

ENGINEER



international scientific journal

ISSUE 3, 2026 Vol. 4

E-ISSN

3030-3893

ISSN

3060-5172



SLIB.UZ
Scientific library of Uzbekistan



A bridge between science and innovation



**TOSHKENT DAVLAT
TRANSPORT UNIVERSITETI**

Tashkent state
transport university



ENGINEER

A bridge between science and innovation

E-ISSN: 3030-3893

ISSN: 3060-5172

VOLUME 4, ISSUE 3

SEPTEMBER, 2026



engineer.tstu.uz

TASHKENT STATE TRANSPORT UNIVERSITY

ENGINEER

INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 4, ISSUE 3 SEPTEMBER, 2026

EDITOR-IN-CHIEF

SAID S. SHAUMAROV

Professor, Doctor of Sciences in Technics, Tashkent State Transport University

Deputy Chief Editor

Miraziz M. Talipov

Doctor of Philosophy in Technical Sciences, Tashkent State Transport University

Founder of the international scientific journal “Engineer” – Tashkent State Transport University, 100167, Republic of Uzbekistan, Tashkent, Temiryo‘lchilar str., 1, office: 465, e-mail: publication@tstu.uz.

The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

The journal is published 4 times a year and contains publications in the following main areas:

- Engineering;
- General Engineering;
- Aerospace Engineering;
- Automotive Engineering;
- Civil and Structural Engineering;
- Computational Mechanics;
- Control and Systems Engineering;
- Electrical and Electronic Engineering;
- Industrial and Manufacturing Engineering;
- Mechanical Engineering;
- Mechanics of Materials;
- Safety, Risk, Reliability and Quality;
- Media Technology;
- Building and Construction;
- Architecture.

Tashkent State Transport University had the opportunity to publish the international scientific journal “Engineer” based on the **Certificate No. 1183** of the Information and Mass Communications Agency under the Administration of the President of the Republic of Uzbekistan. **E-ISSN: 3030-3893, ISSN: 3060-5172.** Articles in the journal are published in English language.

3	
engineer.tstu.uz	A bridge between science and innovation

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

D. Yusupov¹^a, O. Kutbidinov²^b, B. Avazov²

¹Institute of Energy Problems, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

²Tashkent state transport university, Tashkent, Uzbekistan

Abstract:

In this article, a mathematical model and decision-making algorithm based on the theory of fuzzy logic were developed to assess the technical condition of a transformer based on the operational indicators of its oil. In the study, the water content, acid number, amount of mechanical impurities, kinematic viscosity, density, flash point, electrical strength and dielectric loss of transformer oil were selected as the main diagnostic parameters characterizing the technical condition of the transformer. Membership functions were formed for each parameter, a fuzzy rule base was created based on expert knowledge and regulatory documents, and an integral technical condition indicator was calculated using the Mamdani inference algorithm and the centroid method. The results of the study showed that the developed model allows for a comprehensive analysis of the relationship between the diagnostic indicators of transformer oil, determining the degree of degradation of the transformer insulation system, and dividing its technical condition into the categories of "very bad", "bad", "average", "good" and "excellent". The proposed approach serves to increase the operational reliability of transformers, prevent accidents, introduce condition-based maintenance systems, and extend the service life of transformers.

Keywords:

transformer oil, fuzzy logic, mathematical model, technical diagnostics, membership function, decision-making algorithm, defuzzification

1. Introduction

Power transformers are among the most critical and expensive elements of the power system, and their reliable operation is crucial for ensuring the continuity of the power supply. Transformer oil acts as an insulating and cooling medium; therefore, its physicochemical and electrical properties are among the primary factors determining the overall technical condition of the transformer. During operation, under the influence of high temperatures, humidity, oxidation, and electrical loads, the properties of the oil gradually deteriorate, which reduces the reliability of the transformer and leads to various malfunctions. When assessing the technical condition of transformer oil, diagnostic indicators such as water content, acid number, mechanical impurities, electrical strength, dielectric loss, density, kinematic viscosity, and flash point are typically used. However, the separate assessment of these parameters cannot fully and objectively reflect the overall state of the oil, as they have a complex interdependence. Therefore, the development of comprehensive assessment methods that account for the interaction of parameters is one of the most pressing scientific and practical issues. The theory of fuzzy logic allows for the consideration of existing uncertainties in evaluating complex technical systems and the integration of expert knowledge into a mathematical model, making it one of the most optimal tools for solving this task. Based on this, the aim of this study is to develop a mathematical model and a decision-making algorithm based on fuzzy logic, aimed at evaluating the interaction between the diagnostic parameters

of transformer oil and determining its overall technical condition through a single integral indicator.

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

^a <https://orcid.org/0000-0001-6569-4806>

^b <https://orcid.org/0000-0001-9290-5322>



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 and decision-making algorithm based on the theory of fuzzy logic were

developed to assess the technical condition of a transformer based on the operational indicators of transformer oil. The research methodology includes the following main stages: selection and analysis of the main diagnostic parameters of transformer oil, determination of their influence on the technical condition of the transformer, formation of membership functions for the parameters, development of a fuzzy rule base based on expert knowledge, and determination of the integral technical condition of the transformer based on the results obtained. The theoretical basis of the study is the theory of fuzzy logic, the theory of multi-criteria decision-making, and mathematical modeling methods. The initial data were the normative values established in the current regulatory documents on the diagnostic parameters of transformer oil and expert assessments. The theoretical basis of the study is the theory of fuzzy logic, the theory of multi-criteria decision-making, and the theory of mathematical modeling. The integrated application of these theoretical approaches serves as a scientific basis for accurately assessing the technical condition of transformer oil, analyzing degradation processes, and increasing the operational reliability of transformers.

