Application and Comparative Analysis of Fuzzy Inference System for Transformer Fault Diagnosis with Dissolved Gases in Oil

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***Abstract*— Oils are used for cooling and insulation in transformers. The fault currents occurred on transformers can damage windings and insulation. As a result of this incoming fault current, gas emission occurs in materials such as oil and pressboard. The type of these gases released gives information about the fault of the transformer. In this study, it has been studied on the determination of the fault by analyzing the gases released as a result of the failure in 63 transformers using FIS. As a result of the analysis, the results obtained with FIS were compared with analyzed results with IEC 60599 and fault reports from the corporation, which these values obtained. When 63.5% true results were obtained compared to IEC 60599, 97.6% correct results were obtained compared to fault reports of the corporation because 22 of 63 transformer gas values were not actually suitable for applying the IEC Ratio method.**

***Keywords*— DGA interpretation; Dissolved Gas Analysis; Fault prediction methods; Fuzzy Inference System (FIS); Power Transformers.**

I. INTRODUCTION

High voltage is preferred to reduce losses in the transmission of electricity over very long distances. The transformation process between these voltage values is provided by transformers. Power transformers are manufactured as single-phase or three-phase, with their windings in insulating oil for cooling and insulation purposes [1].

Electrical insulation on high voltage equipment plays an important role in the sustainability of electrical transmission systems. Failures in electrical insulation may occur in the interruption of electrical transmission and the malfunction of electrical devices [2]. Moreover, failures in transmission systems can create severe problems for all equipment on transmission systems and end-users.

Power transformers produced at high power generate more heat depending on the amount of current passing through the windings. Unless this generated heat is discharged, the insulation material on the windings may reach the ignition temperature and cause the transformer to burn. The amount of heat that needs to be discharged in distribution transformers is mostly discharged with the help of air. However, the air is not sufficient for heat dissipation in power transformers used in transmission lines. Therefore, transformer oils are preferred to cool for power transformers [3].

Transformer oil inside the tank helps to dissipate the heat in the windings over the tank surface due to its convectional movement. Transformer oils can maintain their stability at high temperatures and have high voltage resistance [4]. The fact that oils have these properties shows that they are good insulating materials in transformers.

When the temperature of the insulation oil exceeds a certain degree, gas formation begins [5]. These dissolved gases expose gas bubbles in the oil. The resulted gases accumulate in the upper part of the transformer oil. Gas bubbles decrease the insulation reliability of transformer oil, so they can cause a breakdown. Buchholz relay used in transformers is used to protect the transformer by deactivating the transformer when the amount of gas formed in the oil exceeds a certain limit [6].

Before a transformer fails, gas values can be analyzed and benefited for determining the probability of failure. Transformers that are likely to fail mostly have gas values that above the standards. The future failure in a transformer can be predicted by analysis of dissolved gases [7, 8].

Commonly used methods for the analysis of dissolved gases are Roger Gas Ratio [9], Duval Triangle [10] and IEC Ratio [11] methods. The most important gases – because they form at high temperatures- are Ethane (C_2H_6), Ethylene (C_2H_4) and Acetylene (C_2H_2) [12]. Additionally, gases such as Hydrogen (H_2), Carbon Dioxide (CO_2) and Nitrogen (N_2) are helped to detecting the reasons of the fault in the transformer.

In this study, it has been studied on the determination of the fault by analyzing the gases released as a result of the failure in 63 transformers using Fuzzy Inference System (FIS). As a result of the analysis, the results obtained with FIS were compared with analyzed results with IEC 60599 and fault reports from the corporation, which these values obtained. When 63.5% true results were obtained compared to IEC 60599, 97.6% correct results were obtained compared to fault reports of the corporation because 22 of 63 transformer gas values weren't actually suitable for applying IEC Ratio method.

