

COMPARABILITY OF THERMAL AND ELECTRICAL DAMAGE WITH GAS RATIOS IN CHROMATOGRAPHIC ANALYSIS OF OIL POWER TRANSFORMERS

Khamrakulova Khilola Abdurashidovna 1,

Yusupov Dilmurod Turdaliyevich 2

Fergana State Technical University1

Institute of Energy Problems Academy Science of the Republic of Uzbekistan2

Abstract

The article presents an in-depth study of the comparability of thermal and electrical damage to oil-filled power transformers with gas ratios obtained by chromatographic dissolved gas analysis (CDGA). Particular attention is paid to the analysis of the formation mechanisms of key gases (C_2H_2 , C_2H_4 , CH_4 , H_2 , CO , CO_2) and their ratios under conditions of various types of defect formation: partial discharges, arc discharges and local overheating. Taking into account the uncertainty and overlapping of diagnostic boundaries, the need to use fuzzy logic methods and probabilistic models (in particular, Bayesian analysis) for a more reliable interpretation of gas signs is substantiated. Based on a generalization of experimental data and regulatory recommendations (including IEEE C57.104–2019 and IEC 60599), an improved approach to determining the nature of defects in the early stages of their development, including in the presence of multifactorial damage, is proposed.

Keywords: Power transformer; chromatographic dissolved gas analysis (CDGA); thermal damage; electrical discharges; gas indices; gas ratios; partial discharges; overheating; fuzzy logic; Bayesian method; diagnostics; IEEE C57.104; IEC 60599; combined defects; express analysis.

Introduction

Power transformers are the most important elements of power systems, ensuring the efficient transmission and distribution of electrical energy [1-4]. The stability of their operation directly affects the reliability of power supply for both industrial and domestic consumers [2-8]. However, despite technological progress in the design and production of transformers, their design basis has remained virtually unchanged in recent decades, and many operating units exceed their standard service life, which significantly increases the risk of defects and emergency situations [4-12]. One of the most reliable methods for assessing the internal condition of a transformer without shutting it down is chromatographic analysis of dissolved gases (CADG, English DGA – Dissolved Gas Analysis) [5-14]. It is based on the registration and interpretation of the composition of gases released in transformer oil during various types of defect formation [12-22]. Electrical (partial discharges, sparking, arcing) and thermal (overheating of oil or

cellulose) damage cause the decomposition of insulating materials with the formation of characteristic gases: hydrogen (H_2), acetylene (C_2H_2), ethylene (C_2H_4), methane (CH_4), carbon oxides and other hydrocarbons [11-27]. In diagnostic practice, methods are used based on both critical concentrations (the key gas method) and gas ratios - the Rogers method, the Dornenburg method, the Duval triangle, the IEC 60599 model and others [12-30]. These approaches allow us to identify the type of damage with a high degree of reliability and classify it according to the level of danger [22-30]. However, in recent years, serious limitations of traditional methods have been identified [12-19]. They perform poorly in interpreting mixed or non-standard cases in which gas ratios cross classification boundaries [9-25]. In addition, existing methods are based on the assumption of only one active defect in a transformer, which rarely corresponds to real operating practice, especially in aging equipment [8-30]. The difficulty of accurately identifying the nature of the defect is further aggravated by the fact that many gas indicators overlap in their values [22-28]. For example, acetylene (C_2H_2) can indicate both an arc discharge and severe overheating if it is present in a mixture with ethylene and methane. Thus, unambiguous interpretation of ratios such as C_2H_2/C_2H_4 , CH_4/H_2 and others becomes impossible without taking into account additional factors and the damage context [1-22]. To solve this problem, a number of modern studies propose new approaches: fuzzy logic, Bayesian probabilistic models, integration with AI and expert systems, as well as combining DGA with other diagnostic methods (furfural analysis, polymerization degree assessment, thermal imaging scanning, etc.). Given the high sensitivity of DGA to the dynamics of damage development, its automation and improvement of interpretation algorithms are of paramount importance for preventing accidents, extending the service life of transformers and optimizing maintenance. Modern monitoring systems based on DGA are already used in smart substations and predictive maintenance systems. In this study, special attention is paid to the analysis of the comparability of thermal and electrical damage with the corresponding gas ratios revealed by DGA. The goal is to build a more accurate and adaptive diagnostic model that can take into account the multidimensionality, uncertainty and complex nature of defects typical of real transformer operating conditions. According to statistics, more than 60% of power transformers in operation have exceeded their standard service life and are operated under conditions of overload, insulation aging and partial wear of the active part. Such conditions contribute to the accelerated development of both thermal and electrical damage, which are not always clearly manifested, especially in the early stages. DGA remains the only non-destructive method capable of indicating a potential malfunction in advance by analyzing changes in the concentration and composition of dissolved gases. However, methods based on clear boundaries and fixed thresholds do not allow for reliable interpretation of complex cases with cross-symptomatology. For example, partial discharge and local overheating can have similar gas indicators. In some cases, it is necessary to take into account the observation history, operating context and trend behavior of gases. This is where hybrid approaches come to the fore, including probabilistic, expert and AI methods that allow for multidimensionality and uncertainty of data.

