

# Transformer Oil Failure Analysis Based on Dissolved Gas Analysis (DGA) Test Using Breakdown Voltage and Fuzzy Logic Methods

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## ABSTRACT

A common problem that occurs in transformers is failure of the insulating oil. One solution to prevent this disruption is to analyze indications of insulating oil failure. Several previous studies on the analysis of transformer insulating oil failure were based on dissolved gas content tests of transformer oil samples. The research was conducted using several methods in processing dissolved gas test results data, such as the TDCG (Total Dissolved Combustible Gas), Roger's Ratio, and Duval's Triangle methods. In this study, two methods were used for comparison, namely the Breakdown Voltage method and the Fuzzy Logic method. The results obtained show that the condition of the insulating oil using fuzzy logic in the Matlab simulation is in accordance with the condition of the transformer insulating oil based on its breakdown voltage characteristics, namely in a normal state. Meanwhile, gas content that is at a high or very high level has a significant impact on the indication of failure in transformer insulating oil, namely the concentration of TDCG and nitrogen gas content.

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## 1. Introduction

The fundamental objective of an electric power system is to continuously meet consumers' electricity demand. Transformers are one example of electrical equipment that plays an important role in the distribution of electrical energy. Therefore, proper transformer maintenance is required to avoid various disturbances that can cause transformer failure (Sinuhaji, 2012). Problems that generally occur in transformers include overheating and overcurrent loading. To avoid these problems, testing is carried out to detect the condition of a transformer. Transformer condition maintenance requires four maintenance guidelines, namely in-service inspection, in-service measurement, shutdown testing, and treatment. Perusahaan Listrik Negara (PLN) has several parameters in testing transformer insulating oil samples, including breakdown voltage, dielectric losses, and Dissolved Gas Analysis (DGA) (Anderson & Fouad, 2002; Demmassabu *et al.*, 2014). The Dissolved Gas Analysis (DGA) test is one of several testing steps for transformers conducted based on differences in dissolved gas content in transformer oil samples. This DGA test can detect the type and total amount of fault gases dissolved in the oil sample. The output of the DGA test is gas concentration data, which are then analyzed to obtain information regarding indications of thermal or electrical damage in the transformer and the causes of decreased transformer efficiency. Previous research conducted in 2014 by Demmassabu, Patras, and Lisi analyzed power

transformer failures based on DGA test results using four techniques, namely the TDCG method, Key Gas, Roger's Ratio, and Duval's Triangle. The study concluded that one indication of transformer failure is overheating of the transformer core, electrical discharge, or overheating disturbances caused by degradation of transformer oil quality (Demmassabu *et al.*, 2014).

Other studies using the DGA method detected gases such as hydrogen, methane, ethylene, ethane, and acetylene in oil, indicating electrical or thermal disturbances (Amsal & Soni, 2025). The use of DGA methods continues to increase, including solutions using machine learning techniques (Al-Sakini *et al.*, 2025). Fuzzy Logic methods have also been applied (Nishtar & Wan, 2024). DGA results from multiple transformers have been further evaluated using fuzzy logic systems (Poonnoy *et al.*, 2021), where various faults are analyzed theoretically and practically to implement early detection technology that can reduce maintenance costs. Another significant study using the DGA method proposed revisions to IEEE gas concentration threshold limits to improve early fault detection capability and enhance maintenance planning and transformer reliability (Velásquez, 2024). Additional studies describe the application of DGA using Logistic Regression, showing very good performance in terms of accuracy, precision, and F1-Score (Wibowo & Hendry, 2024). In this study, two different methods are used, namely the Breakdown Voltage method and the Fuzzy Logic method, to analyze the same issue, namely power transformer insulating oil failure based on DGA testing. Furthermore, the analysis results of both methods are compared to obtain the relationship between Fuzzy Logic analysis data and breakdown voltage characteristics data in indicating transformer insulating oil failure.



