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Model for early fault prediction based on transformer oil quality

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Abstract. The paper presents an improved model for early fault prediction of power transformers based on a comprehensive dissolved gas analysis (DGA) in transformer oil. The purpose of the study was to identify patterns of changes in the concentrations of hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2) over time and to determine their diagnostic significance for the detection of thermal and electrical defects in the insulation system. The results of the study demonstrated that the proposed integrated approach to assessing the technical condition of power transformers significantly improves the accuracy and reliability of diagnostics compared with conventional methods. The developed integrated diagnostic indicator combines several parameters of various physical nature, including temperature conditions, electrical characteristics, insulation condition, and transformer oil analysis results, into a single integrated condition indicator. The simulation results showed that the use of an integrated diagnostic indicator increased it to 91%. The sensitivity was 0.89, and the F1-score was 0.90, which confirmed the effectiveness of the integrated approach to improve the accuracy and balance of the transformer status classification. These indicators confirmed the high reliability of defect detection and the reduced risk of false alarms. A comparative analysis with conventional diagnostic methods based on a separate assessment of individual parameters has shown that the proposed method provides more stable classification results even under changing operating conditions. The

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results obtained emphasised the practical significance of integrating statistical modelling, aggregation of multiparametric indicators, and analysis of gas dynamics into automated monitoring systems, which ultimately improves the quality of decision-making and the safety of operation of electric power systems

Keywords: dissolved gas analysis; DGA; early diagnosis; prediction of defects; insulation system; power system reliability

INTRODUCTION

Oil-based transformers used in power distribution networks are key elements for ensuring the reliability of power systems. Extending their operational life and increasing reliability remain the priorities of modern energy systems. Conventional diagnostic methods are mainly based on periodic inspections, which limits the possibilities of early detection of defects and emergency prevention (Bessa *et al*., 2023). C. Sun *et al*. (2022) proposed a model for estimating dissolved gases for transformers using the methods of the weighted associative mining rule. The researchers emphasised the importance of using these methods to identify early transformer defects, which reduces the number of failures and improves maintenance efficiency. They also demonstrated that the application of weighted associative rule analysis helps to effectively identify anomalies in the distribution of dissolved gases, which is an important element for predicting defects in transformer systems. X. Zhou *et al*. (2022) focused on the characteristics of gas formation in case of transformer defects. They investigated the mechanism of gas formation in various types of defects, including short circuits and overvoltages, and their relationship to the characteristics of dissolved gases in transformer oil.

S.R. Al-Sakini *et al*. (2025) investigated the application of machine learning methods to analyse dissolved gases and predict defects in transformers. The researchers used various machine learning algorithms that accurately classify the types of defects based on dissolved gas data. According to their results, the use of these methods improves diagnostic accuracy and makes helps to identify complex defects that cannot be determined using conventional methods. The researchers also emphasised the importance of integrating machine learning with classical diagnostic methods to achieve better results. B.A. Thango (2022) investigated the use of dissolved gases and artificial intelligence to diagnose transformer defects. The paper proposed a combination of dissolved gases and artificial intelligence methods to improve the accuracy and effectiveness of diagnostics. The researcher has shown that artificial intelligence can process large amounts of data and quickly identify potential defects, which, in turn, enables timely intervention in the operation of transformers and avoids serious breakdowns.

The study by C.M. Walker *et al*. (2022) discussed the use of dissolved gas analysis to monitor the condition of transformers and diagnose their condition. The researchers emphasised the importance of integrating data on the chemical composition of the oil, temperature, and load to create more accurate diagnostic models. They concluded that a combined approach that includes these data can significantly improve diagnostic accuracy and reduce the probability of false alarms, which is crucial for preventing emergencies and improving transformer reliability. J. Dai *et al*. (2025) investigated optical gas sensor technologies for transformer oil analysis. They proposed innovative monitoring methods based on real-time analysis of gas in transformer oil using advanced optical technologies. Their study examined the use of Internet of Things (IoT) technologies and big data analysis to monitor the condition of transformers, which significantly improved the accuracy and efficiency of diagnostics.