II. FUZZY INFERENCE SYSTEM (FIS)

Due to the proximity of fuzzy logic to the daily language, it makes decisions very close to human logic. In this way, the mathematical modeling of non-linear cases in nature is provided by the fuzzy logic method [13]. For real models or modeling languages, two main complications arise [14];

- Real situations aren't often clear and deterministic and can't be fully defined by crisp logic.
- A full description of a real system often requires much more detailed data than a human can recognize, process and understand at the same time.

While making a definition with the fuzzy logic set, equations can be defined with expressions such as "very low", "low", "medium", and "high" [14]. Clusters of fuzzy logic are created through that definition process.

Two analysis methods are commonly used in FIS. These are the Mamdani and Sugeno methods. The generally used method is the Mamdani [15]. Mamdani method is performed in four steps as follows [16];

- Fuzzification of input values,
- Evaluation of the rules by the inference engine,
- Obtaining of fuzzy outputs,
- Defuzzification of fuzzy outputs.

FIS consists of three blocks, as shown in Fig. 1. First, membership functions are created for each input value. Each input value has a degree of belonging to the membership function belongs to it. This process is called fuzzification. Then the rules are determined as in classical logic. In these rules, output values are defined according to each combination that may occur between the inputs. Mamdani style evaluations are implemented, and an output function is created according to determined rules. In conclusion, the COG (Center of Gravity) method is commonly used for generating a single output value from that output function. This process is called defuzzification [16].

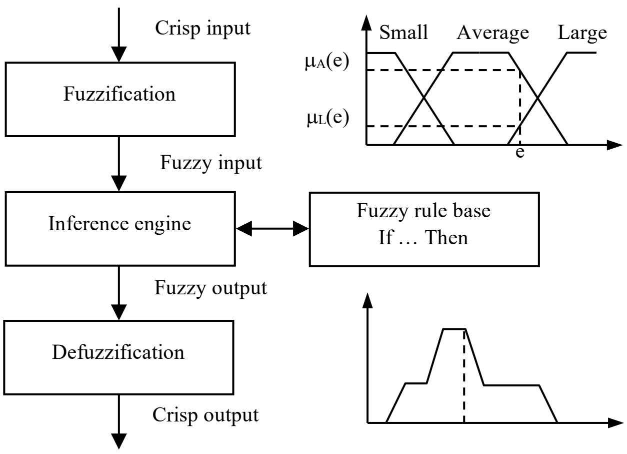

Fig. 1. Fuzzy Inference System [16].

III. APPLICATION OF FIS FOR TRANSFORMER DISSOLVED GASES

Many gas values affect transformer dissolved gases diagnosis. Besides combustible gases, a certain amount of nitrogen and oxygen can also be an indication that the transformer may breakdown. Let's assume that hydrogen and methane values in the transformer oil are between IEC standard nominal values. Nevertheless, total dissolved gases (TDG), total combustible gases (TCG) and proportion of these gases may occur a fault that could disable the transformer. In fact, this is the point why transformer dissolved gas diagnosis should be analyzed by the expert person. This difference between the human and the classical logic mentality has led us to the conclusion that the dissolved gas analysis cannot give accurate results with classical logic. For this reason, fuzzy logic method was used in the analysis of gases and results are obtained closer to correct results [17, 18, 19].

In this study, the analysis was carried out according to the three basic gas ratios specified in the IEC ratio method.

Fuzzy Logic Tool Box in MATLAB is used for FIS applications. According to the IEC ratio method, the X_1, X_2 and X_3 ratios are given in the following equations. Input membership functions defined in the study for X_1, X_2 and X_3 ratios are shown in Fig. 2, Fig. 3 and Fig. 4.

$$X_1 = \frac{C_2H_2}{C_2H_4} \quad (1)$$

$$X_2 = \frac{CH_4}{H_2} \quad (2)$$

$$X_3 = \frac{C_2H_4}{C_2H_6} \quad (3)$$

In these equations;

C_2H_2 : Acetylene
C_2H_4 : Ethylene
CH_4 : Methane
H_2 : Hydrogen
C_2H_6 : Ethane

