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3	
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Assessment of the technical condition of a transformer based on the operational parameters of its oil using the fuzzy logic method

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Abstract:

This article develops a mathematical model for assessing the technical condition of non-traction electrical systems of railway transport based on the operational indicators of transformer oil, as well as an algorithm for determining the integral value of technical condition. In the study, the water content, acid number, mechanical impurity content, kinematic viscosity, density, flash point, electrical strength, and dielectric losses of the transformer oil were selected as the main diagnostic parameters characterizing the technical condition of the system. A mathematical model has been developed that accounts for the relationship between these parameters, and an algorithm for determining the value based on fuzzy logic theory has been proposed for their comprehensive evaluation. For each diagnostic indicator, affiliation functions were formed, a database of fuzzy rules was developed based on expert knowledge and current regulatory documents, and an integral assessment indicator of the technical condition was calculated using the Mamdani inference algorithm and the Centroid method. The results of the study showed that the developed mathematical model and algorithm allow for a comprehensive analysis of transformer oil performance indicators, a reliable assessment of the technical condition of non-draft electrical systems, the determination of the degree of insulation system degradation, and the classification of technical condition into "very poor," "poor," "average," "good," and "excellent" categories. The proposed approach serves as a scientific and practical basis for increasing diagnostic accuracy in non-traction electrical systems of railway transport, preventing emergency situations, improving condition-based maintenance systems, and increasing the operational reliability and service life of transformers.

Keywords:

transformer oil, railway transport, non-traction electrical systems, technical condition assessment, mathematical modeling, Fuzzy Logic, algorithm, diagnostics, operational reliability

1. Introduction

Non-load-bearing electrical systems of railway transport are an important infrastructure that provides uninterrupted electricity to signaling, centralization and blocking (CMB) devices, communication systems, lighting networks, station and depot electricity consumers, and other auxiliary technological facilities. The reliable and uninterrupted operation of these systems directly depends on the technical condition of the transformers used. Malfunctions occurring in transformers lead to power supply interruptions, a decrease in railway traffic safety, an increase in operational costs, and a decrease in energy efficiency. Therefore, the timely and high-precision assessment of the technical condition of transformers is one of the priority scientific and practical tasks in the operation of railway power supply systems. Transformer oil is one of the most important diagnostic objects when assessing the technical condition of a transformer. Transformer oil, being the main element of electrical insulation and cooling environment, reflects important diagnostic information about the physicochemical and thermal processes occurring inside the transformer. During operation, the dielectric properties of the oil change under the influence of high temperature, electric field, moisture, oxidation processes, and mechanical impurities.

As a result, electrical strength decreases, the amount of water and mechanical impurities increases, the acid number and dielectric loss values increase, and parameters such as density, kinematic viscosity, and flash point deviate from standard values. These changes are important diagnostic features characterizing the degree of wear and tear of the transformer insulation system. In operation, the technical condition of transformer oil is assessed by comparing individual diagnostic indicators with the threshold values established by current standards and regulatory documents. However, this approach does not sufficiently account for the interdependence of diagnostic parameters, their complex influence on the overall technical condition of the transformer, and the uncertainties encountered in the measurement results. Especially in cases where several parameters simultaneously approach the normative limit or have partial deviations, it becomes difficult to reliably determine the actual technical condition of the transformer. As a result, the dependence on expert opinion during the evaluation process increases and diagnostic accuracy decreases. In solving this problem, the development of mathematical models based on multi-parameter estimation methods is of great scientific importance. Mathematical modeling allows for the description of functional relationships between diagnostic indicators, a

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comprehensive assessment of their impact on the overall technical condition, and the determination of an integral diagnostic indicator. At the same time, the use of fuzzy logic theory expands the possibilities of mathematical representation of linguistic characteristics of diagnostic parameters, the formation of expert knowledge in conditions of uncertainty, and the creation of a reliable decision-making algorithm. In recent years, there has been a growing interest in using fuzzy logic, artificial intelligence, and multi-criteria decision-making methods in transformer diagnostics. These approaches allow for a comprehensive analysis of transformer oil performance indicators based on a single mathematical model rather than separately, the calculation of the integral value of the technical condition, and an increase in the accuracy and reliability of diagnostic results. Therefore, such a model creates a theoretical and practical basis for the implementation of state-of-the-art maintenance systems. The aim of this study is to develop a mathematical model for the process of assessing the technical condition of transformers used in non-traction electrical systems of railway transport based on the main performance indicators of transformer oil, as well as an algorithm for determining the value of the technical condition. The developed model and algorithm serve to create an effective diagnostic system aimed at a comprehensive analysis of the diagnostic parameters of transformer oil, a quantitative assessment of the technical condition, determining the degree of degradation of the insulation system, and increasing operational reliability.

