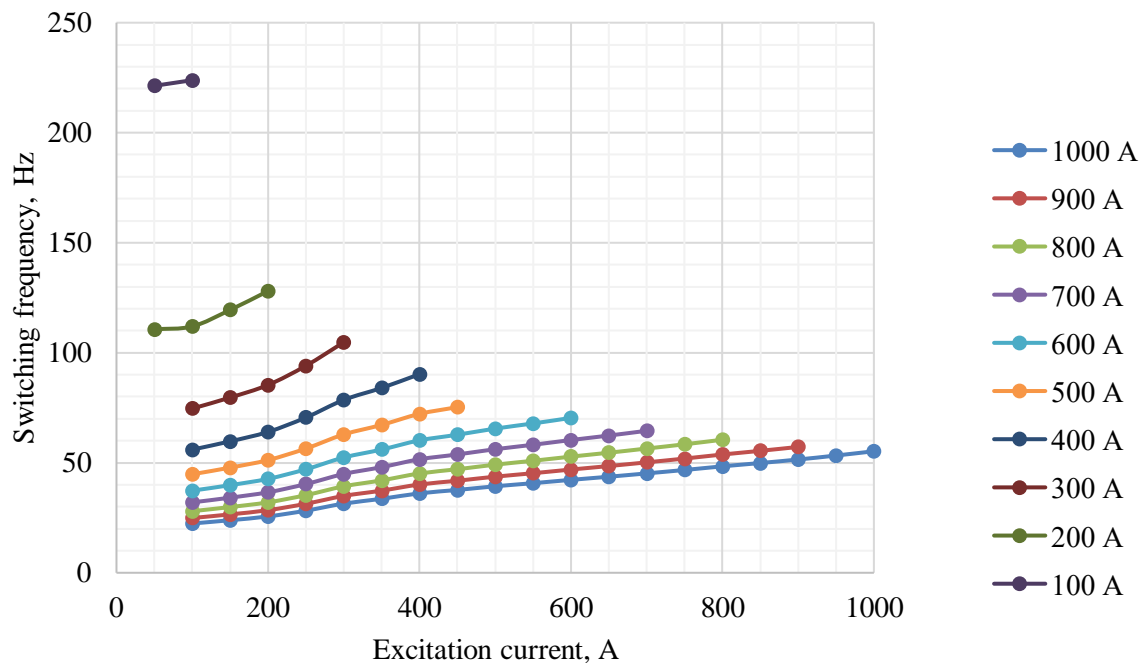


Fig. 10. Dependence of the switching frequency of the VT3 transistor on the excitation current in the field weakening mode with the condition of 10% pulsation of the armature current (armature current is shown on the right)

Then, considering expression (6), the switching frequency should be 290 Hz.

Thus, the study shows the need to take into account the degree of saturation of the magnetic system when determining the switching frequency of a pulse converter.

Discussion of the results. The paper deals with determination of the switching frequency of a pulse converter for power supply and regulation of a DC traction motor. The study was carried out for the traction motor TE-006. It is shown that when determining the switching frequency, it is necessary to take into account the effect of the degree of saturation on the winding inductance. The degree of saturation of the magnetic system has a significant influence on the change in the value of the inductance of the excitation winding. The effect of the saturation degree on the armature inductance is insignificant.

The switching frequency was determined on the condition of ensuring a current ripple coefficient of 10%. This corresponds to the condition of high-quality commutation on the collector. Other aspects arising from the flow of pulsating current were not considered.

In full-field operation, the switching frequency varies from 45 Hz at 1000 A to 114 Hz at 100 A. Therefore, either constant operation of the pulse converter with a frequency of at least 114 Hz is possible, or the switching frequency can vary depending on the current.

The research results show that the switching frequency when working with a weakened field depends on such parameters as: excitation current, armature current and saturation of the magnetic system. When the pulse converter operates at a constant frequency, the switching frequency must be at least 290 Hz for the entire armature current range. At the same time, excitation current pulsations will be close to 10%, and armature current pulsations will be much smaller than 10%.

Thus, the results obtained can be used to create traction systems for diesel locomotives with pulse controllers to power and control DC traction motors.

Conclusions. The paper considers the use of switching regulators for power supply and control of DC traction motors during the modernisation of shunting locomotives. An algorithm for calculating the switching frequency for the selected switching regulator scheme is presented and the necessity of considering the effect of magnetic system saturation on winding inductances is shown. The switching frequency is calculated on the condition of ensuring the current ripple coefficient. It was determined that in the full field mode, the switching frequency should not be lower than 114 Hz. In the weakened field mode, the switching frequency must be higher than 290 Hz.

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Визначення частоти комутації транзисторного перетворювача для тягового колекторного електродвигуна локомотива

Метою даної роботи є визначення частоти комутації транзисторного перетворювача для тягового колекторного двигуна локомотива за критерієм допустимої пульсації струму. Поставлена мета досягається завдяки розв'язанню такого завдання: запропоновано методіку визначення врахування зміни параметрів електродвигуна під час розрахунку частоти комутації транзисторного перетворювача. Особливістю пропонованого підходу є врахування ступеня насичення магнітної системи, оскільки наявні методи розрахунку частоти перемикання або не враховують ступінь насичення магнітної системи, або оцінюють її вплив у спрощеній формі. Найсуттєвішим результатом є підвищення точності розрахунку частоти комутації за рахунок врахування зміни індуктивності обмоток колекторного електродвигуна при зміні ступеня насичення магнітної системи. Виконано розрахунок частоти комутації для тягового двигуна постійного струму з транзисторним перетворювачем. Розглянуто два основні режими роботи електродвигуна: з повним магнітним потоком і з ослабленим магнітним потоком. У результаті розрахунків встановлено, що залежність частоти перемикання від струмів має нелінійний характер. Визначено, що для режиму роботи електродвигуна з ослабленим магнітним потоком частоту перемикання слід визначати з урахуванням процесів як у колах обмотки збудження,

так і в обмотках якірного кола. Найважливішими результатами є визначення частоти перемикання імпульсного перетворювача для живлення і регулювання тягового двигуна в усіх режимах роботи. Запропонована методика дає змогу зробити вибір транзисторних ключів для перетворювача за частотою перемикань.