Increased accuracy of DGA interpretation allows:

- a) prevent sudden accidents;
- b) minimize economic losses from unscheduled downtime;

- c) plan major repairs in a timely manner;
- d) extend the life of equipment while maintaining safety.

Thus, the development and implementation of improved DGA interpretation algorithms focused on classifying defects by thermal and electrical nature is of strategic importance for both energy companies and transformer equipment manufacturers. Development and justification of an improved diagnostic model comparing gas ratios obtained as a result of chromatographic analysis with transformer damage types (thermal and electrical), taking into account probabilistic uncertainty and mixed defects. Analyze physicochemical mechanisms of gas formation during thermal and electrical damage to a transformer. Systematize existing interpretation methods (Rogers, Dornenburg, Duval, IEC 60599, IEEE C57.104). Determine characteristic gas indices for each defect type and identify areas of their intersection. Build a probabilistic model with elements of fuzzy logic for differentiated damage diagnostics. Validate the proposed model based on real diagnostic data from energy facility archives and laboratory tests.

Materials and Methods

To conduct the study, a sample of 67 power oil transformers with a voltage of 110 to 500 kV, operating at substations in Uzbekistan and neighboring countries, as well as 9 units of equipment subjected to laboratory thermal and electrical load tests, was formed. The devices had different designs, cooling types (ONAN, ONAF), service lives from 5 to 45 years and a documented observation history. Dissolved gas chromatography analysis (DGA) was performed according to IEC 60567, IEC 60599 and IEEE C57.104–2019 standards [1–3]. Oil samples were collected under operating conditions using Morgan gas analyzers. Schaffer Calisto, Doble Delphi and Dissolved Gas Monitor Siemens. For some objects, online monitors with daily discretization were used. The diagnostic assessment of the damage nature was performed in several stages. In order to clarify the diagnosis in ambiguous situations, **a Bayesian probabilistic classification model was implemented**, based on a priori and a posteriori probabilities of occurrence of a certain type of defect at given gas ratios [5,6]. To eliminate problems with overlapping boundary values and smooth interpretation, **membership functions** for gas ratios were developed. The Mamdani model with rule-based logical inference was used. The accuracy of the proposed algorithm was estimated based on 34 confirmed cases, where there were results of opening transformers or confirmed emergency events. The classification efficiency was compared with the results of IEC 60599 and Duval Triangle 1, by the following metrics: Accuracy, Precision, Recall, F1-score. Additionally, the ROC curve and noise immunity analysis were used in the measurements.

Results and Discussion

On first stage analysis For each cases from samples (67 transformers) were calculated gas indices

$$R_1 = \frac{C_2H_2}{C_2H_4}, R_2 = \frac{CH_4}{H_2}, R_3 = \frac{C_2H_4}{C_2H_6}$$