Literature review

Assessment of the technical condition of transformers, increasing their reliability and preventing possible failures during operation are one of the important scientific directions of modern power systems. Existing scientific studies have shown that the analysis of the physicochemical and dielectric properties of transformer oil is widely used as an effective diagnostic method for determining the condition of the transformer insulation system.

Studies conducted by Voprikov A.V., Grigoriev N.P. and Parfianovich A.P. considered the issues of extending the service life of power transformers used in traction substations of electric railways. The studies noted that the operational reliability of transformers depends mainly on the condition of the insulation system and the effectiveness of technical maintenance [1].

Bryakin I.V. and co-authors studied methods for monitoring the condition of transformers based on assessing the properties of transformer oil. In this work, the main diagnostic indicators of the oil - electrical strength, moisture content, acid number, mechanical impurities and other physicochemical parameters - are considered as important criteria for determining the degradation of the transformer insulation system [6].

Analytical studies conducted by Soni R. and Mehta B. on monitoring the technical condition of transformers studied the diagnostic capabilities of mineral oils and alternative dielectric fluids. The authors noted that most of the existing diagnostic methods are based on the assessment of individual parameters and the need to develop complex multi-parameter assessment systems [10].

Studies aimed at in-depth study of the physicochemical processes in transformer oil analyzed the impact of moisture content, oxidation products, mechanical impurities and dielectric losses in the oil on the transformer insulation system. Feng Chen and co-authors proposed technologies for

the restoration of transformer insulation oil and data-based restoration systems, in which oil quality control was considered as a means of increasing the operational reliability of the transformer [7].

Nazarychev A.N. and co-authors studied methods for diagnosing the main insulation of transformers based on the electrical strength of the oil. This work shows that the electrical strength of the oil is one of the main diagnostic indicators for determining the technical condition of transformer insulation [13].

In recent years, many studies have been carried out on the use of artificial intelligence methods, in particular, fuzzy logic, neural networks and expert systems in transformer diagnostics. These methods, unlike traditional boundary assessment methods, allow taking into account the interdependence of diagnostic parameters and making more accurate decisions in uncertain conditions. This approach allows combining several operational indicators of transformer oil into a single integral assessment criterion.

Darwish M.M.F. and co-authors developed a new diagnostic method based on infrared spectroscopy to detect faults in transformer oil. This study shows the need for a comprehensive analysis of various physical measurements in modern diagnostic systems [11].

Also, in the works on the cleaning and regeneration of transformer oils using an electric field, Yusupov D.T., Avazov B.K. and other researchers studied the possibilities of reducing impurities in the oil that affect the mechanical and dielectric properties under the influence of an electric field. These studies are aimed at improving the operational performance of transformer oil and extending the service life of transformers [17].

The analysis of the above scientific works shows that in existing studies, effective methods have been developed for assessing individual diagnostic parameters of transformer oil, cleaning oil and monitoring the condition of transformers. However, in most approaches, diagnostic parameters are not evaluated in a comprehensive manner in relation to each other or decisions are made based on strict threshold values. This creates certain limitations in determining the actual technical condition of the transformer in cases where the parameters are uncertain.

Therefore, in this study, the issue of developing a mathematical model and decision-making algorithm based on Fuzzy Logic theory based on eight main operational indicators of transformer oil (electric strength, water content, acid number, mechanical impurities, kinematic viscosity, density, flash point and dielectric losses) is considered as an urgent scientific and practical task. The proposed approach allows taking into account the interaction of diagnostic parameters, determining the degree of degradation of the transformer insulation system and improving maintenance processes.