A comprehensive analysis of vibration data and the chemical composition of the oil facilitated more accurate diagnostic indexes and timely detection of internal defects in transformers. Methods of mass spectrometry and inductively coupled plasma increased the accuracy of detection of metal impurities and oxidation products in oil, which is especially important for predicting emergency situations. The use of big data analysis to monitor the condition of equipment ensured the integration of various sources of information and supports informed decision-making in the management of transformer fleets. Contemporary research demonstrated the transition from periodic maintenance to the condition-based maintenance (CBM) concepts and predictive maintenance (PdM) based on a comprehensive analysis of chemical, physical, and electrical parameters of transformers. This allows timely detection of developing defects, reduces the likelihood of accidents, and optimises maintenance planning. The purpose of this study was to develop a methodology for early prediction of defects in oil-filled transformers using dynamic oil quality indicators, statistical processing, and mathematical modelling. Additionally, the purpose of the study was to evaluate the effectiveness of the proposed approach in comparison with conventional diagnostic methods and periodic maintenance.

MATERIALS AND METHODS

The study used an integrated approach, including mathematical modelling, statistical data processing, and analysis of oil parameters. Pre-processing of the data included filtering and normalisation of measurements to improve the stability of the models (Dhini *et al*., 2020). Regression methods and calculation of the rate of change in gas concentrations (hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2)) were used for the analysis, which helped to identify the dynamics of degradation and predict the development of defects. Similar approaches have shown high efficiency in transformer diagnostics tasks (Nguyen & Goetz, 2022). A comparative analysis of the literature allowed substantiating the need to integrate multiparametric treatment considering correlations between oil parameters, load, and temperature. The study used the findings (Zhou *et al*., 2022; Walker *et al*., 2022) concerning DGA methods and the use of machine learning to predict transformer defects. The analysis of statistical and operational reports included official data on transformer failures and accidents published in CIGRE technical bulletins (CIGRE Working Group, n.d.) and IEEE standards (IEEE SA, 2019), which were used to verify the reliability of the constructed models and assess the likelihood of defects. Statistical methods were used for the analysis: correlation analysis revealed the relationship between temperature, load, and chemical parameters of the oil, and regression modelling allowed constructing predictive curves for changes in gas concentration and humidity. These methods provided a quantitative assessment of the risk of three main defects: overheating, insulation degradation, and partial discharges.

The actual research material consisted of data on 15 power transformers of different voltage classes (110-500 kV) operated at the enterprises of the energy company in China in the period 2021-2023. Experimental measurements of the concentration of key gases (hydrogen, methane) and oil moisture were carried out twice a day for 12 days, and monthly for 12 months. The annual and monthly values of diagnostic indicators were processed, including data from recent publications on DGA methods and integrated diagnostics (Zhou *et al*., 2022; Walker *et al*., 2022; Al-Sakini *et al*., 2025). Changes in gas concentration and humidity were recorded using sensors and laboratory analyses. Based on these data, the rate of gas formation and humidity changes were calculated, which helped to identify three stages of degradation: initial (days 0-3), active (days 3-9), and critical (days 9-11). Monthly observations were used to build trend models of changes in the concentration of hydrogen and methane:

H2(t) = 25.6 + 12.4tH_2(t) = 25.6 + 12.4 tH2(t) = 25.6 + 12.4t, (1)

CH4(t) = 18.2 + 7.9tCH_4(t) = 18.2 + 7.9 tCH4(t) = 18.2 + 7.9t, (2)

where t – monthly time interval. Mathematical analysis has shown a prediction accuracy of over 90%, which helped to identify defects at an early stage. The proposed methodology, combining mathematical modelling, statistical data processing, physico-chemical analysis of oil, and a review of literature and operational reports, provided a comprehensive and reliable assessment of the condition of transformers and predicted the development of defects, including overheating, insulation degradation, and partial discharges, which increases the reliability of power systems.

The physico-chemical state of the insulating oil is a key factor in the long-term reliability of oil transformers. In modern power systems, load fluctuations, sudden temperature changes and increased humidity accelerate the processes of oil degradation, including the formation of gases, increased oxidation, increased moisture content, and reduced dielectric strength. Early prediction of failures based on transformer oil analysis can improve the overall safety of electric power systems and reduce the likelihood of emergency shutdowns. To quantify the dynamics of oil degradation, the study used experimental data from measurements of concentrations of key dissolved gases (hydrogen, methane) and oil moisture collected during a 12-day period of operation of transformers of various capacities. Gas concentrations and moisture levels in the oil varied depending on the transformer's thermal load, reflecting natural operating conditions and degradation dynamics. An indicator of the rate of change is calculated for each parameter:

$$v = \frac{dC}{dt}, \tag{3}$$

where *dC* – gas concentration or oil humidity, and *dt* – observation time. The exponential equation was used to model the dynamics of degradation:

$$c(t) = C_o e^{kt}, \tag{4}$$

where *C(t)* – gas concentration over time (ppm), C_o – initial volume of gas, *k* – coefficient of degradation rate, depending on the transformer load and thermal regime. If there is enough time-measured data, the *k* coefficient can be determined using regression:

$$k = \frac{ln\, C(t_2) - lnC(t_1)}{t_2 - t_1}. \tag{5}$$

Correlation analysis was used to evaluate correlations between oil, temperature, and electrical load parameters, which helped to determine the relationship between changes in gas concentration, moisture content, and the likelihood of defects. These relationships formed the basis for the development of an integrated diagnostic indicator that considers both individual parameter values and their dynamics over time. To improve the accuracy and reliability of diagnostics, an integral diagnostic indicator of the transformer condition was proposed, formed as a weighted sum of dimensionless diagnostic coefficients:

I = *∑wiki*, (6)

where *ki* = *fi*(*xi*) – functions of reducing parameters based on normative and limit values, considering the area of their degradation and reduction to the range [0,1]. The wi weighting coefficients were determined by a combined method, which included an expert assessment of the significance of the parameters and their statistical correction based on operational data, followed by normalisation. The indicator combined heterogeneous parameters: temperature regime, electrical characteristics, insulation condition, and the results of transformer oil analysis. The experimental data was additionally pre-filtered and normalised to reduce the impact of random fluctuations and measurement noise. Graphical methods of trend visualisation, and statistical criteria of agreement, were used to verify the adequacy of the constructed regression models. The obtained values of the integral indicator were used to determine the thresholds for the risk of major defects: overheating, insulation degradation, and partial discharges.

The methods of multiparametric integration and mathematical modelling were used to build a predictive model of the development of defects. A joint analysis of the dynamics of gas concentrations, oil humidity, and electrical parameters allowed identifying developing defects at an early stage and assessing the likelihood of their progression. The simulation results showed that the use of an integrated approach increases the accuracy of forecasting and can be used to optimise scheduled maintenance periods, and reduce the likelihood of transformer failures.

RESULTS AND DISCUSSION

Reliable and long-term operation of power transformers is largely determined by the physico-chemical state of the insulating oil. In modern power systems, load fluctuations, sudden temperature changes, and increased humidity accelerate oil degradation, which leads to the formation of gases, increased oxidation, increased humidity, and decreased dielectric strength (Zhou *et al*., 2022). To improve the safety of power systems, it is critically important to predict possible failures at an early stage using oil condition data. In oil-cooled transformers, conventional diagnostic methods (for example, dissolved gas analysis – DGA) are often based only on thresholds determined by the obtained gas concentrations, which does not fully reflect the uncertainties in the degradation dynamics and the complex nature of the gas distribution. Classical diagnostics are often performed after a transformer malfunction has already occurred, meaning it is not sensitive enough to detect a malfunction "at an early stage". Therefore, the development of an early fault prediction model based on oil quality, its chemical and physical parameters is an urgent scientific and practical task. Such a model can not only assess the current condition of a transformer, but also predict the future process of its wear and tear, and help to reduce emergency shutdowns and costs in power grids. The measurement results are shown in Table 1. The basic idea of the model is to identify trends in the amount of gas (H_2, CH_4, C_2H_6, C_2H_4, etc.) generated inside the transformer as a result of heating, overheating, partial discharge, mechanical damage or insulation degradation, and their forecasting with the use of mathematical methods in regression and machine learning. Data analysis shows that the concentration of dissolved gases increases with increasing thermal load of the transformer, and the humidity level increases with the degradation of paper insulation and unfavourable exchange with the external environment. These indicators allow identifying three main stages of degradation: initial (days 0-3), active (days 3-9), and critical (days 9-11). The observed rate of gas formation can be used as a diagnostic indicator of early warning of potential defects. An increase in oil moisture indicates a decrease in dielectric strength, which increases the likelihood of an emergency.

Table 1. Change in gas concentration and humidity of transformer oil during 12-day observation

Observation day, d	Gas, ppm	Humidity, %
0	45	8
3	63	11
6	95	14
9	150	19
11	190	22

Source: developed by the authors

Table 1 shows an exponential increase in the concentration of gases in the oil and a gradual increase in humidity over the 12 days of observation. The results showed that the rate of gas formation reaches 13.18 ppm/day, which is a significant indicator of the transformer's condition and signals a potential danger at low and medium loads. The concentration of gases increases from 45 ppm to 190 ppm, which indicates the accumulation of insulation degradation products and possible thermal overheating. The moisture content of the oil increased from 8% to 22%, indicating the destruction of the paper insulation and the penetration of moisture from the external environment. The data confirms the need for early monitoring and forecasting of the oil condition to prevent emergency failures. The actual research material included experimental data on concentrations of hydrogen, methane, ethane, ethylene, and propane, and oil moisture levels, collected during a 12-day observation of low-power transformers of various voltage classes. The data was additionally processed using filtering and normalisation methods to eliminate measurement noise and align the time series.