Ключові слова: енергоефективність, рухомий склад, тяговий електродвигун, тягова система, напівпровідниковий перетворювач, частота комутації.

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Increasing the service life of tank car boilers for the transportation of chemical cargoes by using the method of tread protection

The article is devoted to the search for a comprehensive technical solution to increase the service life of tank car boilers by introducing an effective protection method. A significant problem of increasing the service life of tank cars for the transportation of chemicals is the high level of boiler wear, which is associated with corrosion phenomena that arise as a result of the interaction of the inner surface of the boiler with chemical corrosive cargoes. To solve the problem of the possibility of operating tank cars in terms of determining the service life due to corrosion damage, it is necessary to develop and implement comprehensive measures to assess the final service life of tank cars. At the same time, specialists, researchers and scientists face a special task - to maximize the boiler life using a progressive protection method. One of the most promising methods that can reduce the negative impact of corrosion and be applied in practice is the tread protection method. The article presents an algorithm for calculating the tread protection, which makes it possible to determine the required number of surface protection elements. The effectiveness of protection when changing the cathodic polarization is evaluated. The requirements that should determine the principles of construction of the protection system design and its functioning are considered, and a set of technical solutions and measures aimed at ensuring the protection of metal surfaces of the object of study: a tank car boiler.

Keywords: boiler, tank car, cylindrical part, shell, method of tread protection, calculation algorithm.

Introduction. One of the significant factors affecting the integrity of the tank car boiler shell is internal corrosion. This phenomenon is the process of spontaneous destruction of metal as a result of its interaction with an aggressive environment. In most cases, corrosion occurs according to the electrochemical principle when the metal comes into contact with an aqueous medium.

Corrosion of the boiler's inner surface is one of the main reasons for the inability to perform operational functions and is associated with the influence of many factors - high water content of the transported product, high acidity, the content of impurities that increase the rate of corrosion processes, transportation modes, temperature, the condition of the boiler metal surface, etc. These factors can affect the corrosion rate: in some cases, they can reduce it, and in others, they can increase it. Regardless of this, the fundamental danger of corrosion is determined by the presence of the aqueous phase in the transported media.

The process of corrosion causes a decrease in the technical life of the railroad car, partial or complete disruption of the system's functioning, and the inability to participate in the transportation process.

Tank car boilers are vulnerable to corrosion caused by physical processes of contact between different media and chemical reactions that occur as a result of their interaction. Over time, corrosion reduces the integrity of the boiler and eventually penetrates its structure, causing changes in thickness and leading to perforation of the shell, which can lead to the leakage of chemical cargo into the environment and the occurrence of a further man-made disaster.

Since most corrosion occurs inside the boiler, the extent of the danger is usually unknown and hidden until external signs appear, which is often too late to eliminate. The timely detection of such “dangerous” areas is a priority task when conducting technical diagnostics of the boiler surface, and therefore the development of forecasting methods to detect them at an early stage is of particular importance when assessing the technical condition of the railcar structure.

The most typical types of corrosion observed during the operation of tank cars include:

- general corrosion - occurs over the entire surface of the boiler;
- local corrosion - occurs in certain places where the liquid phase of a chemical substance accumulates or is located
 - pitting corrosion - occurs on horizontal surfaces, at the bottom of the boiler and in places where the liquid phase accumulates (bottom sheets).
 - weld metal corrosion - occurs when the weld metal interacts with the boiler metal, causing an electrolytic reaction.

In order to detect corrosion, the boiler must first be emptied of the chemical load, and then a complete internal cleaning using pressure jetting is performed. Next, non-destructive testing is performed to check the metal thickness at various points in the boiler, depending on the selected measurement location. The respective measurements are made for the bottom, middle and top of the boiler shell. If corrosion is detected, measures are taken to eliminate it, in accordance with the restoration technology approved by the repair company.

Among the existing best-known methods of protection (anodic and cathodic methods) against corrosion of metal surfaces, the simplest and most effective in the study of corrosion control and reduction of its consequences is the protector method of corrosion protection, as a type of cathodic method, therefore, it is advisable to use it for the inner surface of tank car boilers used for the transportation of chemicals.