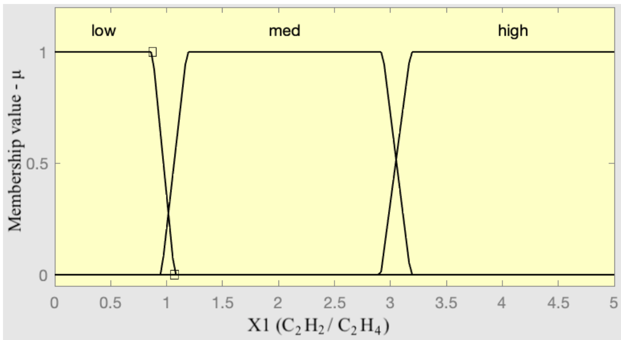

Fig. 2. X_1 (C_2H_2 / C_2H_4) membership function.

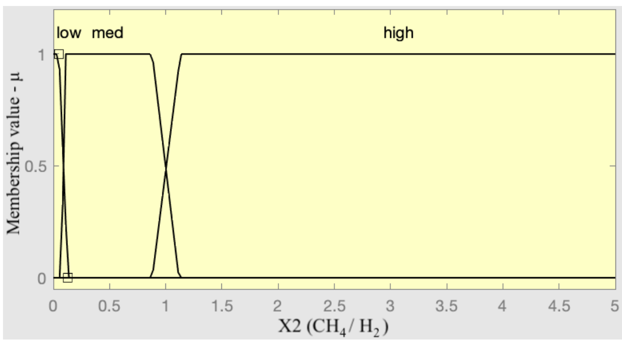

Fig. 3. X_2 (CH_4 / H_2) membership function.

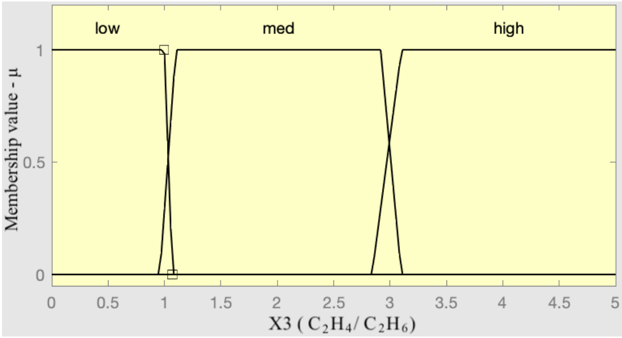

Fig. 4. X_3 (C_2H_4/ C_2H_6) membership function.

The degrees of membership are defined as "low", "medium" and "high" for each input function. Trapezoidal membership functions are used in definitions. The program calculates how much entered value is included in which membership degree and produces an output value according to the written rules. Nineteen rules are defined according to X_1, X_2 and X_3 input membership functions. These rules are created based on the IEC ratio method. Then, output membership functions are created, which are shown in Fig. 5.

The faults determined according to the output membership function and their explanations are shown in Table I. In the last step of the FIS, the degree to which the fault belongs to which output function is indicated with a value between 0-1.

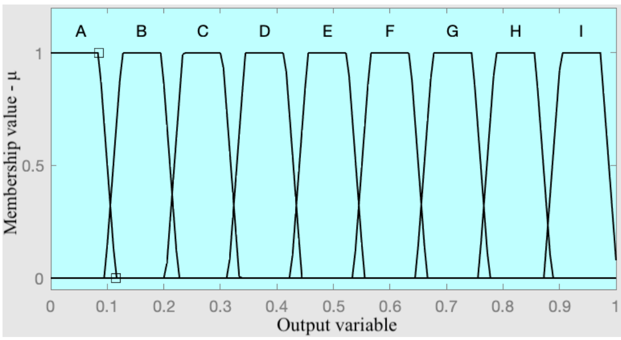

Fig. 5. Determined output membership function.