3. Results

The mathematical model developed to assess the technical condition of the transformer consisted of several consecutive stages that express the relationship between the operational indicators of the transformer oil and the general technical condition of the transformer. Initially, the main diagnostic parameters characterizing the technical condition of the transformer - electrical strength of the oil, water content, acid number, amount of mechanical impurities, kinematic viscosity, density, flash point and dielectric loss - were selected and their normative and operational values were analyzed. At the next stage, membership functions were formed for each diagnostic parameter, linguistic variables and their value ranges were determined, and a fuzzy logic rule base was developed based on expert knowledge and current regulatory documents. The input parameters were processed using the fuzzy inference mechanism, and the integral technical condition indicator of the transformer was calculated through the defuzzification process. Based on the results obtained, it was possible to classify the technical condition of the transformer into the categories of "excellent", "good", "average", "bad" and "very bad". The proposed model serves as a scientific basis for comprehensive consideration of the complex interrelationships between the diagnostic indicators of transformer oil, comprehensive assessment of the degree of degradation of the transformer insulation system, early detection of the possibility of failures, and increasing the operational reliability of the transformer.

Development of a mathematical model for the electrical strength of oil

A mathematical model was developed to assess the electrical strength of transformer oil, taking into account the main factors affecting it.

$$\mu_{(4)}(x_1) = \begin{cases} 1, & \text{if } (x_1 \leq 7); \\ \frac{14-x_1}{7}, & \text{if } (7 < x_1 \leq 14); \\ 0, & \text{if } x_1 > 14; \end{cases} \quad (1.1)$$



$$\mu_{(3)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 7); \\ \frac{x_1-7}{7}, & \text{if } (7 < x_1 \leq 14); \\ 1, & \text{if } (14 < x_1 < 21); \\ \frac{28-x_1}{7}, & \text{if } (21 \leq x_1 < 28); \\ 0, & \text{if } (x_1 \geq 28); \end{cases} \quad (1.2)$$

$$\mu_{(2)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 21); \\ \frac{x_1-21}{7}, & \text{if } (21 < x_1 \leq 28); \\ 1, & \text{if } (28 \leq x_1 < 35); \\ \frac{42-x_1}{7}, & \text{if } (35 \leq x_1 < 42); \\ 0, & \text{if } (x_1 \geq 42); \end{cases} \quad (1.3)$$

$$\mu_{(1)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 35); \\ \frac{x_1-35}{7}, & \text{if } (35 < x_1 \leq 42); \\ 1, & \text{if } (42 \leq x_1 < 49); \\ \frac{56-x_1}{7}, & \text{if } (49 \leq x_1 < 56); \\ 0, & \text{if } (x_1 \geq 56); \end{cases} \quad (1.4)$$

$$\mu_{(0)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 49); \\ \frac{56-x_1}{7}, & \text{if } (49 < x_1 \leq 56); \\ 1, & \text{if } x_1 > 56; \end{cases} \quad (1.5)$$

The following dependency rules have been established between input and output variables:

$$w_{Ktesh(1)} = \min (M F_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{Ktesh(5)} = \min (M F_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (1.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{Ktesh}) = \max (w_{Ktesh(1)}, 0);$$

$$\mu_{(1)}^*(R_{Ktesh}) = \max (w_{Ktesh(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{Ktesh}) = \max (w_{Ktesh(5)}, 0). \quad (1.7)$$

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

$$R_{tesh} = \frac{\sum_{i=1}^5 w_{Ktesh(i)} \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (1.8)$$

Development of a mathematical model for kinematic viscosity

A mathematical model was developed to estimate the kinematic viscosity of transformer oil, taking into account the factors affecting it.

$$\mu_{(4)}(x_1) = \begin{cases} 1, & \text{if } (x_1 \leq 1.6); \\ \frac{3.2-x_1}{1.6}, & \text{if } (1.6 < x_1 \leq 3.2); \\ 0, & \text{if } x_1 > 3.2; \end{cases} \quad (2.1)$$

$$\mu_{(3)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 1.6); \\ \frac{x_1-1.6}{1.6}, & \text{if } (1.6 < x_1 \leq 3.2); \\ 1, & \text{if } (3.2 \leq x_1 < 4.8); \\ \frac{6.4-x_1}{1.6}, & \text{if } (4.8 \leq x_1 < 6.4); \\ 0, & \text{if } (x_1 \geq 6.4); \end{cases} \quad (2.2)$$

$$\mu_{(2)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 4.8); \\ \frac{x_1-4.8}{1.6}, & \text{if } (4.8 < x_1 \leq 6.4); \\ 1, & \text{if } (6.4 \leq x_1 < 8); \\ \frac{9.6-x_1}{1.6}, & \text{if } (8 \leq x_1 < 9.6); \\ 0, & \text{if } (x_1 \geq 9.6); \end{cases} \quad (2.3)$$

$$\mu_{(1)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 8); \\ \frac{x_1-8}{1.6}, & \text{if } (8 < x_1 \leq 9.6); \\ 1, & \text{if } (9.6 \leq x_1 < 11.2); \\ \frac{12.8-x_1}{1.6}, & \text{if } (11.2 \leq x_1 < 12.8); \\ 0, & \text{if } (x_1 \geq 12.8); \end{cases} \quad (2.4)$$

$$\mu_{(0)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 11.2); \\ \frac{12.8-x_1}{1.6}, & \text{if } (11.2 < x_1 \leq 12.8); \\ 1, & \text{if } x_1 > 12.8; \end{cases} \quad (2.5)$$