Analysis of recent research and problem statement. The use of the most effective methods of protecting metal surfaces of various parts of railcars from corrosion is currently one of the most important tasks that needs to be addressed to increase the service life of rolling stock. One of the most effective methods of metal corrosion protection is the tread protection method. It is widely used in the civil engineering industry to protect metal pipelines and structures that are located underground and have direct contact with the ground. In addition, the idea of using a tread protection system was implemented for oil storage tanks. In general, a significant number of publications have been devoted to the design of cathodic protection systems in recent years. The authors of various articles have conducted electrochemical tests of metals [1], modeled the distribution of the electric field of cathodic protection systems located in the ground [2], and developed the design and location of anode grounding in corrosive environments. Article [3] analyzes the mechanisms of external corrosion and the causes of destruction of underground gas and oil pipelines, presents existing monitoring tools for assessing external corrosion and models for preventing corrosion and predicting its occurrence. The authors note that to ensure proper corrosion protection of underground metal structures, it is necessary to design and use cathodic protection systems. Work [4] is devoted to the development of an algorithm for optimizing the system of the auxiliary anode of the grounding grid based on an improved method of simulated annealing. The boundary element method is widely used to model cathodic protection systems for underground and offshore structures. Thus, in [5], the authors used the boundary element analysis to study the effect of the horizontal distance between parallel pipelines, the rate of damage to the insulating coating, the electrical conductivity of the soil, and the anode output current on the interference of parallel pipelines. At the stage of designing a protection system, by changing the layout elements, it is necessary to ensure the overlap of the protection zones of neighboring cathodic stations and thereby reduce the

output currents of cathodic protection stations in the system. The vast majority of works are devoted to various methods for calculating the main parameters of protection systems for different facilities and conditions of placement and operation of pipeline systems. The authors of [6] performed numerical modeling by the boundary element method of anode grounding of deep well casing. In [7], the authors of numerical modeling by the boundary element method determined the distribution of the electric field of the cathodic protection system for structures of complex geometry. An optimization scheme of the corrosion protection system was developed by adjusting the amplitude of the current supplied to the anode, as well as the location and size of the anode layer area. Studies [8-10] propose a new distributed model for the development of a cathodic protection system for oil and gas pipelines. The main difference between the proposed model and the traditional approach is the use of measured soil resistance throughout the structure instead of a fixed average value. However, the complexity of practical implementation and its cost slow down the possibility of application.

Creation of tread protection systems for railway transport requires the development and implementation of design solutions similar to those in related industries where similar solutions have already been implemented, but with a number of features. This is primarily due to the type of chemical cargo, its acidity (pH), temperature and humidity conditions of transportation, the concentration of the liquid phase, which determines the rate of corrosion, etc. An equally challenging task is to develop an algorithm for calculating the required number of anode elements to be used during redox processes and to create a set of measures for timely maintenance of protection systems.

The purpose and tasks of the study. Determining the effect of corrosion of the metal shell of a tank car boiler on its structural strength remains an urgent scientific and technical problem that needs to be solved using methods and implementing a number of measures both during operation and in determining the possibility of further extending the service life of railcars. In accordance with the current regulatory documentation [11], according to the established design load modes, the strength of individual parts of railcars is determined by the permissible stress values. The assessment of strength indicators can be carried out using standard calculation methods or during various types of field tests using measuring equipment. However, the need to assess the service life of the boiler structure of a tank car, which can transport chemical cargoes of various nomenclatures, requires finding the most rational methodology for studying its stress-strain state [12, 13] using adaptive mathematical calculation models. This is especially true for determining the service life of a railroad car based on its technical condition, where a corrosion protection system can be used.

The aim of the presented study is to assess the possibility of extending the service life of tank cars for the transportation of chemicals using the tread method of boiler protection. The tasks are to create a calculation algorithm that can be used to determine the required number of protection elements, determine the strength and density of the protective current on the contact surface of different media, and develop design proposals for further project implementation.

Materials and methods of research. Among the existing best-known methods of corrosion protection of metal surfaces, the simplest and most effective in the study of corrosion control [14] and reduction of its consequences is the tread method of corrosion protection as a type of cathodic method, so it is advisable to use this method for the inner surface of tank car boilers used for the transportation of chemicals.

Due to the fact that an electrolytic bond creates a potential difference between the tread and the metal structure, an electric current flows. This dissolves the active material - the tread (galvanic anode), while the cathode (protective structure) remains inert.

With the help of the projector, the metal structure is polarized, which in turn leads to a shift in the potential of the structure in the negative direction. The metal of the protective structure is shielded on the surface (hydroxide precipitate), which impedes oxygen diffusion and increases the thickness of the protective layer.

This method makes it possible to use electrochemical protection by a galvanic anode against corrosion using the protective properties of the dissolved anode surface deposit formed on the cathodically polarized metal surface.

Use of active corrosion protection by galvanic anodes (protectors) is recommended to be combined with the use of protective paint and varnish coatings, which can significantly reduce current consumption and anode alloy consumption and extend the service life of the protective coating. In the case of using the protective coating without paint and varnish coatings and preliminary surface preparation, cleaning from rust and other surface defects will provide surface protection for approximately 11-14 years (with the application of protective paint and varnish coatings, the service life is almost doubled).

The protective effect is caused by the inhibition of corrosive microelements due to the polarization of the corroded surface. The corrosion system as a binary short-circuited galvanic element (K-A) (Fig. 1), to which a third electrode (Zn) is added, is the most effective protector.

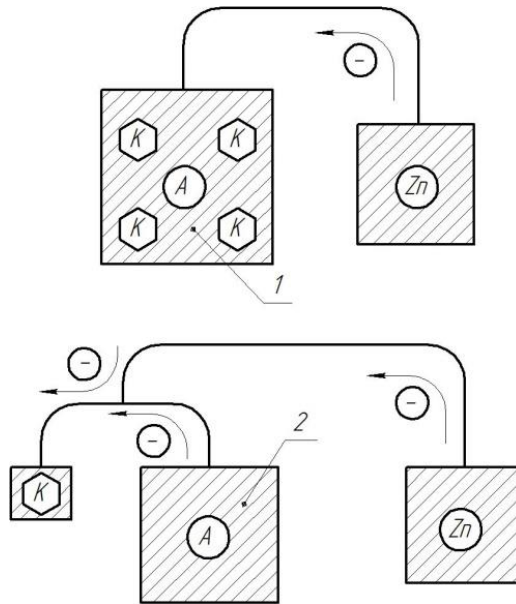


Fig. 1. Schematic representation of the interaction models of the protective system: 1 - contact of the corroding metal (K-A) with the anode (Zn); 2 - equivalent three-electrode model of the protective system.