2. Research methodology

In this study, a mathematical model based on fuzzy logic theory and an algorithm for determining the value of technical condition were developed to assess the technical condition of non-traction electrical systems of railway transport based on the operational indicators of transformer oil. The research methodology includes a comprehensive analysis of the main diagnostic indicators of transformer oil, mathematical modeling of their degree of influence on the overall technical condition of the transformer, and the



formation of an algorithm for determining the value of the technical condition. The theoretical basis of the study consists of the theory of mathematical modeling, fuzzy logic, and multi-criteria decision-making theories. The diagnostic indicators of transformer oil established in current regulatory documents and standards, their limit values, and expert assessments were taken as the primary data.

3. Results

The process of developing the mathematical model consists of several sequential stages representing the relationship between the operational indicators of the transformer oil and the technical condition of the system. Initially, the main diagnostic parameters characterizing the technical condition of transformer oil were selected: electrical strength, water content, acidity, mechanical impurity content, kinematic viscosity, density, flash point, and dielectric losses, and their permissible values based on current regulatory documents and operational results were analyzed. The influence of these parameters on the wear level of the transformer insulation system was studied, and a mathematical model describing its technical condition was formulated.

In the developed mathematical model, membership functions were formed for each indicator, linguistic variables and their set of values were determined, and a database of fuzzy logic rules was developed based on expert knowledge and current regulatory documents. These rules made it possible to comprehensively evaluate individual indicators of transformer oil based on a single mathematical model. The algorithm for determining the technical condition value was formulated based on the principle of sequential processing of diagnostic parameters. At the first stage of the algorithm, the operational parameters of the transformer oil are taken and fuzzified using membership functions. At the next stage, an uncertain assessment of the technical condition is generated based on a database of fuzzy rules using the Mamdani inference mechanism. In the final stage, defassification is performed using the centroid method, and the numerical value of the transformer's technical condition is determined.

The results obtained showed that the developed mathematical model and value determination algorithm allow for a comprehensive analysis of the operational indicators of transformer oil. As a result of the integrated assessment, it was possible to divide the technical condition of the transformer into categories of "excellent," "good," "average," "bad" and "very bad," to assess the degree of degradation of the insulation system and to predict the risk of malfunctions. The proposed model increases the accuracy of the diagnostic process, reduces the influence of subjective expert assessments, and ensures reliable decision-making based on multi-parameter diagnostic data. The developed mathematical model and value determination algorithm increase the efficiency of assessing the technical condition of transformers used in non-traction electrical systems of railway transport. This approach serves as a scientific basis for automated processing of transformer oil diagnostics results, improving condition-based maintenance systems, increasing operational reliability, and preventing emergency situations.

3.1. Development of a mathematical model for the amount of mechanical impurities

To estimate the amount of mechanical impurities in transformer oil, a mathematical model was developed that determines the patterns of their change during operation.

$$\begin{aligned}
 M F_{(1)}(x) &= \begin{cases} 1, & \text{agar } (x_1 \leq 0.014); \\ 1 - \frac{x - 0.014}{0.028 - 0.014}, & \text{agar } (0.014 < x_1 \leq 0.028); \\ 0, & \text{agar } x_1 > 0.028; \end{cases} \\
 M F_{(2)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 0.014 \text{ or } x \geq 0.056); \\ \frac{x - 0.014}{0.028 - 0.014}, & \text{agar } (0.014 < x \leq 0.028); \\ 1, & \text{agar } (0.028 < x \leq 0.042); \\ 1 - \frac{x - 0.042}{0.056 - 0.042}, & \text{agar } (0.042 < x \leq 0.056); \end{cases} \\
 M F_{(3)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 0.042 \text{ or } x \geq 0.084); \\ \frac{x - 0.042}{0.056 - 0.042}, & \text{agar } (0.042 < x_1 \leq 0.056); \\ 1, & \text{agar } (0.056 < x \leq 0.07); \\ 1 - \frac{x - 0.07}{0.084 - 0.07}, & \text{agar } (0.07 < x < 0.084); \end{cases} \\
 M F_{(4)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 0.07 \text{ or } x \geq 0.112); \\ \frac{x - 0.07}{0.084 - 0.07}, & \text{agar } (0.07 < x_1 \leq 0.084); \\ 1, & \text{agar } (0.084 < x \leq 0.098); \\ 1 - \frac{x - 0.098}{0.112 - 0.098}, & \text{agar } (0.098 < x < 0.112); \end{cases} \\
 M F_{(5)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 0.098); \\ \frac{x - 0.098}{0.112 - 0.098}, & \text{agar } (0.098 < x \leq 0.112); \\ 1, & \text{agar } (0.084 < x \leq 0.098); \end{cases}
 \end{aligned}$$