The following dependency rules have been established between input and output variables:

$$w_{Kqov(1)} = \min (M F_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{Kqov(5)} = \min (M F_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (2.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{Kqov}) = \max (w_{Kqov(1)}, 0);$$

$$\mu_{(1)}^*(R_{Kqov}) = \max (w_{Kqov(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{Kqov}) = \max (w_{Kqov(5)}, 0) \quad (2.7)$$

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

$$R_{qov} = \frac{\sum_{i=1}^5 w_{Kqov(i)} \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (2.8)$$

Development of a mathematical model for the amount of mechanical impurities

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

$$\mu_{(4)}(x_1) = \begin{cases} 1, & \text{if } (x_1 \leq 0.014); \\ \frac{0.028-x_1}{0.014}, & \text{if } (0.014 < x_1 \leq 0.028); \\ 0, & \text{if } x_1 > 0.028; \end{cases} \quad (3.1)$$

$$\mu_{(3)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 0.014); \\ \frac{x_1-0.014}{0.014}, & \text{if } (0.014 < x_1 \leq 0.028); \\ 1, & \text{if } (0.028 \leq x_1 < 0.042); \\ \frac{0.056-x_1}{0.014}, & \text{if } (0.042 \leq x_1 < 0.056); \\ 0, & \text{if } (x_1 \geq 0.056); \end{cases} \quad (3.2)$$

$$\mu_{(2)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 0.042); \\ \frac{x_1-0.042}{0.014}, & \text{if } (0.042 < x_1 \leq 0.056); \\ 1, & \text{if } (0.056 \leq x_1 < 0.07); \\ \frac{0.084-x_1}{0.014}, & \text{if } (0.07 \leq x_1 < 0.084); \\ 0, & \text{if } (x_1 \geq 0.084); \end{cases} \quad (3.3)$$

$$\mu_{(1)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 0.07); \\ \frac{x_1-0.07}{0.014}, & \text{if } (0.07 < x_1 \leq 0.084); \\ 1, & \text{if } (0.084 \leq x_1 < 0.098); \\ \frac{0.112-x_1}{0.014}, & \text{if } (0.098 \leq x_1 < 0.112); \\ 0, & \text{if } (x_1 \geq 0.112); \end{cases} \quad (3.4)$$

$$\mu_{(0)}(x_1) = \begin{cases} 0, & \text{if } (x_1 \leq 0.098); \\ \frac{0.112-x_1}{0.014}, & \text{if } (0.098 < x_1 \leq 0.112); \\ 1, & \text{if } x_1 > 0.112; \end{cases} \quad (3.5)$$



The following dependency rules have been established between input and output variables:

$$w_{K.mex.a(1)} = \min(MF_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{K.mex.a(1)} = \min(MF_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (3.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{K.mex.a}) = \max(w_{K.mex.a(1)}, 0);$$

$$\mu_{(1)}^*(R_{K.mex.a}) = \max(w_{K.mex.a(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{K.mex.a}) = \max(w_{K.mex.a(5)}, 0) \quad (3.7)$$

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

$$R_{mex.a} = \frac{\sum_{i=1}^5 w_{K.mex.a(i)} * \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (3.8)$$

Development of a mathematical model for determining water content

A mathematical model has been developed to estimate the water content in transformer oil. This model allows 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.

$$MF_{(1)}(x) = \begin{cases} 1, & \text{if } (x \leq 7); \\ 1 - \frac{x-6}{12-6}, & \text{if } (6 < x \leq 12); \\ 0, & \text{if } (x \geq 12); \end{cases} \quad (4.1)$$

$$MF_{(2)}(x) = \begin{cases} 0, & \text{if } (x \leq 6 \text{ or } x \geq 24); \\ 1 - \frac{x-6}{12-6}, & \text{if } (6 < x \leq 12); \\ 1, & \text{if } (6 < x \leq 12); \\ 1 - \frac{x-6}{12-6}, & \text{if } (18 < x < 24); \end{cases} \quad (4.2)$$

$$MF_{(3)}(x) = \begin{cases} 0, & \text{if } (x \leq 18 \text{ or } x \geq 36); \\ \frac{x-18}{24-18}, & \text{if } (18 < x \leq 24); \\ 1, & \text{if } (24 < x \leq 30); \\ 1 - \frac{x-30}{36-30}, & \text{if } (30 < x < 36); \end{cases} \quad (4.3)$$

$$MF_{(4)}(x) = \begin{cases} 0, & \text{if } (x \leq 42); \\ \frac{x-42}{48-42}, & \text{if } (42 < x \leq 48); \\ 1, & \text{if } (x \geq 48); \end{cases} \quad (4.4)$$

$$MF_{(5)}(x) = \begin{cases} 0, & \text{if } (x \leq 30 \text{ or } x \geq 48); \\ \frac{x-42}{36-30}, & \text{if } (30 < x \leq 36); \\ 1, & \text{if } (36 < x \leq 42); \\ 1 - \frac{x-42}{48-42}, & \text{if } (42 < x < 48); \end{cases} \quad (4.5)$$

The following dependency rules have been established between input and output variables:

$$w_{K.suv(1)} = \min(MF_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{K.suv(1)} = \min(MF_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (4.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{K.suv}) = \max(w_{K.suv(1)}, 0);$$

$$\mu_{(1)}^*(R_{K.suv}) = \max(w_{K.suv(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{K.suv}) = \max(w_{K.suv(5)}, 0) \quad (4.7)$$

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

$$R_{suv} = \frac{\sum_{i=1}^5 w_{K.suv(i)} * \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (4.8)$$

Development of a mathematical model for determining the amount of acidity

A mathematical model has been developed to estimate the acid number of transformer oil. This model allows us to characterize the degree of oxidation and degradation of the oil during operation and to assess its impact on the technical condition of the insulation system.