TABLE I. FAULT TYPES BASED ON IEC METHOD

Outputs	Fault Type
NF(A)	No Fault
LP(B)	Partial discharges of low energy
HP(C)	Partial discharges of high energy
LD(D)	Discharges of low energy
HD(E)	Discharges of low energy
VLT(F)	Thermal Faults, t <150 °C
LT(G)	Thermal Faults, 150 °C < t < 300 °C
MT(H)	Thermal Faults, 300 °C < t < 700 °C
HT(I)	Thermal Faults, t >700 °C

IV. RESULTS

A comparison was made between the results obtained from the analysis using FIS and the gas measurement values taken from 63 transformers in operation provided by the corporation. However, the IEC ratio method does not give a result for all the faults in the transformers we evaluated. For example, a transformer that is decided to be deactivated according to the gas values measured by the corporation is suitable to remain in operation when it is examined according to the IEC method.

TABLE II. THE RESULTS OF FAULT TYPES BASED ON IEC METHOD

Sample	Total Examples	True	Partially True	False
Number	63	32	8	23
Ratio	%100.0	%50.8	%12.7	%36.5

In Table II, when the transformer fault reports from the corporation are compared with the outputs of the project, it is seen that 63.5% accuracy is obtained. In the remaining 36.5%, the results of the IEC-based study do not reflect the truth. The reason for this is that corporation experts take into account many values at the same time, such as the total dissolved gas amount, nitrogen amount, oxygen amount, age of the transformer during the examination.

When a new examination is made among the data obtained from the corporation, for which only the IEC method can be applied, the comparison of the project with the actual results is as given in Table III.

TABLE III. COMPARISON OF FIS RESULTS WITH FAULT REPORTS OF CORPORATION THAT SUITABLE FOR IEC ANALYSIS

Sample	Total Examples	True	Partially True	False
Number	41	32	8	1
Ratio	%100.0	%78.0	%19.5	%2.5

The partially true part is the number of cases in which the program outputs between low-energy discharge and high-energy discharge to the fault, which is actually a low-energy discharge.

As shown in Table III, FIS has an accuracy rate of 97.5% in the analysis carried out in this context. The following finding was found as a result of the investigation made for the failures that could not be determined according to the IEC rates. It has been found that the X_1 ratio is impressive in determining the fault in the values where X_2 is less than 1 and X_3 is greater than 2. When X_2 and X_3 are at the specified values, this situation has no equivalent in IEC. However, as a result of the research, it might be T3 fault sign that when the X_1 value is below 0.1.

In addition, if it is seen that the X_1 value is too small in cases where the output is D_2 fault in the study, it has been determined that this situation may actually be a T3 fault. This judgment was obtained as a result of the examinations made in the fault reports of the corporation.

V. CONCLUSION

In this study, the condition of 63 transformers, which under maintenance was analyzed with the FIS model. The results obtained from the FIS model were compared with the results of the IEC ratio method and fault reports of the corporation. As a result of the studies, it has been shown that fuzzy logic can be applied in the examinations made before the failure of transformers, which is one of the most important equipment of electrical transmission.

Since there is no specific rule while creating membership functions in this method, the experience of the person who created these functions on the subject comes to the fore. In addition to the input variables, many more gases can be examined. However, due to the similarity of fuzzy logic with human logic, the number of rules must be determined for each input variable increases exponentially.

As a result, in the fuzzy logic study based on the IEC ratio method, it has been shown that fuzzy logic can detect faults accurately at a rate of 97.5%. Gas values which can be added as input variables such as Nitrogen, Oxygen, Carbon Dioxide or Total dissolved gas amount, will enable the project to give results even closer to the expert evaluation.

References

[1] A. Küchler, *High Voltage Engineering: Fundamentals: Technology-Applications*, Germany: Springer, 5. Ed. 2018.

[2] M. M. Ispirli and A. E. Yilmaz, "An investigation on characteristics of tracking failure in epoxy resin with harmonic and fractal dimension analysis", Turkish Journal of Electrical Engineering and Computer Science, vol. 26 (1), pp. 245-256, 2018.