Figure 1. High-voltage power transformer

A transformer is an electrical device capable of transferring electrical energy from one electrical circuit to another through magnetic coupling and operates based on the principle of electromagnetic induction (Tobi, 2018). A power transformer is defined as an electrical device used to transfer electrical power from high voltage to lower voltage levels or vice versa. Based on operating voltage, transformers are classified into 500/150 kV and 150/70 kV transformers, also known as Interbus Transformers (IBT). According to PLN Standard 61:1997, high-voltage power transformers are those with primary voltage above 20 kV. In Indonesia, commonly used high-voltage power transformers have primary voltages of 66 kV, 150 kV, 275 kV, and higher, including 500 kV (Sutrayono, 2015). The working principle of transformers based on electromagnetic induction states that differences in electric fields or currents generate magnetic fields, and changes in magnetic fields or magnetic flux generate induced fields. When the transformer primary winding is connected to an alternating voltage source, current flows in the primary winding (Mardiyanto, 2019).



Figure 2. Transformer oil

Transformer oil is a liquid obtained from refined crude oil. Organic materials such as pyranol and silicone are among its components. Transformer oil serves as a liquid insulating material and functions as a coolant. As an insulating medium, transformer oil must withstand disturbances such as breakdown voltage, and as a cooling medium, it must be capable of dissipating heat generated by transformer operation. Commonly used insulating oils include mineral insulating oil and synthetic insulating oil (Sinuhaji, 2012).

## 2. Methods

The stages of the research process are shown in the flowchart in Figure 3.



Figure 3. Research flowchart

Analysis of indications of transformer insulating oil failure is conducted by designing a fuzzy logic system and Matlab simulation based on DGA test data to determine transformer insulating oil condition. The fuzzy logic system design includes the following stages.

1. Fuzzification

Fuzzification converts non-fuzzy (numerical) variables into fuzzy or linguistic variables to identify input data and clarify the system.

2. Membership Function

Determining membership functions is a crucial step in fuzzy logic. Various curve types can be used, but this study applies trapezoidal curves because they better represent safe operating limits for gas contamination in transformer insulating oil. Nine types of gases are identified, and their membership degrees are categorized into three levels: normal, high, and very high.

3. Rule Construction

Fuzzy rules define relationships among all inputs. Output categories used to determine transformer insulating oil condition are dangerous, maintenance, and normal.

4. Defuzzification

Defuzzification converts fuzzy outputs into crisp values. The Maximum of Mean (MOM) technique is applied.

5. Rule Testing

Rule testing ensures the accuracy of the designed fuzzy logic system and verifies whether its outputs meet expected conditions.

### 3. Results

#### 3.1 Fuzzy Logic System for Determining Transformer Insulating Oil Condition

In the Dissolved Gas Analysis (DGA) test, the presence of disturbances can be identified through the analysis of three types of gas concentrations, namely TDCG gas, nitrogen, and third gases such as methane, acetylene, ethylene, ethane, carbon monoxide, and carbon dioxide contained in transformer insulating oil. Basically, the use of DGA testing can directly determine the condition of transformer insulating oil by using DGA data from each transformer. However, by using the DGA test alone, the actual level of transformer insulating oil condition cannot be determined. Therefore, the fuzzy logic method is used to build dissolved gas membership functions in order to determine the actual condition of transformer insulating oil so as to avoid the occurrence of transformer failure. The input gas contents are used to build a fuzzy system so that the condition of transformer insulating oil can be identified. This fuzzification process is carried out to develop membership functions for dissolved gas contents in transformer insulating oil obtained from DGA testing. Membership degrees with input gas concentrations that are in a normal condition are classified into the "normal" membership degree, while input gas concentrations that are in an abnormal condition are classified into the "very high" membership degree. Meanwhile, input gas concentrations that lie between normal and abnormal conditions are classified into the "high" membership degree. In arranging the rules for completing this fuzzy logic system, the condition of transformer insulating oil is determined by the presence of TDCG, nitrogen, and third gases. The use of AND, NOT, and other fuzzy operators in the Matlab application makes the arrangement of fuzzy logic rules more efficient and easier to implement. Arcing condition is a very dangerous condition indicating transformer failure. This is because when arcing occurs, electrical sparks appear in the transformer insulating oil, which can cause transformer damage to the extent that replacement of the insulating oil is required. For the "maintenance" condition, the failure indication that arises is excessive temperature or overheating of the insulating oil, requiring oil washing or purification to prevent transformer failure.

Meanwhile, in the “normal” condition, no disturbance symptoms are found, so the transformer can operate normally. Defuzzification is a method used to produce output according to the designed fuzzy logic system to solve problems related to transformer insulating oil condition. The output membership functions built to determine insulating oil condition with three membership degrees, namely normal, maintenance, and dangerous, are shown in Figure 4.