$$MF_{(1)}(x) = \begin{cases} 1, & \text{if } (x \leq 0.01); \\ 1 - \frac{x-0.01}{0.02-0.01}, & \text{if } (0.01 < x < 0.02); \\ 0, & \text{if } (x \geq 0.02); \end{cases} \quad (5.1)$$

$$MF_{(2)}(x) = \begin{cases} 0, & \text{if } (x \leq 0.01 \text{ or } x \geq 0.04); \\ \frac{x-0.01}{0.02-0.01}, & \text{if } (0.01 < x \leq 0.02); \\ 1, & \text{if } (0.02 < x \leq 0.03); \\ 1 - \frac{x-0.05}{0.06-0.05}, & \text{if } (0.03 < x < 0.04); \end{cases} \quad (5.2)$$

$$MF_{(3)}(x) = \begin{cases} 0, & \text{if } (x \leq 0.03 \text{ or } x \geq 0.06); \\ \frac{x-0.03}{0.04-0.03}, & \text{if } (0.03 < x \leq 0.04); \\ 1, & \text{if } (0.04 < x \leq 0.05); \\ 1 - \frac{x-0.05}{0.06-0.05}, & \text{if } (0.05 < x < 0.06); \end{cases} \quad (5.3)$$

$$MF_{(4)}(x) = \begin{cases} 0, & \text{if } (x \leq 0.07); \\ 1 - \frac{x-0.01}{0.02-0.01}, & \text{if } (0.07 < x < 0.08); \\ 1, & \text{if } (x \geq 0.08); \end{cases} \quad (5.4)$$

$$MF_{(5)}(x) = \begin{cases} 0, & \text{if } (x \leq 0.05 \text{ or } x \geq 0.04); \\ \frac{x-42}{36-30}, & \text{if } (0.05 < x \leq 0.06); \\ 1, & \text{if } (0.06 < x \leq 0.07); \\ 1 - \frac{x-42}{48-42}, & \text{if } (0.07 < x < 0.08); \end{cases} \quad (5.5)$$

The following dependency rules have been established between input and output variables:

$$w_{K.kis(1)} = \min(MF_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{K.kis(1)} = \min(MF_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (5.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{K.kis}) = \max(w_{K.kis(1)}, 0);$$

$$\mu_{(1)}^*(R_{K.kis}) = \max(w_{K.kis(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{K.kis}) = \max(w_{K.kis(5)}, 0) \quad (5.7)$$

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

$$R_{kis} = \frac{\sum_{i=1}^5 w_{K.kis(i)} * \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (5.8)$$

Development of a mathematical model for determining the flash point

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



$$M F_1(x) = \begin{cases} 1 & \text{if } (x \leq 27); \\ 1 - \frac{x-27}{54-27}, & \text{if } (27 < x < 54); \\ 0 & \text{if } (x \geq 54); \end{cases} \quad (6.1)$$

$$M F_2(x) = \begin{cases} 0, & \text{if } (x \leq 27 \text{ or } x \geq 108); \\ \frac{x-27}{54-27}, & \text{if } (27 < x \leq 54); \\ 1, & \text{if } (54 < x \leq 81); \\ 1 - \frac{x-81}{108-81}, & \text{if } (81 < x < 108); \end{cases} \quad (6.2)$$

$$M F_3(x) = \begin{cases} 0, & \text{if } (x \leq 81 \text{ or } x \geq 162); \\ \frac{x-81}{108-81}, & \text{if } (81 < x \leq 108); \\ 1, & \text{if } (108 < x \leq 135); \\ 1 - \frac{x-135}{162-135}, & \text{if } (135 < x < 162); \end{cases} \quad (6.3)$$

$$M F_4(x) = \begin{cases} 0 & \text{if } (x \leq 189); \\ 1 - \frac{x-189}{216-189}, & \text{if } (189 < x < 216); \\ 1 & \text{if } (x \geq 216); \end{cases} \quad (6.4)$$

$$M F_5(x) = \begin{cases} 0, & \text{if } (x \leq 135 \text{ or } x \geq 216); \\ \frac{x-135}{162-135}, & \text{if } (135 < x \leq 162); \\ 1, & \text{if } (162 < x \leq 189); \\ 1 - \frac{x-189}{216-189}, & \text{if } (189 < x < 216); \end{cases} \quad (6.5)$$

The following dependency rules have been established between input and output variables:

$$w_{Kchaq.h.(1)} = \min(M F_1(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{Kchaq.h.(1)} = \min(M F_5(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (6.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{Kchaq.h.}) = \max(w_{Kchaq.h.(1)}, 0);$$

$$\mu_{(1)}^*(R_{Kchaq.h.}) = \max(w_{Kchaq.h.(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{Kchaq.h.}) = \max(w_{Kchaq.h.(5)}, 0) \quad (6.7)$$

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

$$R_{chaq.h.} = \frac{\sum_{i=1}^5 w_{Kchaq.h.(i)} \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (6.8)$$

Development of a mathematical model for determining density

To estimate the density of transformer oil, a mathematical model was developed that takes into account the main factors affecting it.