3.2. Development of a mathematical model for determining water content

A mathematical model was developed to estimate the water content in the transformer oil. This model allows for describing the patterns of moisture content changes during operation, assessing its impact on the electrical and physicochemical properties of the transformer insulation system, and diagnosing the technical condition of the oil.

$$\begin{aligned}
 M F_{(1)}(x) &= \begin{cases} 1, & \text{agar } (x \leq 7); \\ 1 - \frac{x - 6}{12 - 6}, & \text{agar } (6 < x \leq 12); \\ 0, & \text{agar } (x \geq 12); \end{cases} \\
 M F_{(2)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 6 \text{ or } x \geq 24); \\ 1 - \frac{x - 6}{12 - 6}, & \text{agar } (6 < x \leq 12); \\ 1, & \text{agar } 6 < x \leq 12; \\ 1 - \frac{x - 6}{12 - 6}, & \text{agar } (18 < x < 24); \end{cases} \\
 M F_{(3)}(x) &= \begin{cases} 0, & \text{agar } (x \leq 18 \text{ or } x \geq 36); \\ \frac{x - 18}{24 - 18}, & \text{agar } (18 < x \leq 24); \\ 1, & \text{agar } 24 < x \leq 30; \\ 1 - \frac{x - 30}{36 - 30}, & \text{agar } (30 < x < 36); \end{cases}
 \end{aligned}$$



$$M F_4(x) = \begin{cases} 0, & \text{agar } (x \leq 42); \\ \frac{x-42}{48-42}, & \text{agar } (42 < x \leq 48); \\ 1, & \text{agar } (x \geq 48); \end{cases}$$

$$M F_{(5)}(x) = \begin{cases} 0, & \text{agar } (x \leq 30 \text{ or } x \geq 48); \\ \frac{x-42}{36-30}, & \text{agar } (30 < x \leq 36); \\ 1, & \text{agar } 36 < x \leq 42; \\ 1 - \frac{x-42}{48-42}, & \text{agar } (42 < x < 48); \end{cases}$$

3.3. Development of a mathematical model for determining acid content

A mathematical model has been developed to estimate the acid number of transformer oil. This model allows for the description of the oxidation state and degradation process of oil during operation, as well as the assessment of the impact on the technical condition of the insulation system.

$$M F_1(x) = \begin{cases} 1, & \text{agar } (x \leq 0.01); \\ 1 - \frac{x-0.01}{0.02-0.01}, & \text{agar } (0.01 < x < 0.02); \\ 0, & \text{agar } (x \geq 0.02); \end{cases}$$

$$M F_{(2)}(x) = \begin{cases} 0, & \text{agar } (x \leq 0.01 \text{ or } x \geq 0.04); \\ \frac{x-0.01}{0.02-0.01}, & \text{agar } (0.01 < x \leq 0.02); \\ 1, & \text{agar } 0.02 < x \leq 0.03; \\ 1 - \frac{x-0.05}{0.06-0.05}, & \text{agar } (0.03 < x < 0.04); \end{cases}$$

$$M F_{(3)}(x) = \begin{cases} 0, & \text{agar } (x \leq 0.03 \text{ or } x \geq 0.06); \\ \frac{x-0.03}{0.04-0.03}, & \text{agar } (0.03 < x \leq 0.04); \\ 1, & \text{agar } 0.04 < x \leq 0.05; \\ 1 - \frac{x-0.05}{0.06-0.05}, & \text{agar } (0.05 < x < 0.06); \end{cases}$$

$$M F_4(x) = \begin{cases} 0, & \text{agar } (x \leq 0.07); \\ 1 - \frac{x-0.01}{0.02-0.01}, & \text{agar } (0.07 < x < 0.08); \\ 1, & \text{agar } (x \geq 0.08); \end{cases}$$

$$M F_{(5)}(x) = \begin{cases} 0, & \text{agar } (x \leq 0.05 \text{ or } x \geq 0.04); \\ \frac{x-42}{36-30}, & \text{agar } (0.05 < x \leq 0.06); \\ 1, & \text{agar } 0.06 < x \leq 0.07; \\ 1 - \frac{x-42}{48-42}, & \text{agar } (0.07 < x < 0.08); \end{cases}$$