In the polarized corrosion diagram (Fig. 2), the point S defines the corrosion potential V_x and corrosion current without the use of electrochemical cathodic protection (without contact with the anode); V_y is the total potential of the three-electrode system after the protector is attached.

The diagram shows that the corrosion current is significantly reduced after the protector is attached compared to the initial current ($V_x S$). Therefore, the more negative the initial tread potential and the flatter the anode polarization curve of the tread, the greater the shift in the potential of the three-electrode system V_y to the negative side and the lower the final corrosion current of the micropairs. If the total system potential is sufficiently shifted in the negative direction (to the potential V_a^0), the corrosion current can be zero - complete protection occurs.

In accordance with the phenomenon of the differential effect, it becomes necessary to introduce a protective effect coefficient $K_{\text{ax.e.p.}}$ when reducing the operation of corrosion microcouples by increasing the current density of external cathodic polarization by one. At the same time, the dependence of the protective effect constant on the value of the cathodic and anodic polarization of the system when the polarization curves are close to straight lines $K_{\text{ax.e.p.}}$ will be approximately constant and the overall protective effect is proportional to the cathodic current density.

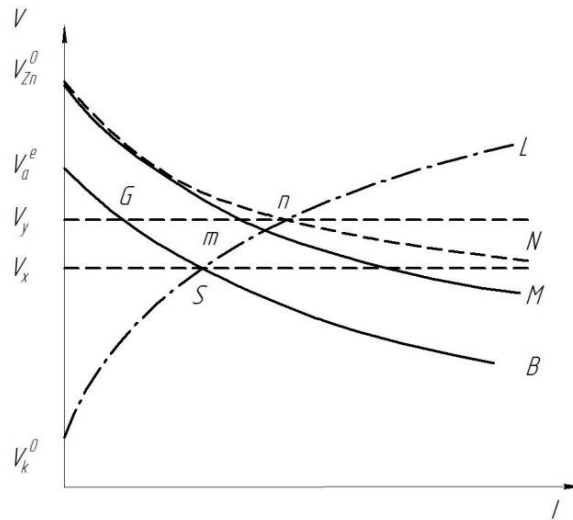


Fig. 2. Polarization diagram of corrosion:

$V_a^e B$ – anode curve of a composite electrode; $V_k^0 L$ – cathode curve of a compound electrode;
 $V_{Zn}^0 M$ – curve for anode contact; $V_{Zn}^0 N$ – general anode curve.

The diagram (Fig. 3) shows the ideal cathode $V_k^0 c$ and anode $V_a^e A$ curves for the studied corrosion system under the given conditions, and V_x is the potential of the corrosive system in the absence of electrochemical protection. If electrochemical protection is used by attaching a protector or cathodic polarization from the outside by applying a voltage, then the potential of the corrosive system will be shifted to a more negative value V'_x . In this case, the corrosion current will decrease from the value $V'_x b$ to $V'_x a$ and the external cathode current will be equal to the value ac . Full protection will be provided if, during the cathodic polarization process, the potential of the corroding system becomes more negative than the value of the initial potential of the anodic process V_a^e .

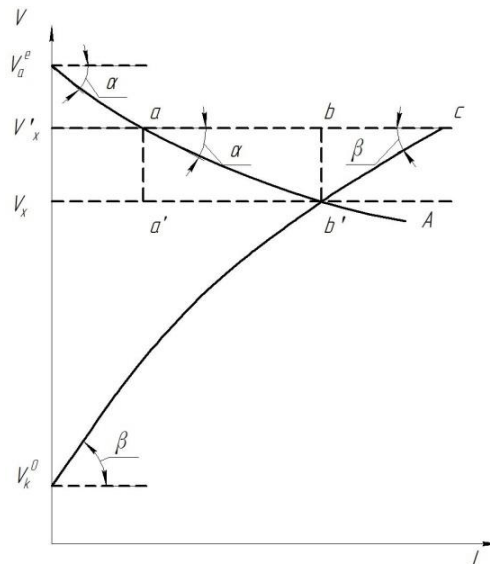


Fig. 3. Polarization diagram for determining the tread effect coefficient

If we consider the polarization curves at their intersection as straight lines, we can show that there is a direct proportionality between the protective effect and the density of the applied cathodic current.

This condition is fulfilled with a high degree of probability at a low value of the external cathodic polarization current.

Based on the graphical construction (Fig. 3), the voltage potential can be written using the following expressions:

$$\Delta V = b \cdot c \cdot \operatorname{tg} \beta, \quad (1)$$

$$\Delta V = a \cdot b \cdot \operatorname{tg} \alpha, \quad (2)$$

Dividing the first expression by the second, we get:

$$\frac{bc}{ab} = \frac{\operatorname{tg} \alpha}{\operatorname{tg} \beta}, \quad (3)$$

After the conversion, we can write this expression as follows:

$$\frac{bc}{ab} + 1 = \frac{\operatorname{tg} \alpha}{\operatorname{tg} \beta} + 1,$$

Or otherwise:

$$\frac{bc + ab}{ab} = \frac{\operatorname{tg} \alpha + \operatorname{tg} \beta}{\operatorname{tg} \alpha}, \quad (4)$$

The segment aa' is the protective effect of cathodic polarization by an external current I , which is graphically represented by the segment $ac = ab + bc$.