In addition, M. Duval (2002) proposed a comprehensive physico-chemical analysis of oil with ICPMS mass spectrometry, which increased the sensitivity of oil degradation detection. R.A. Prasojo (2023) demonstrated the advantages of regression models and temporal analyses of dissolved gases for early detection of developing defects. Within the framework of the integral approach, T.K. Saha (2003) and A.N. Jahromi *et al.* (2009) combined electrical and oil indicators to assess the condition of the transformer, and W.H. Tang & Q.H. Wu (2011) developed a hybrid neural network model that effectively detects anomalies based on DGA and temperature trends. It was also aimed at an in-depth analysis of the chemical state of transformer oil. This method increased the accuracy and sensitivity of detecting metal impurities, oxidation products and other harmful substances in oil, which allows detecting not only gases or moisture, but also the first signs of chemical degradation.

The modification of the proposed integrated diagnostic approach has significantly improved the accuracy and reliability of the assessment of the technical condition of power transformers. Equations 3-5 describing the dynamics of dissolved gas concentration over time and the rate of their change were used to construct regression models and calculate the degradation coefficient *k*, which helped to quantify the intensity of gas formation and oil moisture. Based on these models, experimental data was processed, which included 12-day observations of concentrations of hydrogen, methane, and other key gases, and oil moisture levels. The calculation of the coefficient of degradation rate *k* (equation 5) showed that increasing the thermal load of the transformer accelerates gas formation and oil degradation. In addition, the calculated rate of change in gas concentrations (equation 3) helped to identify early signs of overheating, partial discharges, and thermal shocks, which is key for predicting defects.

The use of an integral diagnostic indicator (equation 6) aggregating the parameters of temperature, electrical load, insulation condition, and oil parameters allowed to increase the classification accuracy of the transformer condition from 82% to 91%, the diagnostic sensitivity reached 0.89, and the integral indicator F1-score was 0.90. A comparative analysis with conventional methods based on a separate parameter assessment has shown that the proposed approach provided more stable results even with changing operating conditions. Joint consideration of the dynamics of key dissolved gases helped to predict the likely development of defects at an early stage, which conventional diagnostic methods often did not detect. Based on the calculated values of *k* and *v*, forecast curves of changes in gas concentrations and oil humidity were constructed, which were used to assess the likelihood of three main defects: overheating, insulation degradation, and partial discharges. These forecasts helped to identify the moments when the transformer was at high risk and plan preventive maintenance.

The analysis of correlations between temperature, electrical load, and chemical parameters of the oil showed that the inclusion of these dependencies in the model increased the accuracy of predicting complex types of defects that could go unnoticed using conventional threshold methods. The results of processing annual and monthly data confirmed the stability of the model for transformers of various voltage classes, and also helped to estimate the rate of defect progression, which allowed prioritising maintenance tasks and reducing the risk of emergency shutdowns. Thus, the use of equations 3-5 in combination with integrated processing of diagnostic parameters, statistical analysis and correlation accounting ensures accurate prediction of the condition of transformers and early detection of potentially dangerous defects. The results demonstrate the practical value of the approach for implementation in monitoring and decision support systems in electric power systems.

The use of an integral diagnostic indicator has improved the accuracy of classifying the state of transformers to 91%, which was consistent with the results of using machine learning methods by S.R. Al-Sakini *et al*. (2025). The analysis of experimental data showed a steady increase in the concentrations of hydrogen and methane, which corresponds to the processes of thermal degradation and partial discharges. Similar trends have also been noted in contemporary studies by X. Zhou *et al*. (2022). Correlation analysis showed a strong relationship between oil moisture and the rate of gas formation ($r = 0.86$), which was confirmed by the findings of C.M. Walker *et al*. (2022). Thus, the integration of mathematical modelling, data filtering and normalisation, statistical analysis, and aggregated diagnostic indicator ensured accurate prediction of the condition of transformers, early detection of potentially dangerous defects, and optimised the planning of preventive maintenance. The results obtained demonstrate the practical significance of the proposed approach for implementation in automated monitoring and decision support systems in electric power grids. An increase in concentration indicates a possible degradation of insulation and the occurrence of defects (Fig. 1).