$$M F_1(x) = \begin{cases} 1 & \text{if } (x \leq 180); \\ 1 - \frac{x-188}{360-180}, & \text{if } (180 < x < 360); \\ 0 & \text{if } (x \geq 360); \end{cases} \quad (7.1)$$

$$M F_2(x) = \begin{cases} 0, & \text{if } (x \leq 181.4 \text{ or } x \geq 721.4); \\ \frac{x-181.4}{361.4-181.4}, & \text{if } (181.4 < x \leq 361.4); \\ 1, & \text{if } (361.4 < x \leq 541.4); \\ 1 - \frac{x-541.4}{721.4-541.4}, & \text{if } (541.4 < x < 721.4); \end{cases} \quad (7.2)$$

$$M F_3(x) = \begin{cases} 0, & \text{if } (x \leq 540 \text{ or } x \geq 1080); \\ \frac{x-540}{720-540}, & \text{if } (540 < x \leq 720); \\ 1, & \text{if } (720 < x \leq 900); \\ 1 - \frac{x-900}{1080-900}, & \text{if } (900 < x < 1080); \end{cases} \quad (7.3)$$

$$M F_4(x) = \begin{cases} 0, & \text{if } (x \leq 900 \text{ or } x \geq 1440); \\ \frac{x-900}{1080-900}, & \text{if } (900 < x \leq 1080); \\ 1, & \text{if } (1080 < x \leq 1260); \\ 1 - \frac{x-1260}{1440-1260}, & \text{if } (1260 < x < 1440); \end{cases} \quad (7.4)$$

$$M F_5(x) = \begin{cases} 0 & \text{if } (x \leq 1260); \\ \frac{x-1260}{1440-1260}, & \text{if } (1260 < x < 1440); \\ 1 & \text{if } (x \geq 1440); \end{cases} \quad (7.5)$$

The following dependency rules have been established between input and output variables:

$$w_{Kzich(1)} = \min(M F_1(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{Kzich(1)} = \min(M F_5(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (7.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{Kzich}) = \max(w_{Kzich(1)}, 0);$$

$$\mu_{(1)}^*(R_{Kzich}) = \max(w_{Kzich(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{Kzich}) = \max(w_{Kzich(5)}, 0) \quad (7.7)$$

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

$$R_{zich} = \frac{\sum_{i=1}^5 w_{Kzich(i)} \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (7.8)$$

Development of a mathematical model for dielectric losses

To estimate the dielectric losses of transformer oil, a mathematical model was developed that takes into account the main factors affecting it.

$$M F_1(x) = \begin{cases} 1, & \text{if } (x \leq 0.1); \\ 1 - \frac{x-0.1}{0.2-0.1}, & \text{if } (0.1 < x \leq 0.2); \\ 0, & \text{if } x > 0.2; \end{cases} \quad (8.1)$$

$$M F_2(x) = \begin{cases} 0, & \text{if } (x \leq 0.1 \text{ or } x \geq 0.4); \\ \frac{x-0.1}{0.2-0.1}, & \text{if } (0.1 < x \leq 0.2); \\ 1, & \text{if } (0.2 < x \leq 0.4); \\ 1 - \frac{x-0.3}{0.4-0.3}, & \text{if } (0.3 < x < 0.4); \end{cases} \quad (8.2)$$

$$M F_3(x) = \begin{cases} 0, & \text{if } (x \leq 0.3 \text{ or } x \geq 0.6); \\ \frac{x-0.3}{0.4-0.3}, & \text{if } (0.3 < x \leq 0.4); \\ 1, & \text{if } (0.4 < x < 0.5); \\ 1 - \frac{x-0.5}{0.6-0.5}, & \text{if } (0.5 < x < 0.6); \end{cases} \quad (8.3)$$

$$M F_4(x) = \begin{cases} 1 - \frac{x-0.1}{0.2-0.1}, & \text{if } (0.1 < x \leq 0.2); \\ 1, & \text{if } x > 0.2; \end{cases} \quad (8.4)$$

$$M F_5(x) = \begin{cases} 0, & \text{if } (x \leq 0.5 \text{ or } x \geq 0.8); \\ \frac{x-0.5}{0.6-0.5}, & \text{if } (0.5 < x \leq 0.6); \\ 1, & \text{if } (0.6 < x < 0.7); \\ 1 - \frac{x-0.7}{0.8-0.7}, & \text{if } (0.7 < x < 0.8); \end{cases} \quad (8.5)$$



The following dependency rules have been established between input and output variables:

$$w_{Kd.i.(1)} = \min (M F_{(1)}(x_1), 1) \rightarrow \mu_{(5)}(y_1);$$

.....

$$w_{Kd.i.(1)} = \min (M F_{(5)}(x_1), 1) \rightarrow \mu_{(5)}(y_1) \quad (8.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{Kd.i.}) = \max (w_{Kd.i.(1)}, 0);$$

$$\mu_{(1)}^*(R_{Kd.i.}) = \max (w_{Kd.i.(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{Kd.i.}) = \max (w_{Kd.i.(5)}, 0) \quad (8.7)$$

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

$$R_{d.i.} = \frac{\sum_{i=1}^5 w_{Kd.i.(i)} * \mu_i^*(y_1)}{\sum_{i=1}^5 \mu_i^*(y_1)} \quad (8.8)$$

Development of a mathematical model for the general state of oil

To assess the overall technical condition of the transformer oil, a mathematical model was developed that accounts for changes in the values of its eight main indicators. The model allows for the assessment of the general technical condition of the oil and the prediction of the result.

$$M F_1(R) = \begin{cases} 1, & \text{if } (R \leq 10); \\ 1 - \frac{R-10}{20-10}, & \text{if } (10 < R \leq 20); \\ 0, & \text{if } R > 20; \end{cases} \quad (9.1)$$

$$M F_2(R) = \begin{cases} 0, & \text{if } (R \leq 10 \text{ or } R \geq 40); \\ \frac{R-10}{20-10}, & \text{if } (30 < R \leq 40); \\ 1, & \text{if } (32 \leq R < 48); \\ 1 - \frac{R-30}{40-30}, & \text{if } (40 \leq R < 50); \end{cases} \quad (9.2)$$

$$M F_3(R) = \begin{cases} 0, & \text{if } (R \leq 30 \text{ or } R \geq 60); \\ \frac{R-30}{40-30}, & \text{if } (30 < R \leq 40); \\ 1, & \text{if } (40 \leq R < 50); \\ 1 - \frac{R-50}{60-50}, & \text{if } (50 \leq R < 60); \end{cases} \quad (9.3)$$

$$M F_4(R) = \begin{cases} 1, & \text{if } (R \leq 70); \\ 1 - \frac{R-40}{50-40}, & \text{if } (70 < R \leq 80); \\ 1, & \text{if } R > 80; \end{cases} \quad (9.4)$$

$$M F_5(R) = \begin{cases} 0, & \text{if } (x \leq 50 \text{ or } R \geq 80); \\ \frac{R-50}{60-50}, & \text{if } (50 < R \leq 60); \\ 1, & \text{if } (60 \leq R < 70); \\ 1 - \frac{R-70}{80-70}, & \text{if } (70 \leq R < 80); \end{cases} \quad (9.5)$$