Then we have a ratio for the segment aa' :

$$\frac{I}{aa'} = \frac{\operatorname{tg} \alpha + \operatorname{tg} \beta}{\operatorname{tg} \beta}, \quad (5)$$

Where we get it from:

$$aa' = \frac{\operatorname{tg} \beta}{\operatorname{tg} \alpha + \operatorname{tg} \beta} I, \quad (6)$$

Or otherwise:

$$aa' = K_{\text{ax.eff.}} \cdot I, \quad (7)$$

At constant values of α and β , the protective effect coefficient will be constant in value. If we assume that the cathodic and anodic polarizations are linearly dependent on the current density, i.e. $\operatorname{tg} \alpha = P_a$ and $\operatorname{tg} \beta = P_k$, then the protective effect coefficient can be written in the form:

$$K_{\text{ax.eff.}} = \frac{P_k}{P_k + P_a} = \frac{1}{1 + \frac{P_a}{P_k}}, \quad (8)$$

Therefore, the protective effect, i.e. the reduction of the local current with an increase in the external cathodically polarized current, will be greater the greater the cathodic polarization of the corrosion

protection system.

If the polarization curves are close to straight lines, this rule will be valid over the entire range of polarization currents. If the polarization curves cannot be considered as straight, then this rule will be observed only at relatively small values of the external current compared to the value determined by the abscissa of the intersection point of the polarization curves.

The variant of tread protection for tank car boilers proposed by the authors of the article involves the use of groups of treads that are placed in blocks in the boiler (Fig. 4). Calculation of the parameters of tread protection involves determining the number of parallel extended treads and their total weight, which provide a given degree of protection of tanks according to the method described below.

Calculation of the protective cathodic polarization is carried out by the formula:

$$\Delta\varphi_{II} = 0,081\lg(1 - P_s), \quad (9)$$

where P_s – degree of protection of the tank car boiler against corrosion.

Minimum required protective current density on the surface of the tank car boiler is defined as:

$$j_3 = \frac{|\Delta\varphi_{II}|}{P_c}, \quad (10)$$

where P_c – polarization resistance of steel.

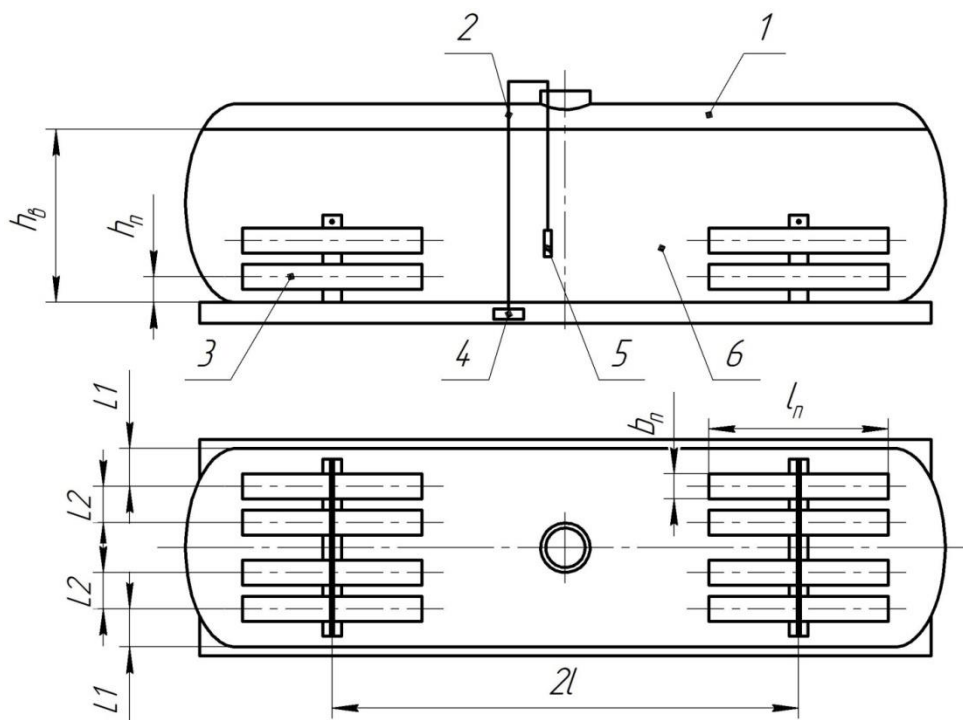


Fig. 4. Scheme of tread protection of a tank car boiler for chemical cargo transportation:

1 - tank car boiler; 2 - electric conductor; 3 - tread block; 4 - control and measuring equipment; 5 - electrode; 6 - liquid chemical cargo.

Arc angle of the circumference of the tank car boiler, which is wetted with the liquid phase, is calculated by the formula

$$\psi = 360 - 2 \arccos \frac{2h_g - D}{D}, \quad (11)$$

where h_g – level of the liquid phase in the tank car boiler.