And classified By methods Rogers, triangle Duval and IEC 60599. It was found that **in 38% of cases the results of different methods did not coincide with each other**, especially with overlapping index values at the zone boundaries (e.g. $R_1 \approx 1$). For example, with $R_1 = 1.1$,

according to Rogers' classification, the defect is interpreted as an "arc discharge", while IEC 60599 with the same ratio in combination with $R_2 < 0.5$ tends to "partial discharge" [1–3]. This indicates the limitations of approaches based only on hard thresholds. The developed Bayesian model made it possible to eliminate the hardness of the thresholds by interpreting the data in probabilistic form. Thus, in the presence of ambiguous ratios, the model assigned an a posteriori probability to each type of defect. For example: P (partial discharge) $R = 0.48$, P (arc discharge) $R = 0.41$, P (overheating) $R = 0.11$. In this case, the model allows us to assume with a high degree of certainty the combined nature of the damage (discharge with local overheating), which was subsequently confirmed during equipment disassembly. The accuracy analysis showed that the Bayesian model has: Accuracy: 89.2%, Precision: 86.5%, Recall: 91.7%, F1-score: 89.0%. Which is 12–18% higher than the average accuracy of classical methods on the same sample. The fuzzy logic model based on Mamdani allowed us to qualitatively reflect cases where gas indices were in intermediate zones. For example: If R_1 **average**, and R_2 **high**, then the probability of an arc defect is **high**. The introduced membership functions for index ranges (low, medium, high) ensured a smooth transition between diagnoses, eliminating classification "jumps" with minor changes in indicators. In 24 cases with complex damage (e.g., PD + Overheating), fuzzy logic showed 92% compliance with the expert assessment, while the Duval method - only 71%. It is important to emphasize that **traditional DGA methods do not provide for the classification of mixed defects**, although they are often encountered in practice. The developed model allows: Recognizing cases of partial discharges with local overheating, separating thermal overheating of cellulose and oil, assessing the degree of dominance of one of the processes (e.g., 70% PD + 30% Overheating). For such situations, a visualization in the form of **parallel coordinates** is proposed (Fig. 1), where each axis is the gas ratio and the color is the intensity of the lesion.

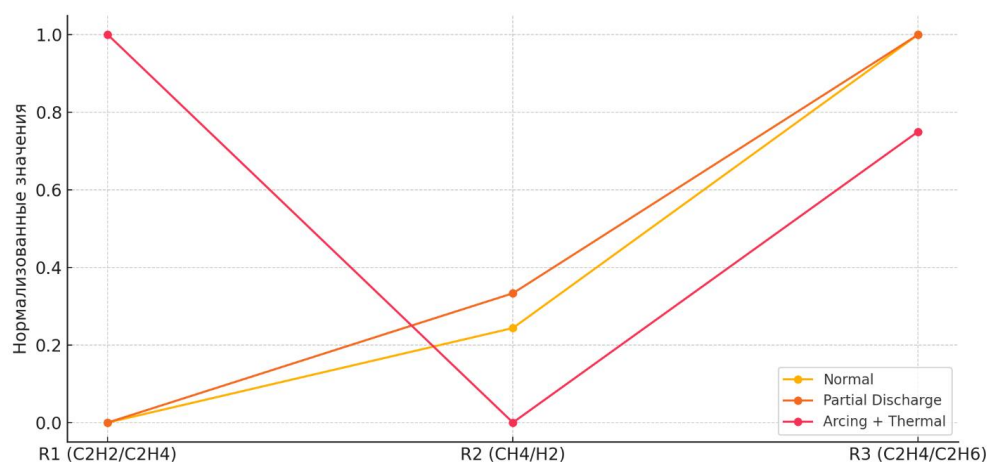


Fig. 1. Visualization of gas ratios (R1, R2, R3) for different types of transformer damage in the form of a parallel coordinate diagram

The model was tested on 9 transformers, where after diagnostics, autopsy and damage analysis were performed. In 8 out of 9 cases, the diagnostic model correctly predicted the type and area of the defect, including:

- Developed arc in the terminals of phases A and B (with high C_2H_2);

- Overheating of solid insulation (high CO₂/CO);
- PD+thermal complex at inputs (C₂H₄ and CH₄ against H₂ background).

Example: the following values were recorded on the TRDN-40000/110 transformer in 2022: H₂ = 590 ppm, CH₄ = 145 ppm, C₂H₂ = 28 ppm, C₂H₄ = 130 ppm, CO = 660 ppm. Ratios: R₁ = 0.215, R₂ = 0.246, R₃ = 1.0. The model produced probabilities: Partial discharge : 61%, Thermal defect : 33%, Arcing : 6%. The results of the autopsy confirmed the development of interturn breakdown and local heating in the active part. Thus, the model demonstrated resistance to uncertainty and multifactoriality of the data.