The following dependency rules have been established between input and output variables:

$$w_{moy(1)} = \min (M F_{(1)}(R_1), 1) \rightarrow \mu_{(5)}(R_{moy});$$

.....

$$w_{moy(1)} = \min (M F_{(5)}(R_1), 1) \rightarrow \mu_{(5)}(R_{moy}) \quad (9.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{moy}) = \max (w_{moy(1)}, 0);$$

$$\mu_{(1)}^*(R_{moy}) = \max (w_{moy(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{moy}) = \max (w_{moy(5)}, 0) \quad (9.7)$$

The exact value of the output variable is determined by a diffusion process based on **the centroid** method for a

generalized indefinite set and is calculated using the following expression:

$$R_{moy} = \frac{\sum_{i=1}^{62225} w_{moy(i)} * \mu_i^*(R_{moy})}{\sum_{i=1}^5 \mu_i^*(R_{moy})} \quad (9.8)$$

Development of a mathematical model for the technical condition of a transformer

To assess the technical condition of a transformer, taking into account changes in the values of eight key oil parameters. The model allows assessing the overall technical condition of the transformer and predicting the outcome.

$$M F_1(R) = \begin{cases} 1, & \text{if } (R \leq 10); \\ 1 - \frac{R-10}{20-10}, & \text{if } (10 < R \leq 20); \\ 0, & \text{if } R > 20; \end{cases} \quad (10.1)$$

$$M F_2(R) = \begin{cases} 0, & \text{if } (R \leq 10 \text{ or } R \geq 40); \\ \frac{R-10}{20-10}, & \text{if } (30 < R \leq 40); \\ 1, & \text{if } (32 \leq R < 48); \\ 1 - \frac{R-30}{40-30}, & \text{if } (40 \leq R < 50); \\ 0, & \text{if } (R \leq 30 \text{ or } R \geq 60); \end{cases} \quad (10.2)$$

$$M F_3(R) = \begin{cases} \frac{R-30}{40-30}, & \text{if } (30 < R \leq 40); \\ 1, & \text{if } (40 \leq R < 50); \\ 1 - \frac{R-50}{60-50}, & \text{if } (50 \leq R < 60); \end{cases} \quad (10.3)$$

$$M F_4(R) = \begin{cases} 1, & \text{if } (R \leq 70); \\ 1 - \frac{R-10}{20-10}, & \text{if } (70 < R \leq 80); \\ 1, & \text{if } R > 80; \end{cases} \quad (10.4)$$

$$M F_5(R) = \begin{cases} 0, & \text{if } (x \leq 50 \text{ or } R \geq 80); \\ \frac{R-50}{60-50}, & \text{if } (50 < R \leq 60); \\ 1, & \text{if } (60 \leq R < 70); \\ 1 - \frac{R-70}{80-70}, & \text{if } (70 \leq R < 80); \end{cases} \quad (10.5)$$

The following dependency rules have been established between input and output variables:

$$w_{tr(1)} = \min (M F_{(1)}(R_1), 1) \rightarrow \mu_{(5)}(R_{tr});$$

.....

$$w_{tr(1)} = \min (M F_{(5)}(R_1), 1) \rightarrow \mu_{(5)}(R_{tr}) \quad (10.6)$$

Determine the general membership function for each fuzzy set in the output variable:

$$\mu_{(0)}^*(R_{tr}) = \max (w_{tr(1)}, 0);$$

$$\mu_{(1)}^*(R_{tr}) = \max (w_{tr(2)}, 0);$$

...

$$\mu_{(5)}^*(R_{tr}) = \max (w_{tr(5)}, 0) \quad (10.7)$$

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

$$R_{tr} = \frac{\sum_{i=1}^5 w_{tr(i)} * \mu_i^*(R_{tr})}{\sum_{i=1}^5 \mu_i^*(R_{tr})} \quad (10.8)$$

Assessment algorithm (Algorithm). In order to automate the process of assessing the technical condition of a transformer based on the operational indicators of transformer oil and to increase the accuracy and reliability of diagnostic results, an assessment algorithm based on the theory of fuzzy logic was developed. This algorithm is aimed at a comprehensive analysis of the diagnostic parameters of transformer oil, taking into account their interaction and determining the general technical condition of the transformer based on an integral assessment indicator, consists of several consecutive stages and allows for a comprehensive analysis of the physicochemical and electrical properties of transformer oil.



At the first stage of the algorithm, the main diagnostic parameters of transformer oil (electrical strength, water content, mechanical impurities, acid number, dielectric loss, density, flash point and kinematic viscosity) determined as a result of laboratory tests are entered into the system. At the next stage, these parameters are compared with the normative values established in current standards. At the final stage, defuzzification is performed using the centroid method, which calculates the integral technical condition indicator of the transformer and determines whether it belongs to one of the categories of "excellent", "good", "average", "bad" or "very bad". The proposed algorithm allows for a systematic analysis of the diagnostic parameters of transformer oil, a comprehensive assessment of the technical condition of the transformer and the initial detection of possible malfunctions during operation. This algorithm serves as an effective tool for improving decision-making efficiency, reducing maintenance costs, and ensuring the operational reliability of transformers in Condition-Based Maintenance systems (Figure 1).