Area of the inner surface of the tank car boiler in contact with the water phase is calculated using the formula

$$S_u = \frac{\psi}{360} \cdot \pi D L_u + 1,3 \left(\frac{\pi D^2 \psi}{2 \cdot 360} + \frac{D^2}{2} \cdot \sin \frac{(360 - \psi)}{2} \cdot \cos \frac{(360 - \psi)}{2} \right), \quad (12)$$

where D – internal diameter of the tank car boiler;

L_u – length of the cylindrical part of the tank car boiler;

ψ – arc angle of the circumference of the tank car boiler wetted with the liquid phase.

Protective surface area of the tank car boiler is calculated by the formula

$$S_3 = S_u \cdot S_0, \quad (13)$$

where S_0 – defect rate of the corrosion protection coating of the tank car boiler.

Current required to protect the inner surface of the tank car boiler is determined by the formula

$$I_{II} = j_3 \cdot S_3, \quad (14)$$

Calculation of the current strength that can be provided by one row of treads is based on the formula

$$I = \frac{m_0 \cdot N \cdot L_u \cdot K_e}{T_{II} \cdot q}, \quad (15)$$

where m_0 – weight of one running meter of tread rod;

N – number of rows of projectors;

L_u – length of the cylindrical part of the tank car boiler;

K_e – tread weight utilization rate;

T_{II} – design service life of the treads;

q – anodic dissolution rate of the tread.

Calculation of the number of rows of treads that provide the required current strength to protect the inner surface of the tank car boiler using the formula

$$N = \frac{I_{II}}{I}, \quad (16)$$

Tread utilization rate is determined by the formula:

$$A = \frac{2h_{II}(D - h_{II})}{D \cdot A_{II}}, \quad (17)$$

where h_{II} – height of the tread in the tank car;

A_{II} – cross-sectional area of the tread rod;

D – internal diameter of the tank car boiler.

Calculation of the total resistance between the tread and the tank car, with the calculated number of rows of treads N

$$R = \frac{1}{\psi} \left[\frac{4(\rho_B \delta_{II} + P_c)}{(2L_y + D)DS_0} + \frac{\rho_B}{\sqrt{N}} \ln(A + \sqrt{A^2 - 1}) \right], \quad (18)$$

where ψ – arc angle of the circumference of the tank car boiler wetted with the liquid phase;

ρ_B – resistivity of the liquid phase of the chemical mixture in the tank car boiler;

δ_{II} – thickness of the anti-corrosion coating of the inner surface of the tank car boiler;

P_c – polarization resistance of the steel from which the boiler is made;

L_y – length of the cylindrical part of the tank car boiler;

S_0 – defect rate of the anti-corrosion coating;

N – number of rows of treads.

Calculation of the protective current of the tank car boiler

$$I_B' = \frac{\Delta\varphi_e + \Delta\varphi_{II}}{R + \frac{P_{II}}{\pi A_{II} L_y N}}, \quad (19)$$

where $\Delta\varphi_e$ – difference in the natural potentials of the tread and the boiler;

$\Delta\varphi_{II}$ – protective cathodic polarization;

P_{II} – polarization resistance of the steel from which the boiler is made.

Verification of the adequacy of the mass of the calculated number of treads to ensure the protective current I_B'' during the design life of the treads T_{II} can be performed if $I_B'' > I_B'$ the mass of the calculated number of treads is sufficient.

$$I_B'' = \frac{m_0 \cdot N \cdot L_y \cdot K_g}{T_{II} \cdot q}, \quad (20)$$

Calculation of the protective current density in the lower part of the tank car boiler

$$j = \frac{4 \cdot I_B' \cdot K_T}{(2L_y + D) \cdot D \cdot S_0 \cdot \psi}, \quad (21)$$

where K_T – coefficient of uneven distribution of current density along the perimeter of the tank car boiler shell.

For example, here is a calculation of tread protection based on the input data (Table 1).

In accordance with the methodology of the above calculation and according to the input data in formula (9), the protective cathode polarization is first determined, the potential of which is equal to $\Delta\varphi_{II} = -0,104$ V. The obtained value of the voltage potential corresponds to the value of the minimum required protective current density on the surface of the tank car boiler $0,11$ A/m². Taking into account that the level of the liquid phase in the boiler is assumed to be equal $h_g = 2,85$ m to the arc angle of the circumference of the tank car boiler, which is wetted by the liquid phase, will be equal to $\psi = 308^\circ$.

The protective surface area of the tank car boiler is approximately equal 10 % to the area of the inner surface of the boiler and, in accordance with the accepted geometric dimensions, is determined by formula (12) and is $S_{II} = 92,94$ m². The calculated current required to protect the inner surface of the boiler is equal to $I_{II} = 0,967$ A. Taking into account that the strength of the protective current $I_B'' = 1,01$ A

during the design life of the treads $T_{\text{т}} = 5$ years is greater than the minimum required $I_b' = 0,15$ A, i.e., the condition is met $I_b'' > I_b'$, the mass of one running meter of the tread rod $m_0 = 8,3$ kg/m will be sufficient for use.

Table 1. Input data for the calculation

Parameter, dimensionality	Value
Degree of protection of the tank car boiler against corrosion	0,95
Polarization resistance of steel, $\text{Om} \cdot \text{m}^2$	0,1
Liquid phase level in the tank car boiler, m	2,85
Inner diameter of the tank car boiler, m	3,0
Length of the cylindrical part of the tank car boiler, m	9,614
Defectiveness coefficient of the corrosion protective coating of the tank car boiler	0,1
Weight of one running meter of tread rod, kg/m	8,3
Tread weight utilization rate	0,75
Design service life of treads, years	5
Anode dissolution rate of the tread, kg/A·h	11,9
Height of the tread in the tank car, m	0,1
Cross-sectional area of the tread rod, m^2	0,021
Resistivity of the liquid phase of a chemical mixture in a tank car boiler, $\text{Om} \cdot \text{m}$	0,15
Thickness of the anti-corrosion coating of the inner surface of the tank car boiler, m	$1,5 \cdot 10^{-4}$
Difference in natural potentials of tread and boiler, volts	0,3

The presented dependence (Fig. 5) of the ratio of the current density on the bottom of the boiler to the current density of the entire protective surface on the number of projectors determines the required number of elements of the protection system. As can be seen from the graph, the minimum threshold value of the ratio should be $j / j_3 = 1,2$.