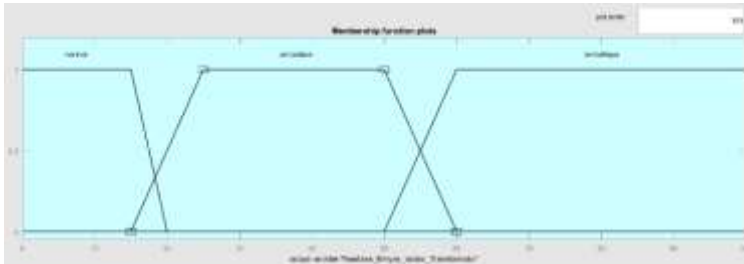


Figure 4. Output membership function of transformer insulating oil condition

Rule testing is carried out to verify the accuracy of the designed fuzzy logic system and to determine whether the output of the system matches the expected results. Based on this rule testing, it can also be determined which gas contents are most dominant in determining the condition of transformer insulating oil.

**3.2 Results of Transformer Insulating Oil Condition Based on Matlab Simulation and Breakdown Voltage Characteristics**

The condition of transformer insulating oil in this study is simulated using Simulink in the Matlab application with several input components, namely the concentrations of dissolved gases in transformer insulating oil. These dissolved gas concentration values are obtained from DGA test data conducted by PLN and are expressed in ppm (parts per million). Furthermore, these input components are connected to a component in the form of an FLC or Fuzzy Logic Controller. Then, based on the connected input components, an output component is produced in the form of the membership degree of transformer insulating oil condition. The dissolved gas content data from the DGA test output for power transformer 1 are shown in Table 1.

Table 1. DGA Test Result Data of Power Transformer 1

| No. | Gas Content                   | Concentration (ppm) |
|-----|-------------------------------|---------------------|
| 1   | TDCG                          | 1995.144            |
| 2   | H <sub>2</sub>                | 172.891             |
| 3   | N <sub>2</sub>                | 104171.217          |
| 4   | CH <sub>4</sub>               | 275.795             |
| 5   | CO                            | 1144.485            |
| 6   | CO <sub>2</sub>               | 4672.504            |
| 7   | C <sub>2</sub> H <sub>4</sub> | 18.158              |
| 8   | C <sub>2</sub> H <sub>6</sub> | 383.814             |
| 9   | C <sub>2</sub> H <sub>2</sub> | 0.000               |

The fuzzy logic result for the insulating oil condition of power transformer 1 after being given input in the form of dissolved gas concentrations in Table 1 is shown in Figure 5.

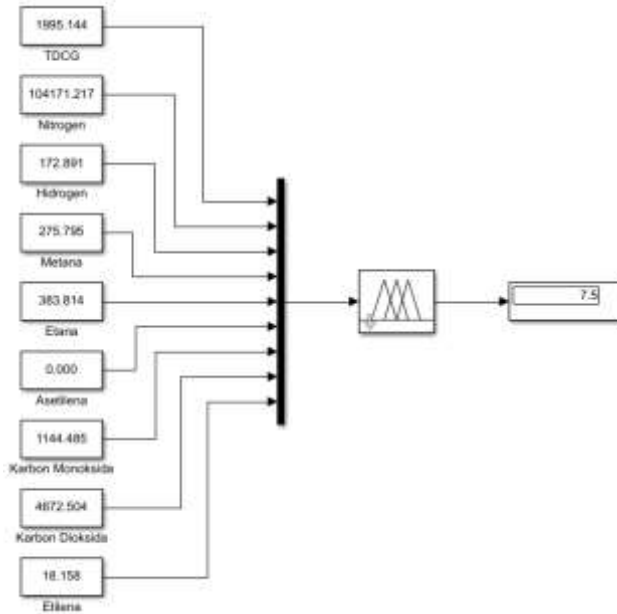


Figure 5. Fuzzy Logic Output Result for Power Transformer 1

The output in the form of a membership degree for the insulating oil condition of power transformer 1 is at “7.5”. This output indicates that the insulating oil of power transformer 1 is classified as being in a normal condition and that there are no disturbance symptoms in the transformer insulating oil. This can also be seen from the DGA test output data where the concentration of each dissolved gas content is within the normal condition limit. The output result also indicates that periodic maintenance is not required to prevent transformer failure. Referring to the breakdown voltage characteristics data, power transformer 1 has a breakdown voltage test result of “99.8”, where this value is classified as good. This breakdown voltage value is consistent with the output obtained through fuzzy logic, namely that the transformer insulating oil is in a normal condition. The dissolved gas content data from the DGA test output for power transformer 2 are shown in Table 2.