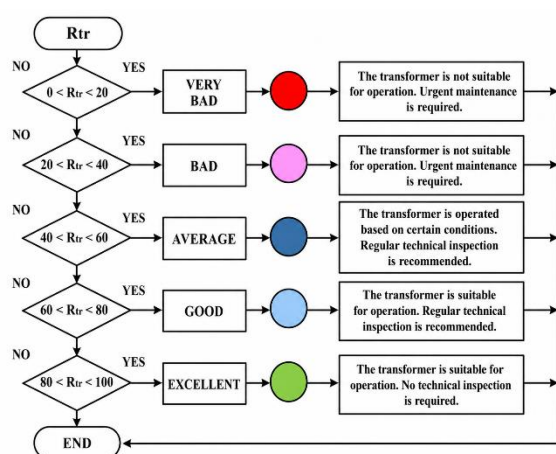


Fig. 1. Algorithm for assessing the technical condition of a transformer based on the operational performance of its oil and making operational decisions based on the fuzzy logic method

4. Conclusion

In this study, a mathematical model based on fuzzy logic theory was developed to assess the technical condition of a transformer based on eight main operational indicators of transformer oil (electrical strength, water content, acid number, amount of mechanical impurities, kinematic viscosity, density, flash point and dielectric loss). The developed model allows for a comprehensive analysis of the impact of diagnostic parameters on the state of the transformer insulation system and the determination of the overall technical condition of the transformer, taking into account their interdependence.

An evaluation algorithm based on fuzzy logic has been developed, which allows for a quick and reliable assessment of the technical condition of a transformer based on diagnostic indicators of transformer oil, increasing operational safety, and providing recommendations for maintenance or repair. The proposed algorithm provides automatic processing of diagnostic data and classification of the technical condition of the transformer into the categories of "excellent", "good", "average", "bad" and "very bad".

The proposed mathematical model and integral evaluation algorithm allow for the diagnosis of the technical condition of the transformer, assessment of the degree of degradation of the insulation system, and early detection of possible failures based on a comprehensive analysis of the operational parameters of the transformer oil. This approach serves as an effective scientific and methodological tool for increasing the operational reliability of transformers, preventing accidents, improving maintenance systems, and optimizing technical monitoring processes.

References

- [1] Voprikov A.V., Grigoriev N.P., Parfianovich A.P. Extending the Life of Power Transformers of Traction Substations of Alternating Current of Electric Railways // *Advances in Intelligent Systems and Computing*. – Springer International Publishing, 2020. – Vol. 1115. – P. 52–59. <https://eurekamag.com/research/102/803/102803915.php>
- [2] Chothani N.G., Patel D., Parekh C. Advancement in Infrastructure and Design Technology of Power Transformer. – Singapore: Springer Nature, 2025. ISBN: 978 981 96 9420 4. <https://link.springer.com/book/10.1007/978-981-96-9420-4>
- [3] Muhammad S.S., Abdulrazak S., Bakare G.A., Abdulhafiz S., Nazif D.M. Modelling and analysis of a power transformer using finite element analysis // *Asian Journal of Science, Technology, Engineering, and Art*. – 2025. – Vol. 3, No. 3, pp. 902–920. <https://doi.org/10.58578/ajstea.v3i3.5703>
- [4] J. Wajda. Comparison of Annual Electrical Energy Losses of Conventional and Superconductive Transformers in Power Lines // *Journal of Automation, Electronics and Electrical Engineering*. – 2025. – Vol. 12, No. 3, pp. 112–125. <https://oeconomia.pl/jaeef/article/view/3478>
- [5] C.D. Capulong, J. Reyes, M. Santos. Analysis of Failure Rate Due to Transformer Loadings of Commonly Used Transformers in Porac Substation // *Journal of Science, Technology and Engineering Research*. – 2025. – Vol. 6, No. 2, pp. 107–117. <https://dergipark.org.tr/en/download/article-file/4972902>
- [6] Bryakin I.V., Bochkarev I.V., Khrumshin V.R., Gasiyarov V.R., Liubimov I.V. Power transformer condition monitoring based on evaluating oil properties // *Machines*. – 2022. – Vol. 10, No. 8, Art. 630. <https://www.mdpi.com/2075-1702/10/8/630>
- [7] Feng Chen, Li Wang, Zhiyao Zheng, Bin Pan, Yujia Hu, Kexin Zhang. Data driven based full recovery technology and system for transformer insulating oil // *Energies*. – 2024. – Vol. 17, No. 24, Art. 6345. <https://www.mdpi.com/1996-1073/17/24/6345>
- [8] Nurubeyli T.K., Hashimov A.M., Imamverdiyev N.E., Mammadova G.N. Complex physicochemical analysis of transformer oil parameters using the inductively coupled plasma mass spectrometry technique // *Electrical Engineering & Electromechanics*. – 2025. – No. 2, pp. 79–84.
- [9] Yusupov D.T., Rakhmatova M., Tashmatova Sh. Study of optimal temperature during adsorption cleaning of transformer oil under conditions of long term operation // *E3S Web of Conferences*. – 2023. – Vol. 383, Art. 04058. <https://doi.org/10.1051/e3sconf/202338304058>
- [10] Soni R., Mehta B. A review on transformer condition monitoring with critical investigation of mineral



oil and alternate dielectric fluids // Electric Power Systems Research. – 2023. – Vol. 214, Part B, Art. 108954.