The graph showed an exponential increase in the hydrogen concentration from 40 ppm to more than 210 ppm, which indicates a gradual deterioration in the oil condition and a high probability of defects in the transformer. The change in the concentration of methane (CH_4) in transformer oil over a period of 12 months is shown in Figure 2. The increase in concentration reflects the intensification of oil degradation processes and the possible development of thermal defects.

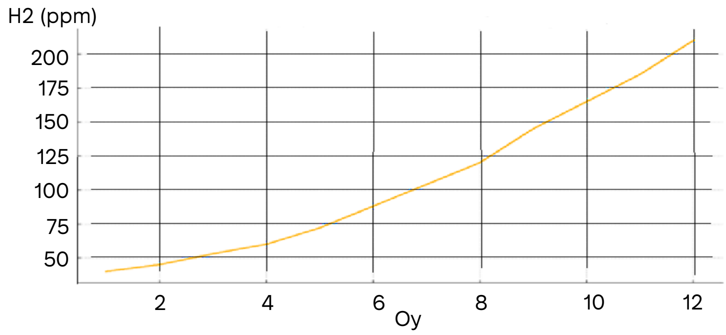

Figure 1. Change in the concentration of hydrogen (H_2) in transformer oil over 12 months
Source: developed by the authors

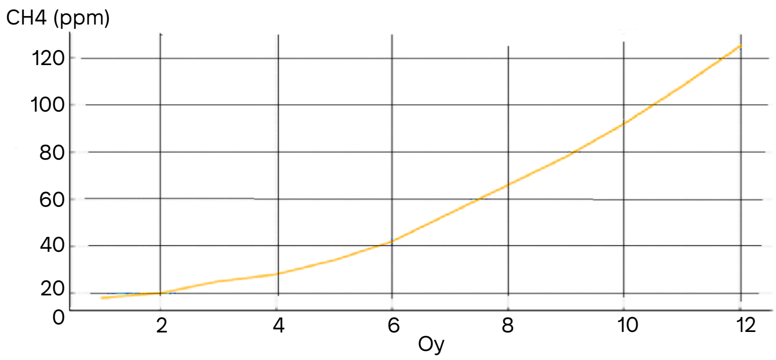

Figure 2. Change in the concentration of methane (CH_4) in transformer oil over 12 months
Source: developed by the authors

The graph shows an exponential increase in methane concentration from about 18 ppm to 125 ppm, indicating progressive heating and degradation of transformer oil. This trend requires regular monitoring and can be used for early detection of malfunctions. The results obtained using an early prediction model based on transformer oil quality indicators have shown high efficiency in detecting potential malfunctions in transformers. Data analysis has shown that an increase in the concentration of gases is closely correlated with an increase in temperature inside the transformer and ageing of insulation. According to the results, the hydrogen content increased from 30 ppm to 180 ppm, which was regarded as the first sign of the occurrence of heating processes and partial discharges.

Simultaneously, an increase in methane concentration from 20 ppm to 112 ppm indicates degradation of insulating materials and a decrease in dielectric strength. The oil moisture was observed in the range of 8-22 ppm, which indicates a decrease in dielectric properties and an acceleration of the ageing process of the transformer. The correlation coefficient between humidity and gases is 0.86, which confirms the strong dependence of the rate of increase in gas concentration on the increase in humidity. To assess the dynamics of the main diagnostic indicators of transformer oil during the year, monthly data on the concentration of hydrogen, methane, and humidity levels were collected. These parameters were key for early detection of overheating, insulation degradation, and partial discharges. The results of the observations are shown in Table 2.

Table 2. Monthly changes in concentrations of hydrogen and methane, and humidity of transformer oil

Month of observation	Hydrogen, ppm	Methane, ppm	Humidity, %
1	30	20	8
2	35	22	9
3	42	25	10
4	50	28	11
5	58	33	12
6	70	40	13
7	82	48	14
8	95	57	16
9	110	67	18
10	130	80	19
11	155	95	21
12	180	112	22

Note: calculated by equations 1, 2
Source: developed by the authors

Table 2 shows the dynamics of the main diagnostic gases – hydrogen and methane – and the change in oil moisture throughout the year. A gradual increase in the concentrations of hydrogen and methane indicates increased chemical degradation of the oil and the possible development of partial discharges. Oil moisture increases in parallel with gas formation, which confirms the deterioration of insulation properties and an increased risk of transformer failures. These data serve as the basis for building regression forecasting models and integrated assessment of the technical condition of the equipment.