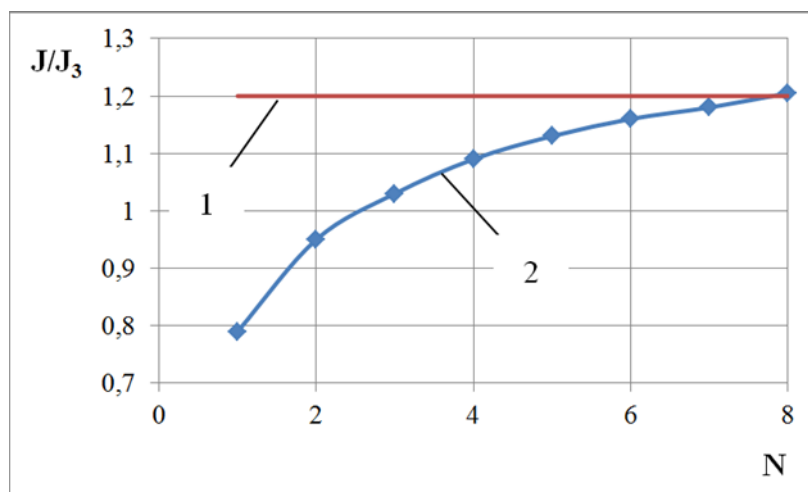


Fig. 5. Calculated graphical dependence of the protective current density on the number of treads:

1 – minimum limit value of the protective current density; **2** – calculated value of the protective current density for N protectors.

According to the results of the calculations, it was found that in order to achieve the minimum permissible current density in order to protect the boiler surface, it is necessary to use $N=8$ units of protectors.

The graphical dependence (Fig. 6) of the protective current strength on the total resistance arising between the tread and the tank car under the action of the protection system with a change in the number of treads $N=1\div 8$ can be represented in accordance with the equation of a polynomial curve $y=0,2268x^2-0,7023x+0,6575$ of degree two.

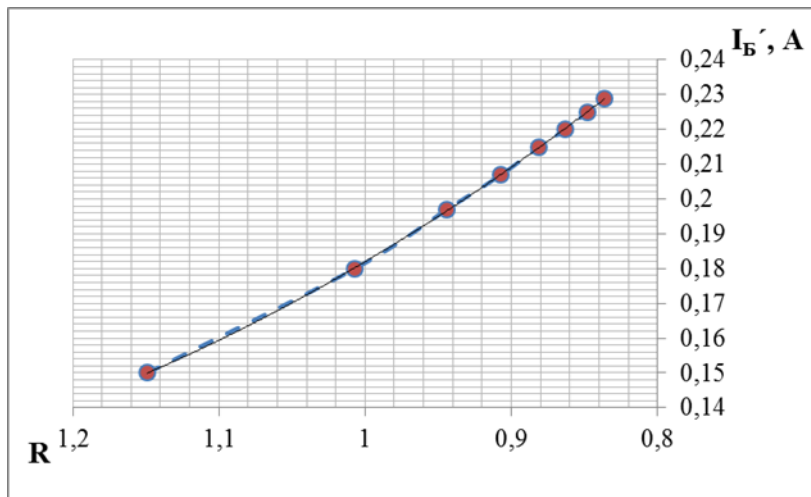


Fig. 6. Calculated graphical dependence of the protective current on the total resistance for the number of protectors $N = 1\div 8$

As can be seen from the graph (Fig. 6), a decrease in total resistance leads to an increase in the strength of the protective current. When using the minimum number of protective elements sufficient to protect the boiler surface, the protective current increases by 1,52 times, while the value of the total resistance drops by 27,3 percent.

The protection system is presented in the form of a complex containing two blocks of protectors with galvanic anodes, combined into independent groups located at a certain distance from each other inside the tank car boiler (Fig. 7).

Such groups are stirred in the lower part of the boiler and fixed by the mechanism of fixing the tread block in the selected spatial position. Installation and dismantling of the block part protectors is performed at the place of their installation. The anodes can be connected using a parallel or series connection scheme to the active group.

The protectors are connected to the tank car boiler body by means of resistors, the resistances of which should be calculated depending on the type of chemical cargo in order to limit the maximum current of the protector. A voltage regulator is connected to the resistors according to the scheme to determine the potential difference between the cathode (the inner surface of the boiler body) and the anode (the tread). The effectiveness of the tread protection is determined by the value of cathodic polarization (electrolyte potential shift), which is measured relative to the working electrodes, or by means of a potential measuring unit (control and measuring equipment) brought out and mounted on the tank car boiler frame.

Development of a set of technical solutions for protecting the inner surface of a tank car boiler from corrosion is based on the following requirements:

1) boiler protection can be designed as a built-in block or individual structural design, independent of the boiler size.

2) protection system can be used as a backup system when using cathodic protection schemes.