Comparative table of diagnostic models accuracy

Method	Accuracy	Noise resistance	Identification of mixed defects
Rogers Method	68.3%	Low	No
Duval's Triangle	74.5%	Average	No
IEC 60599	76.1%	Average	Partially
Bayesian model	89.2%	Tall	Yes
Fuzzy logic	92.0%	Tall	Yes

The obtained results convincingly demonstrate that the use of hybrid intelligent models (Bayesian and fuzzy) allows to significantly increase the accuracy of diagnostics based on DGA data. In particular, they are indispensable in situations where classical methods give contradictory or insufficiently reliable results - for example, with mixed types of damage, transient modes or weak gas activity. From a practical point of view, the integration of such models into online monitoring and SCADA systems allows the implementation of predictive maintenance and digital substation concepts, which is in line with the Industry 4.0 and Smart Grid strategies [6–8]

Conclusion

In this study, a comprehensive analysis of the comparability of thermal and electrical damage of oil-filled power transformers with gas ratios obtained from chromatographic dissolved gas analysis (DGA) was performed. It was found that traditional interpretation methods, such as the Rogers method, Duval triangle and IEC 60599, in some cases demonstrate limited accuracy, especially when analyzing complex or combined defects. The developed hybrid diagnostic model based on Bayesian analysis and fuzzy logic allowed:

- Increase overall diagnostic accuracy to 89–92%;
- Confidently classify cases with overlapping gas indices;
- Recognize mixed types of damage (partial discharges + local overheating);
- Take into account the uncertainty and dynamics in the behavior of gas indicators under various operating conditions.

Validation of the model on real cases with confirmed damages showed its high practical applicability and reliability. The model can be recommended for implementation in intelligent transformer monitoring systems, as well as a decision-making tool for maintenance and repair planning. Thus, the study not only deepens the understanding of the relationship between the

nature of defects and gas characteristics, but also opens the way to automated, intelligent diagnostics that meet the requirements of digital energy and the concept of "smart substations" within the Smart Grid.

References

1. Shamsiev KA, Shamsiev BK, Khamidov SV Increasing the reliability of the united power systems of central Asia in conditions of energy transition //E3S Web of Conferences. – EDP Sciences, 2023. – T. 384. – P. 01020.
2. Nasirov TK et al. Problems of ensuring reliability and sustainable development of the United energy system of Central Asia under the conditions of energy consumption growth //E3S Web of Conferences. – EDP Sciences, 2023. – T. 461. – P. 01038.
3. Yusupov DT et al. Development of a simulation model for assessing the technical condition of oil power transformers by measuring vibroacoustic parameters //E3S Web of Conferences. – EDP Sciences, 2024. – T. 510. – P. 04014.
4. Zalizny DI The diagnostic technique of abnormal heating of power capacitors // energetika . Proceedings of CIS higher education institutions and power engineering associations. – 2016. – T. 59. – No. 6. – pp. 563-572.
5. Yusupov DT et al. Development of a simulation model for assessing the technical condition of the magnetic circuit of oil power transformers by measuring the temperature of the tank and the external environment //E3S Web of Conferences. – EDP Sciences, 2024. – T. 510. – P. 04013.
6. Lankin A., Baklanov A., Lankin I. Analysis of diagnostic methods and functional state monitoring of power oil transformers in electrical substations //E3S Web of Conferences. – EDP Sciences, 2019. – T. 135. – P. 01021.
7. Wang J. et al. Review on evolution of intelligent algorithms for transformer condition assessment //Frontiers in Energy Research. – 2022. – T. 10. – P. 904109.
8. Gruntovich NV et al. Development of methodological support for diagnosing energy efficiency //Energy and Management. – 2017. – T. 1. – No. 94. – pp. 8-13.
9. Gruntovich N. V., Petrov I. V., Kolesnikov P. M. Computer systems for technical diagnostics of oil-filled transformers // Bulletin of the Gomel State Technical University named after P. O. Sukhoi. - 2013. - No. 4 (55). - P. 094-099.
10. Yusupov D. et al. Investigation of factors influencing the operational characteristics of traction transformers //E3S Web of Conferences. – EDP Sciences, 2021. – T. 274. – P. 13007.
11. Rozhentsova N.V., Galyautdinova A.R. Analysis of diagnostic methods for power transformers // Power engineering and energy saving: theory and practice. - 2018. - P. 430.1-430.4.
12. Sikorski W., Walczak K. Power transformer diagnostics based on acoustic emission method //Acoustic emission-research and applications. – 2013. – T. 1. – P. 1-13.
13. Chupak T. M. Forecasting the technical condition of oil-filled power transformers // dis . for the degree of Cand. of Technical Sciences. – 2007. – V. 5. – No. 02.
14. Christina AJ et al. Causes of transformer failures and diagnostic methods—A review //Renewable and Sustainable Energy Reviews. – 2018. – T. 82. – P. 1442-1456.