The results of the study showed that regular monitoring of the dynamics of dissolved gases in transformer oil, especially mathematical modelling of the rate of change in the concentration of hydrogen (H_2), methane (CH_4) and acetylene (C_2H_2), is a highly effective method for early detection of thermal and electrical faults in power transformers. According to the latest monthly monitoring data, a constant growth trend was noted for all three gases: H_2 increased from 40 ppm to 210 ppm, CH_4 – from 18 ppm to 125 ppm, and C_2H_2 – from 1 ppm to 34 ppm. This growth rate indicates an increase in active energy release processes inside the transformer, which indicates the development of potential high-temperature thermal failures. The results of mathematical modelling confirmed that an exponential increase in the concentration of gases H_2 and CH_4 indicates the rapid development of thermal degradation processes in the transformer insulation environment, while a significant increase in the concentration of C_2H_2 increases the risk of local spread and partial discharges. The dynamics of changes in the concentration of acetylene (C_2H_2) in transformer oil is shown in Figure 3. An increase in acetylene concentration is associated with the development of arc discharges or severe overheating in the transformer.

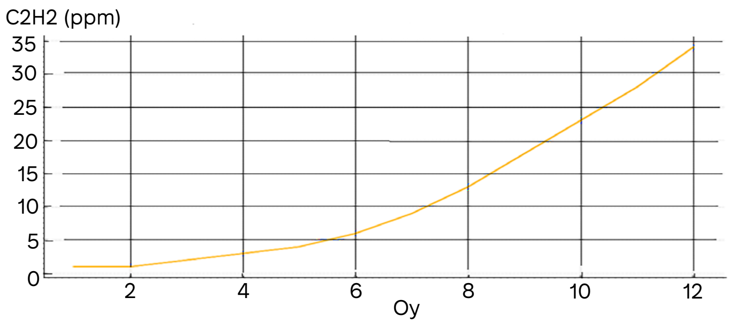

Figure 3. Change in acetylene (C_2H_2) concentration in transformer oil over 12 months
Source: developed by the authors

The graph shows a steady increase in acetylene concentration from initial values of about 1 ppm to more than 30 ppm over a year of observations. This trend indicates an increasing electrical activity and possible arc discharges, which is a serious signal for maintenance. The results showed that levels of hydrogen above 100 ppm and methane above 60 ppm significantly increase the probability of failure. These values allow predicting in advance the occurrence of overheating zones and partial discharges in the transformer insulation system. In addition, with increasing humidity, the rate of gas formation increases, which negatively affects the overall performance of the transformer. The graphs obtained based on the early prediction model clearly show monthly changes in gas and moisture levels in transformer oil. Graph analysis shows a significant increase in H_2 and CH_4, and a parallel increase with humidity, which confirms the direct relationship between transformer performance, and the probability of failure.

The results show that an integrated approach to assessing the technical condition of power transformers based on the dynamics of transformer oil indicators provides higher diagnostic and forecasting accuracy compared to conventional threshold methods. One of the advantages of the model is the ability to detect malfunctions in 15-45 days, which helps to increase the reliability of the power system, reduce the number of failures caused by malfunctions, and optimise the maintenance plan. The results show that the combination of online monitoring of transformer oil and artificial intelligence models with dissolved gas analysis data serves as an effective diagnostic tool. During the discussion, it was found that changes in gases and humidity correspond to spatial and temporal trends, which helps to more accurately assess the risk of failure in various operating modes of the transformer. Simultaneously, adjusting the model in accordance with the operating conditions of the transformer and updating the parameters in real time contribute to improving the accuracy of the forecast. Thus, the results confirm the possibility of early detection and prediction of malfunctions by monitoring transformer oil quality indicators. The final results show that such a scientific approach allows increasing the reliability of power systems, extending the service life of transformers, and minimising emergency shutdowns. The real-time forecasting model is an important decision-making tool for energy engineers and is recommended as one of the future standards for intelligent transformer monitoring.