- 3) protection with the help of protectors should be used with a certain calculated specific electrical resistance in accordance with the type of protectors, their number, material and electrolytic medium;
- 4) tread protection installations should be equipped with control and measuring devices and, if necessary, regulating resistors or shunts;
- 5) protection shall consist of single or group installations, with the choice of the type and arrangement of protectors being made taking into account the specific conditions of installation at the facility;
- 6) the protective current density on the surface of the tank car boiler from projectors should be taken into account in the design calculation.

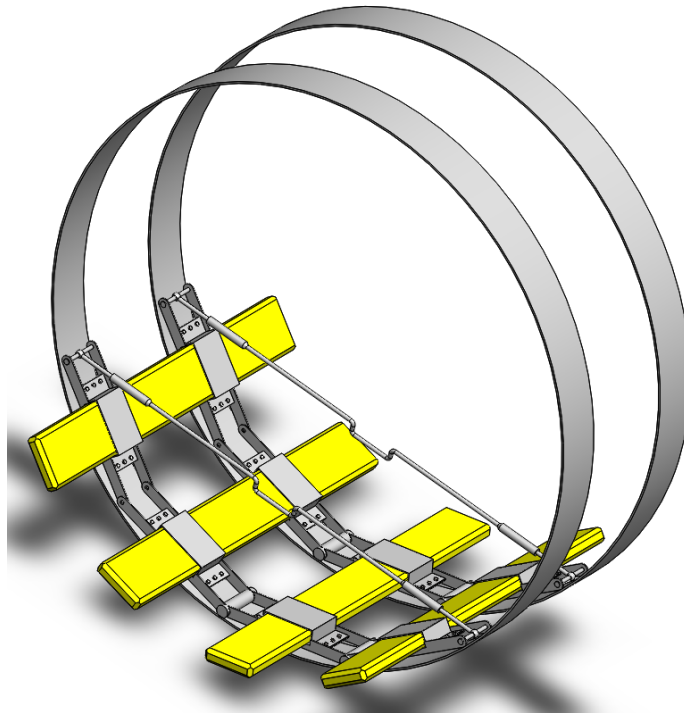


Fig. 7. Basic unit of the model of the tank car boiler corrosion protection system

The set of technical solutions includes:

- proposals for the creation of a block protection system for the tank car boiler;
- development of drawings for the protection mechanism;
- creation of a model of the protection system;
- development of a schedule of scheduled diagnostic work to determine the technical condition of the inner surface of the tank car boiler after the introduction of corrosion protection systems;
- application of an ultrasonic method for monitoring the thickness of the boiler shell metal according to the developed measurement scheme.

Conclusions. The decrease in the technical life of a railroad car is associated with corrosion processes. Tank car boilers are one of the most vulnerable parts to corrosion caused by physical processes of contact between different media and chemical reactions that occur in them as a result of their direct interaction. Over time, corrosion reduces the integrity of the boiler by penetrating its structure, causing changes in thickness and leading to a loss of strength properties of the shell metal. The occurrence of corrosion phenomena and their spread is a particularly dangerous factor in the transportation of chemical corrosive cargoes in tank wagon boilers, as it significantly accelerates chemical reactions of oxidation of the boiler shell metal and poses a threat not only of premature repair or even replacement of the boiler, but also of man-made disasters in the event of chemical leakage into the environment.

Introduction of a number of complex measures is aimed at ensuring the required degree of

anticorrosion maintenance of the tank car boiler during a long period of use and ensuring an increase in the resource of the tank car in operation. The developed algorithm for calculating the tread protection system involves: determining the cathodic polarization of the metal surface of the boiler; calculating the minimum required protective density and current; providing the required number of rows of treads that determine the level of protection of the structure. In the course of the work, it was found that the protective effect will be greater, the greater the cathodic polarization of the corrosion protection system with a decrease in local current with an increase in external cathodically polarized current.

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Збільшення ресурсу котлів вагонів-цистерн для перевезення хімічних вантажів за рахунок використання методу протекторного захисту

Стаття присвячена питанням пошуку комплексного технічного рішення щодо збільшення ресурсу котлів вагонів-цистерн за рахунок впровадження ефективного методу захисту. Суттєвою проблемою збільшення ресурсу вагонів-цистерн для перевезення хімічних вантажів є високий рівень зносу котла, що пов'язано з корозійними явищами, які виникають внаслідок взаємодії внутрішньої поверхні котла з хімічними корозійно-активними вантажами. Для вирішення задачі з можливості експлуатації вагонів-цистерн в умовах визначення терміну служби внаслідок отримання корозійних пошкоджень є необхідність розробки і проведення комплексних заходів з оцінки остаточного ресурсу вагонів-цистерн. При цьому перед фахівцями, дослідниками та науковцями постає особливе завдання – забезпечити максимальне збільшення ресурсу котла з використанням прогресивного методу захисту. Одним з найбільш перспективних методів, який може зменшувати негативний вплив дії корозії та бути застосований практично є протекторний метод захисту. В статті представлено алгоритм розрахунку протекторного захисту, який надає змогу визначити необхідну кількість елементів захисту поверхні. Надана оцінка ефективності захисту при зміні катодної поляризації. Розглянуто вимоги, які мають визначати принципи побудови конструкції системи захисту та її функціонування, а також запропоновано комплекс технічних рішень та заходів, спрямованих на забезпечення захисту металевих поверхонь об'єкта дослідження: котла вагон-цистерни.
Ключові слова: котел, вагон-цистерна, циліндрична частина, оболонка, метод протекторного захисту, алгоритм розрахунку.

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