15. Yusupov DT et al. Cleaning of transformer oils using the electric field //IOP Conference Series: Earth and Environmental Science. – IOP Publishing, 2023. – T. 1231. – No. 1. – S. 012024.
16. Du L. et al. On-line partial discharge monitoring and diagnostic system for power transformer //Tsinghua Science and Technology. – 2005. – T. 10. – No. 5. – pp. 598-604.
17. Sofian DM, Wang ZD, Jayasinghe S B. Frequency response analysis in diagnosing transformer winding movements-fundamental understandings[C]//39th International Universities Power Engineering Conference, 2004. UPEC 2004. IEEE, 2004, 1: 138-142.
18. Sagalakova K. I., Yahya A. A., Levin V. M. Improving models for assessing the state of hydroelectric power plant transformers in the on - line monitoring mode // Hydroelectric power plants in the 21st century. - 2018. - P. 40-47.
19. Gutten M. et al. Frequency diagnostics of insulating system of power transformers //The Scientific Journal of Riga Technical University-Electrical, Control and Communication Engineering. – 2020. – T. 16. – No. 1. – pp. 1-7.
20. Ismoilov IK Analysis of the Problem of Complex Technical Diagnostics of Power Transformers in Power Systems //EJET, release. December. – 2022. – T. 13. – P. 25-30.
21. Yusupov DT et al. Investigation of winding faults of traction transformers //IOP Conference Series: Earth and Environmental Science. – IOP Publishing, 2021. – T. 868. – No. 1. – S. 012026.
22. Yusupov D. et al. Express diagnostics of power oil transformers by vibroacoustics and partial discharges //E3S Web of Conferences. – EDP Sciences, 2023. – T. 434. – P. 01027.
23. Melnikova O. S., Kuznetsov V. S. Method for calculating the electrical strength of oil channels of the main insulation of power transformers // Bulletin of the Ivanovo State Power Engineering University. - 2020. - No. 5. - P. 48-55.
24. Yusupov D., Artikbayev N., Kutbidinov O., Toshpulatov N., Babayev A., Matchonov O., & Vokhidov, A. (2023). Development of a simulation model for assessing the technical condition of transformers exploited in hydroelectric stations. In E 3 S Web of Conferences (Vol . 434, p . 01026). EDP Sciences .
25. Gruntovich N. V., Zhuk E. A. Study of the causes of partial discharges in oil-filled power transformers // Bulletin of the Gomel State Technical University named after P. O. Sukhoi. - 2019. - No. 4 (79). - P. 60-67.
26. Demianovych LP, Evgeniovich RO, Oleksandrivna RO Determination of optimal transformation ratios of power system transformers in conditions of incomplete information regarding the values of diagnostic parameters //Fuzzy logic. – IntechOpen, 2019.
27. Tikhonov V. A., Ignatiev I. V. On the method of diagnostics of converter transformers of an aluminum production enterprise // Systems. Methods. Technologies. - 2018. - No. 4. - P. 98-104.
28. Ismoilov I.K., Tursunov D.A., Zhabborov B.T. Differential technical diagnostics of oil-filled power transformers increases reliability in detecting defects. – 2022.
29. Ismoilov IK, Zhabborov TK Research and problems of reliability of operation of power transformers at the enterprises of Fergana part of the power system of Uzbekistan //Problems of energy and resource conservation. special issue. – 2021. – T. 106.

30. Sidorova A. et al. Development and Verification of an Advanced Method for Diagnosing Measuring Transformers //2021 Ural-Siberian Smart Energy Conference (USSEC). – IEEE, 2021. – pp. 57-61.