3.4. Development of a mathematical model for determining the flash temperature

A mathematical model has been developed to estimate the flash point of transformer oil.

$$M F_1(x) = \begin{cases} 1 & \text{agar } (x \leq 27); \\ 1 - \frac{x-27}{54-27}, & \text{agar } (27 < x < 54); \\ 0 & \text{agar } (x \geq 54); \end{cases}$$

$$M F_{(2)}(x) = \begin{cases} 0, & \text{agar } (x \leq 27 \text{ or } x \geq 108); \\ \frac{x-27}{54-27}, & \text{agar } (27 < x \leq 54); \\ 1, & \text{agar } (54 < x \leq 81); \\ 1 - \frac{x-81}{108-81}, & \text{agar } (81 < x < 108); \end{cases}$$

$$M F_{(3)}(x) = \begin{cases} 0, & \text{agar } (x \leq 81 \text{ or } x \geq 162); \\ \frac{x-81}{108-81}, & \text{agar } (81 < x \leq 108); \\ 1, & \text{agar } (108 < x \leq 135); \\ 1 - \frac{x-135}{162-135}, & \text{agar } (135 < x < 162); \end{cases}$$

$$M F_4(x) = \begin{cases} 0 & \text{agar } (x \leq 189); \\ 1 - \frac{x-189}{216-189}, & \text{agar } (189 < x < 216); \\ 1 & \text{agar } (x \geq 216); \end{cases}$$

$$M F_{(5)}(x) = \begin{cases} 0, & \text{agar } (x \leq 135 \text{ or } x \geq 216); \\ \frac{x-135}{162-135}, & \text{agar } (135 < x \leq 162); \\ 1, & \text{agar } (162 < x \leq 189); \\ 1 - \frac{x-189}{216-189}, & \text{agar } (189 < x < 216); \end{cases}$$

3.5. Development of a mathematical model for determining density

A mathematical model was developed to evaluate the density of transformer oil, taking into account the main factors influencing it.

$$M F_1(x) = \begin{cases} 1 & \text{agar } (x \leq 180); \\ 1 - \frac{x-188}{360-180}, & \text{agar } (180 < x < 360); \\ 0 & \text{agar } (x \geq 360); \end{cases}$$

$$M F_{(2)}(x) = \begin{cases} 0, & \text{agar } (x \leq 181.4 \text{ or } x \geq 721.4); \\ \frac{x-181.4}{361.4-181.4}, & \text{agar } (181.4 < x \leq 361.4); \\ 1, & \text{agar } (361.4 < x \leq 541.4); \\ 1 - \frac{x-541.4}{721.4-541.4}, & \text{agar } (541.4 < x < 721.4); \end{cases}$$

$$M F_{(3)}(x) = \begin{cases} 0, & \text{agar } (x \leq 540 \text{ or } x \geq 1080); \\ \frac{x-540}{720-540}, & \text{agar } (540 < x \leq 720); \\ 1, & \text{agar } (720 < x \leq 900); \\ 1 - \frac{x-900}{1080-900}, & \text{agar } (900 < x < 1080); \end{cases}$$

$$M F_{(4)}(x) = \begin{cases} 0, & \text{agar } (x \leq 900 \text{ or } x \geq 1440); \\ \frac{x-900}{1080-900}, & \text{agar } (900 < x \leq 1080); \\ 1, & \text{agar } (1080 < x \leq 1260); \\ 1 - \frac{x-1260}{1440-1260}, & \text{agar } (1260 < x < 1440); \end{cases}$$



$$M F_5(x) = \begin{cases} 0 & \text{agar } (x \leq 1260); \\ \frac{x - 1260}{1440 - 1260}, & \text{agar } (1260 < x < 1440); \\ 1 & \text{agar } (x \geq 1440); \end{cases}$$

3.6. Development of a mathematical model for dielectric losses

A mathematical model has been developed to assess the dielectric losses of transformer oil, taking into account the main factors affecting it.