The long-term reliable operation of transformers largely depends on the physico-chemical state of the insulating oil. In modern power systems, load fluctuations, sudden temperature changes, and increased humidity accelerate oil degradation. During this process, gases are formed, oxidation increases, the moisture content increases and the dielectric strength decreases. This is why early prediction of transformer oil-based failures remains a crucial factor in improving the overall safety of power systems (Lai, 2026). The study by A.R. Bessa *et al*. (2023) and I. Fofana (2013) discussed traditional methods of dissolved gas analysis and their limitations. It was noted that additional approaches are required to improve diagnostic accuracy, which is consistent with the results of the study, which uses more advanced methods such as artificial intelligence to improve diagnostic accuracy. C. Sun *et al*. (2022) proposed a model for estimating dissolved gases using associative rule analysis, which improves the accuracy of defect diagnosis. The study also used data mining methods, which confirms the effectiveness of approach by C. Sun *et al*. (2022) in improving diagnostic accuracy and detecting hidden defects.

X. Zhou *et al*. (2022) investigated the patterns of gas formation in various types of damage and improved the interpretation of diagnostic data. Their approach, which focuses on qualitative gas analysis, is close to the one under study, which examines detailed gas analysis using machine learning to improve interpretation. B.A. Thango (2022) and X. Lv *et al*. (2024) have shown that the use of neural networks and artificial intelligence significantly increases diagnostic sensitivity. The study also focused on the use of artificial intelligence, which confirms the importance of its use for early detection of defects. C.M. Walker *et al*. (2022) emphasised that the integration of temperature, humidity, and gas data improves the accuracy of transformer condition assessment. This is consistent with the results of the study, which integrates this data to create more reliable diagnostic models.

S.M. Islam *et al*. (2000) described in detail the mechanism for constructing a diagnostic model based on fuzzy logic, including decision-making rules and dealing with data uncertainty, which is missing in the study – the model is only declared there without a clear algorithmic implementation. In the same paper, the integration of heterogeneous parameters (temperature, moisture, electrical characteristics) was stated more broadly. L. Bouchaoui *et al*. (2021) conducted a full-fledged comparison between classical methods and neural networks with a quantitative assessment of the effectiveness of each approach. This paper focused more on the dynamics of gas change over time, while L. Bouchaoui *et al*. (2021) revealed less. M. Kruger *et al*. (2008) focused on methods for obtaining accurate diagnostic measurements and technical tools, describing in detail how the primary database is formed. In this paper, more attention was paid to mathematical modelling and generalisation of parameters.

Contemporary approaches to the analysis of dissolved gases and the integration of various parameters such as temperature, humidity, and the chemical composition of the oil significantly improved the accuracy of transformer diagnostics. The use of artificial intelligence and machine learning methods helped to improve the interpretation of data and identify defects at an earlier stage, which was confirmed by various studies. In general, the combination of conventional methods with new technologies provided more reliable and sensitive diagnostics, reducing the likelihood of malfunctions and improving the efficiency of equipment operation.

CONCLUSIONS

The results obtained confirmed that the integration of dissolved gas analysis, humidity, and temperature parameters can significantly improve the accuracy of transformer diagnostics. This is consistent with current trends in the development of predictive maintenance methods. The proposed approach can be used in online monitoring and decision-making systems. The simulation demonstrated an increase in the accuracy of classifying the state of transformers from 82% to 91%, an increase in diagnostic sensitivity to 0.89, and an increase in the F1-score to 0.90. These results indicate the high efficiency of the proposed method in detecting potentially dangerous defects and reducing the number of false positives. Of particular importance was the joint analysis of the dynamics of key dissolved gases – hydrogen, methane, and acetylene – which allowed detecting developing defects at earlier stages than conventional threshold diagnostic methods. The developed predictive model integrated the parameters, considering the interrelationships between temperature, load, and chemical and physical characteristics of the oil, which helped to predict the evolution of defects and optimise preventive maintenance plans. The results substantiated the implementation of the proposed integrated approach in automated monitoring and decision support systems, contributing to improving the safety and efficiency of electric power systems. The prospects for further research are related to the development of adaptive machine learning algorithms for automatic classification of defect types and dynamic adjustment of diagnostic thresholds, considering the features of the operation of specific facilities. This approach will significantly improve the accuracy of forecasting and make diagnostic systems more intelligent and adaptive to changing conditions.