[11] Darwish M.M.F., Hassan M.H.A., Abdel Gawad N.M.K., Lehtonen M., Mansour D.E.A. A new technique for fault diagnosis in transformer insulating oil based on infrared spectroscopy measurements // High Voltage. – 2024. – Vol. 9, No. 2, pp. 319–335. <https://doi.org/10.1049/hve2.12479>

[12] Hu H., Liu Y., Li Y., et al. Traction power systems for electrified railways: evolution, state and future trends // Railway Engineering Science. – 2023. – Vol. 32, No. 1, pp. 1–19. <https://doi.org/10.1007/s40534-023-00320-6>

[13] A.N. Nazarychev, O.S. Melnikova, I.I. Sulynenkov. Diagnostics of main insulation of power transformers using statistical criterion of oil dielectric strength // Electricity. – 2022. – No. 9, pp. 22–32. <https://doi.org/10.24160/0013-5380-2022-9-22-32>

[14] D.T. Yusupov, B.K. Avazov. Theoretical solutions for cleaning transformer oils using an electric field taking into account the effects of environments. IV International Scientific and Technical Conference “Actual Issues of Power Supply Systems”: ICAIPSS2024. – 2025. – Vol. 3331, No. 1, Art. 050018. <https://doi.org/10.1063/5.0306610>

[15] D.T. Yusupov, B.K. Avazov, O.M. Kutbidinov, M. Bazarov. Cleaning of transformer oils using the electric field // IOP Conference Series: Earth and Environmental Science. – IOP Publishing, 2023. – Vol. 1231, No. 1, Art. 012024. <https://orcid.org/0000-0003-3732-5185>

[16] U.T. Berdiev, B.K. Avazov, F.F. Sulaymonov, U.N. Berdiyrov, F. Turg'unova. The study of electric motors based on composite materials. IV International Scientific and Technical Conference “Actual Issues of Power Supply Systems”: ICAIPSS2024. – 2025. – Vol. 3331, No. 1, Art. 030046. <https://doi.org/10.1063/5.0305937>

[17] D.T. Yusupov, B.K. Avazov. Experimental analysis of the process of purifying transformer oil from various impurities under the influence of a constant electric field and assessment of mathematically modeled results // Liquid and Gaseous Energy Resources. – 2025. – Vol. 5, No. 2, pp. 19–30. <https://doi.org/10.21595/lger.2025.25476>

[18] Amirov S.F., Sharapov S.A., Sulliev A.K., Boltaev O.T. Biparametric resonant transformer sensor of large linear movements // AIP Conference Proceedings. – AIP Publishing, 2023. – Vol. 2624, No. 1, Art. 030007(1–9). <https://doi.org/10.1063/5.0132847>

[19] Boltayev O.T., Akhmedova F.A. Induced voltage from traction lines and methods of reducing its influence on adjacent communication lines // International Journal on Integrated Education. – 2021. – Vol. 4, Issue 4, pp. 265–271.

[20] Smith R., Johnson R. Electrostatic cleaning of transformer oil using high electric fields // IEEE Transactions on Dielectrics and Electrical Insulation. –

2018. – Vol. 25, No. 4, pp. 1234–1245. <https://doi.org/10.1109/TDEI.2018.00123>

[21] H. Zhang, L. Li. Power transformer fault detection: a comparison of machine learning techniques // Energies. – 2023. – Vol. 17, No. 1, Art. 77. <https://www.mdpi.com/1996-1073/17/1/77>

[22] Sorte S., Monteiro A.F., Ventura D., Salgado A., Oliveira M.S.A., Martins N. Power transformers cooling design: a comprehensive review // Energies. – 2025. – Vol. 18, No. 5, Art. 1051. <https://doi.org/10.3390/en18051051>

[23] A. Malik, T. S. Sidhu, A. G. A. M. Ali. Fuzzy logic based transformer condition assessment using dissolved gas analysis // IEEE Transactions on Dielectrics and Electrical Insulation. – 2016. – Vol. 23, No. 5. – pp. 2760–2768. <https://doi.org/10.1109/TDEI.2016.7736864>

[24] M. Wang, A. J. Vandermaar, K. D. Srivastava. Review of condition assessment of power transformers in service // IEEE Electrical Insulation Magazine. – 2002. – Vol. 18, No. 6. – pp. 12–25. <https://doi.org/10.1109/MEI.2002.1044335>

[25] S. Tenbohlen, T. Strasser. A statistical approach to transformer fault diagnosis using dissolved gas analysis // IEEE Transactions on Power Delivery. – 2007. – Vol. 22, No. 3. – pp. 1639–1647. <https://doi.org/10.1109/TPWRD.2007.899775>

[26] M. Duval. A review of faults detectable by gas-in-oil analysis in transformers // IEEE Electrical Insulation Magazine. – 2002. – Vol. 18, No. 3. – pp. 8–17. <https://doi.org/10.1109/MEI.2002.1014963>.

Information about the author

Dilmurod Yusupov

Institute of Energy Problems,
Academy of Sciences of the
Republic of Uzbekistan
E-mail: dilmurod85@list.ru
Tel.: +99897 480 28 07
<https://orcid.org/0000-0001-6569-4806>

Odiljon Kutbidinov

Tashkent state transport
university, Department of
“Electrical engineering”
E-mail: qutbidinov_o@tstu.uz
Tel.: +998 97 461 60 03
<https://orcid.org/0000-0001-9290-5322>

Bobomurod Avazov

Tashkent state transport
university, Department of
“Electrical engineering”
E-mail: avazovbk@gmail.com
Tel.: +99893 5933827



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 conditions28

J. Djumanov, M. Sobirov

A multi-layer information model and adaptive algorithms for monitoring hybrid energy supply in IoT-based telecommunication networks33

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