$$M F_1(x) = \begin{cases} 1, & \text{agar } (x \leq 0.1); \\ 1 - \frac{x - 0.1}{0.2 - 0.1}, & \text{agar } (0.1 < x \leq 0.2); \\ 0, & \text{agar } x > 0.2; \end{cases}$$

$$M F_2(x) = \begin{cases} 0, & \text{agar } (x \leq 0.1 \text{ or } x \geq 0.4); \\ \frac{x - 0.1}{0.2 - 0.1}, & \text{agar } (0.3 < x \leq 0.4); \\ 1, & \text{agar } (3.2 \leq x < 4.8); \\ 1 - \frac{x - 0.3}{0.4 - 0.3}, & \text{agar } (0.4 \leq x < 0.5); \end{cases}$$

$$M F_3(x) = \begin{cases} 0, & \text{agar } (x \leq 0.3 \text{ or } x \geq 0.6); \\ \frac{x - 0.3}{0.4 - 0.3}, & \text{agar } (0.3 < x \leq 0.4); \\ 1, & \text{agar } (0.4 \leq x < 0.5); \\ 1 - \frac{x - 0.5}{0.6 - 0.5}, & \text{agar } (0.5 \leq x < 0.6); \end{cases}$$

$$M F_4(x) = \begin{cases} 1, & \text{agar } (x \leq 0.7); \\ 1 - \frac{x - 0.1}{0.2 - 0.1}, & \text{agar } (0.7 < x \leq 0.8); \\ 1, & \text{agar } x > 0.8; \end{cases}$$

$$M F_5(x) = \begin{cases} 0, & \text{agar } (x \leq 0.5 \text{ or } x \geq 0.8); \\ \frac{x - 0.5}{0.6 - 0.5}, & \text{agar } (0.5 < x \leq 0.6); \\ 1, & \text{agar } (0.6 \leq x < 0.7); \\ 1 - \frac{x - 0.7}{0.8 - 0.7}, & \text{agar } (0.7 \leq x < 0.8); \end{cases}$$

Relationship rules are set between input and output variables:

$$w_{fiz-xim(0)} = \min(\mu_{(0)}(x_1), \mu_{(0)}(x_2), \mu_{(0)}(x_3), \dots, \mu_{(0)}(x_8)) \rightarrow \mu_{(0)}(y_1);$$

$$w_{fiz-xim(25)} = \min(\mu_{(0)}(x_1), \mu_{(0)}(x_2), \mu_{(0)}(x_3), \dots, \mu_{(1)}(x_8)) \rightarrow \mu_{(0)}(y_1);$$

Determining the common membership function for each unknown set in the output variable:

$$\mu_{(0)}^*(y_1) = \max(\mu_{(0)}(y_1), \mu_{(0)}(y_1), \mu_{(0)}(y_1), \dots, \mu_{(0)}(y_1))$$

$$\mu_{(1)}^*(y_1) = \max(\mu_{(1)}(y_1), \mu_{(1)}(y_1), \mu_{(1)}(y_1), \dots, \mu_{(1)}(y_1))$$

$$\dots$$

$$\mu_{(25)}^*(y_1) = \max(\mu_{(4)}(y_1), \mu_{(4)}(y_1), \mu_{(4)}(y_1), \dots, \mu_{(4)}(y_1))$$

The exact value of the output variable is determined by a diffusion process based on the **centroid (centroid)** method for a generalized fuzzy set and is calculated by the following expression:

$$R_{n.t.} = \frac{\sum_{i=1}^{25} w_{fiz-xim(i)} * \mu_i^*(y_1)}{\sum_{i=1}^{25} \mu_i^*(y_1)}$$

3.7. Evaluation algorithm (Algorithm). This algorithm allows for a rapid and accurate assessment of the technical condition value of non-load-bearing electrical systems using an integral indicator based on transformer oil parameters.

An algorithm for determining the technical condition value of non-traction electrical systems was developed, taking into account the indicators of electrical strength, kinematic viscosity, mechanical impurities, water content, acid number, flash point, density, and dielectric losses of transformer oil (Fig. 1).