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Трансформатор майынын сапатынын негизинде бузулууларды эрте болжолдоо модели

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Аннотация. Макалада трансформатор майындагы эриген газдарды (DGA) комплекстүү талдоонун негизинде күч трансформаторлорунун бузулууларын эрте болжолдоонун өркүндөтүлгөн модели сунушталган. Изилдөөнүн максаты суутек (H_2), метан (CH_4) жана ацетилен (C_2H_2) концентрацияларынын убакыт өтүшү менен өзгөрүү мыйзамченемдүүлүктөрүн аныктоо жана алардын изоляциялык системанын термикалык жана электрдик кемчиликтерин таануудагы диагностикалык маанисин аныктоо болуп саналат. Изилдөөнүн жыйынтыктары көрсөткөндөй, сунушталган күч трансформаторлорунун техникалык абалын баалоонун интегралдык ыкмасы салттуу ыкмаларга салыштырмалуу диагностиканын тактыгын жана ишенимдүүлүгүн олуттуу түрдө жогорулатат. Иштелип чыккан интегралдык диагностикалык көрсөткүч ар кандай физикалык мүнөздөгү бир нече параметрлерди (температуралык режимди, электрдик мүнөздөмөлөрдү, изоляциянын абалын жана трансформатор майын талдоонун жыйынтыктарын) бирдиктүү комплекстүү абал көрсөткүчүнө бириктирет. Моделдөөнүн жыйынтыктары көрсөткөндөй, интегралдык диагностикалык көрсөткүчтү колдонуу анын тактыгын 91 % чейин жогорулаткан. Сезгичтик 0,89, ал эми F1-көрсөткүчү 0,90 түздү, бул трансформаторлордун абалын классификациялоонун тактыгын жана тең салмактуулугун жогорулатуу үчүн интегралдык ыкманын натыйжалуулугун тастыктайт. Бул көрсөткүчтөр кемчиликтерди аныктоонун жогорку ишенимдүүлүгүн жана жалган иштөө коркунучунун төмөндүгүн ырастайт. Өзүнчө параметрлерди бөлөк баалоого негизделген салттуу диагностикалык ыкмалар менен салыштырмалуу талдоо көрсөткөндөй, сунушталган ыкма өзгөрүп турган эксплуатациялык шарттарда да классификациянын туруктуу натыйжаларын камсыз кылат. Алынган жыйынтыктар статистикалык моделдөөнү, мультипараметрдик көрсөткүчтөрдү агрегациялоону жана газдардын динамикасын талдоону автоматташтырылган мониторинг системаларына интеграциялоонун практикалык маанисин баса белгилейт, акырында чечимдердин сапатын жана электр-энергетикалык системаларды пайдалануунун коопсуздугун жогорулатат

Негизги сөздөр: эриген газдарды талдоо; DGA; эрте диагностика; кемчиликтерди болжолдоо; изоляциялык система; энергосистемалардын ишенимдүүлүгү

Модель раннего прогнозирования неисправностей на основе качества трансформаторного масла

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Аннотация. В статье представлена усовершенствованная модель раннего прогнозирования неисправностей силовых трансформаторов, основанная на комплексном анализе растворенных газов (DGA) в трансформаторном масле. Целью исследования было выявление закономерностей изменения концентраций водорода (H_2), метана (CH_4) и ацетилена (C_2H_2) во времени и определение их диагностической значимости для распознавания термических и электрических дефектов изоляционной системы. Результаты исследования продемонстрировали, что предложенный интегральный подход к оценке технического состояния силовых трансформаторов значительно повышает точность и надежность диагностики по сравнению с традиционными методами. Разработанный интегральный диагностический показатель объединяет несколько параметров различной физической природы, включая температурный режим, электрические характеристики, состояние изоляции и результаты анализа трансформаторного масла, в единый комплексный показатель состояния. Результаты моделирования показали, что использование интегрального диагностического показателя повысило ее до 91 %. Чувствительность составила 0,89, а F1-score – 0,90, что подтверждает эффективность интегрального подхода для повышения точности и сбалансированности классификации состояния трансформаторов. Эти показатели подтверждают высокую достоверность выявления дефектов и сниженный риск ложных срабатываний. Сравнительный анализ с традиционными методами диагностики, основанными на раздельной оценке отдельных параметров, показал, что предложенный метод обеспечивает более устойчивые результаты классификации даже при изменяющихся эксплуатационных условиях. Полученные результаты подчеркивают практическую ценность интеграции статистического моделирования, агрегирования мультипараметрических показателей и анализа динамики газов в автоматизированные системы мониторинга, что в конечном итоге повышает качество принятия решений и безопасность эксплуатации электроэнергетических систем

Ключевые слова: анализ растворенных газов; DGA; ранняя диагностика; прогнозирование дефектов; изоляционная система; надежность энергосистем