[3] J. Winders, *Power Transformers: Principles and Applications*, New York, USA: CRC Press, 2002.

[4] M. Sezer, *Transformer Maintenance and Insulation Oil*, Turkey: Cagdas Publisher, 2008 (in Turkish).

[5] N. H. Malik, A. A. Al-Arainy, and M. I. Qureshi, *Electrical Insulation in Power Systems*, Boca Raton, USA: CRC Press, 2018.

[6] S. Tenbohlen, D. Uhde, J. Poittevin, H. Borsi, P. Werle, U. Sundermann, and H. Matthes, "Enhanced diagnosis of power transformers using on-and off-line methods: Results, examples and future trends" in *Cigré Session 2000*, no. 12-204, 2000.

[7] S. Köroglu, A. Demircali, M. Yildiz, E. Cali, and G. Mihci "Diagnosis of power transformer faults with dissolved gas analysis", in *National Conference on Electrical and Electronics Engineering (ELECO 2014)*, 27-29 November 2014.

[8] H.-C. Sun, Y.-C. Huang, and C.-M. Huang, "A Review of Dissolved Gas Analysis in Power Transformers", Energy Procedia, vol. 14, pp. 1220 – 1225, 2012.

[9] R. R. Rogers, "IEEE and IEC Codes to Interpret Incipient Faults in Transformers, Using Gas in Oil Analysis", IEEE Transactions on Electrical Insulation, vol. EI-13(5), pp. 349-354, 1978, doi: 10.1109/TEI.1978.298141.

[10] M. Duval, "The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers", IEEE Electrical Insulation Magazine, vol. 24(6), pp. 22-29, 2008.

[11] *Mineral oil-filled electrical equipment in service - Guidance on the interpretation of dissolved and free gases analysis*, IEC 60599:2015, 2015. [Online]. Avaible: https://webstore.iec.ch/publication/23323

[12] H. T. Yang and C. C. Liao, "Adaptive Fuzzy Diagnosis System for Dissolved Gas Analysis of Power Transformers", IEEE Transactions on Power Delivery, Vol. 14(4), pp. 1342-1350, 1999.

[13] H. J. Zimmermann, *Fuzzy set theory and its applications*, Germany: Springer, 2011.

[14] E. Kemik, "Determination of power transformer faults by fuzzy logic and self-regulated mapping method", Pamukkale University, Institute of Science and Technology, Department of Electrical and Electronics Engineering, 2016 (in Turkish).

[15] K. Arikan, Ö. Kalenderli, A. Kara, A. Font, and E. Onal, "The prediction of AC breakdown voltage using fuzzy inference system", in *18th International Symposium on High Voltage Engineering (ISH 2013)*, 25-30 August 2013.

[16] S. Guillaume and B. Charnomordic, "Fuzzy Inference Systems to Model Sensory Evaluation", in *Intelligent Sensory Evaluation*, D. Ruan and X. Zeng, Eds., Germany: Springer, 2004. doi: 10.1007/978-3-662-07950-8_11

[17] M. R. Ahmed, M. A. Geliel, and A. Khalil, "Power transformer fault diagnosis using fuzzy logic technique based on dissolved gas analysis", in *21st Mediterranean Conference on Control & Automation*, 25-28 June, 2013.

[18] Q. Su, C. Mi, L. L. Lai, and P. Austin, "A fuzzy dissolved gas analysis method for the diagnosis of multiple incipient faults in a transformer", IEEE Transactions on Power Systems, vol. 15(2), pp. 593-598, 2000.

[19] Y. Benmahamed, O. Kherif, M. Teguar, A. Boubakeur, and S. S. M. Ghoneim, "Accuracy Improvement of Transformer Faults Diagnostic Based on DGA Data Using SVM-BA Classifier", Energies, vol. 14(10), 2970, 2021. doi: 10.3390/en14102970.