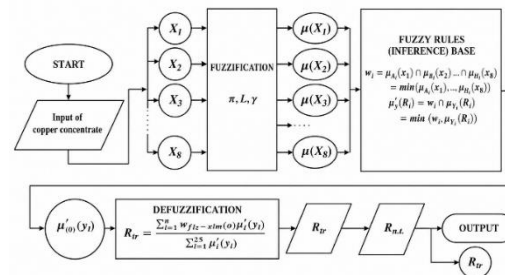


Fig. 1. Algorithm for determining the technical condition value of non-load-bearing electrical systems: $w_{fiz-xim(j)}$ $X_1, X_2, \dots, X_8$ - main oil indicators; - input variables; $\mu_{(0)}^*(y_i)$ - output variables; R_r - technical condition of the transformer, $R_{n.t.}$ - technical condition of the non-traction system

The proposed algorithm for determining the value of the technical condition of non-load-bearing electrical networks at the initial stage includes eight main indicators of transformer oil (electric strength, water content, acid number, mechanical impurities, kinematic viscosity, density, flash point, and dielectric losses) as input variables. These indicators are phassified using membership functions. At the next stage, based on the Mamdani interface, fuzzy logic rules are applied to form a fuzzy assessment of the technical situation. At the final stage, defuzzification is carried out using the Centroid method, and the technical condition indicator of the transformer R_r is determined. Depending on the technical condition of the transformer, the technical condition of the non-draft electrical system is categorized as "very bad," "bad," "average," "good," or "excellent," and the value of the system's technical condition is determined.

4. Conclusion

In this study, a mathematical model of the process for assessing the technical condition of non-load-bearing electrical systems of railway transport was developed based on eight main indicators of transformer oil (electric strength, water content, acidity, mechanical impurity content, kinematic viscosity, density, flash point, and dielectric losses). The developed model allows for a comprehensive assessment of the impact of diagnostic parameters on the overall technical condition of the transformer and the consideration of their interdependence.

Based on the diagnostic indicators of transformer oil, an algorithm has been developed for the integral assessment of the technical condition of non-load-bearing electrical systems of railway transport and the determination of its value. The proposed algorithm allows for the processing of diagnostic data, the numerical expression of the technical condition, and the classification of the transformer's condition into "very bad," "bad," "average," "good" and "excellent" categories.

The proposed mathematical model and algorithm for determining the technical condition value allow for a



comprehensive analysis of transformer oil performance indicators, the determination of the degradation level of the transformer insulation system, and a reliable assessment of the technical condition value. This approach serves as an effective scientific and methodological basis for improving condition-based maintenance systems in non-traction electrical systems of railway transport, increasing the reliability of transformer operation, preventing emergency situations, and optimizing technical monitoring processes.

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Kh. Tuychiev, Kh. Tuychiev

Assessment and improvement of constructive safety of the Damas light passenger vehicle.....5

A. Azizov, F. Sindarov

Comparison of the switch control circuit with main supply and central supply circuit, and analysis of the sequence of operation of the HIIC block.....10

O. Khamidov, B. Gayratov, Sh. Kudratov, F. Djuraev

An intelligent diagnostic approach based on oil analysis for assessing the technical condition of diesel locomotive engines.....14

O. Shokirov

Scientific and practical justification of safe vehicle speeds in mountainous areas of the M-39 highway of international importance.....18

M. Sobirov, A. Hamidov

Security analysis of windows local authentication recovery techniques and defensive mechanisms.....24

U. Ziyamukhamedova, J. Nafasov, E. Turgunaliev, B. Nematov, D. Akhmedova

Investigation of the tribological properties of modified composite materials used under abrasive wear conditions 28

J. Djumanov, M. Sobirov

A multi-layer information model and adaptive algorithms for monitoring hybrid energy supply in IoT-based telecommunication networks 33

D. Yusupov, O. Kutbidinov, B. Avazov

Assessment of the technical condition of a transformer based on the operational parameters of its oil using the fuzzy logic method.....38

E. Abdurahmanova

Application of artificial intelligence in modeling non-stationary oil filtration in multilayer porous media and data reliability issues.....46

K. Musulmanov, U. Sangirov, M. Abdullaeva

Assessment of cycling infrastructure and bikeability in Tashkent city.....50

D. Yusupov, B. Avazov, O. Kutbidinov

Assessment of the technical condition of a transformer based on the operational parameters of its oil using the fuzzy logic method.....54