Table 2. DGA Test Result Data of Power Transformer 2

| No. | Gas Content                   | Concentration (ppm) |
|-----|-------------------------------|---------------------|
| 1   | TDCG                          | 267.486             |
| 2   | H <sub>2</sub>                | 22.629              |
| 3   | N <sub>2</sub>                | 59345.412           |
| 4   | CH <sub>4</sub>               | 20.124              |
| 5   | CO                            | 198.486             |
| 6   | CO <sub>2</sub>               | 1052.236            |
| 7   | C <sub>2</sub> H <sub>4</sub> | 9.412               |
| 8   | C <sub>2</sub> H <sub>6</sub> | 11.248              |
| 9   | C <sub>2</sub> H <sub>2</sub> | 5.228               |

The fuzzy logic result for the insulating oil condition of power transformer 2 after being given input in the form of dissolved gas concentrations in Table 2 is shown in Figure 6.

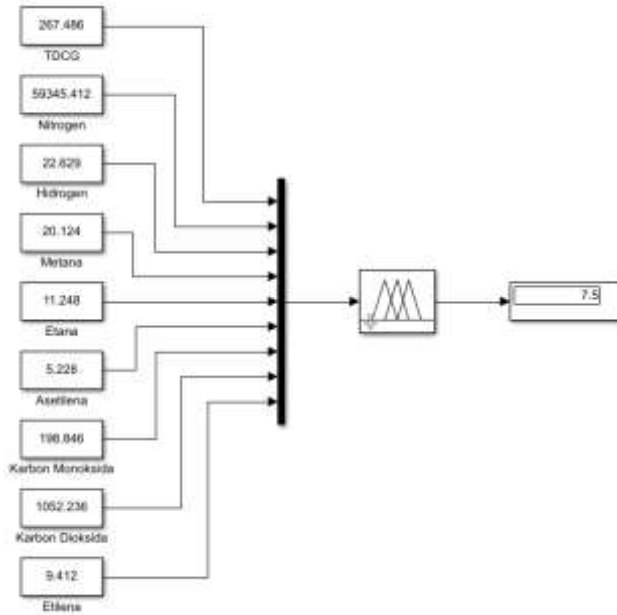


Figure 6. Fuzzy Logic Output Result for Power Transformer 2

The output in the form of a membership degree for the insulating oil condition of power transformer 2 is at “7.5”. This output indicates that the insulating oil of power transformer 2 is classified as being in a normal condition and that there are no disturbance symptoms in the transformer insulating oil. This can also be seen from the DGA test output data where the concentration of each dissolved gas content is within the normal condition limit. The output result also indicates that periodic maintenance is not required to prevent transformer failure. Referring to the breakdown voltage characteristics data, power transformer 2 has a breakdown voltage test result of “95.9”, where this value is classified as good. This breakdown voltage value is consistent with the output obtained through fuzzy logic, namely that the transformer insulating oil is in a normal condition. The dissolved gas content data from the DGA test output for power transformer 3 are shown in Table 3.

Table 3. DGA Test Result Data of Power Transformer 3

| No. | Gas Content                   | Concentration (ppm) |
|-----|-------------------------------|---------------------|
| 1   | TDCG                          | 354.412             |
| 2   | H <sub>2</sub>                | 3.241               |
| 3   | N <sub>2</sub>                | 95077.843           |
| 4   | CH <sub>4</sub>               | 71.747              |
| 5   | CO                            | 149.325             |
| 6   | CO <sub>2</sub>               | 3467.935            |
| 7   | C <sub>2</sub> H <sub>4</sub> | 5.534               |
| 8   | C <sub>2</sub> H <sub>6</sub> | 99.465              |
| 9   | C <sub>2</sub> H <sub>2</sub> | 25.101              |

The fuzzy logic result for the insulating oil condition of power transformer 3 after being given input in the form of dissolved gas concentrations in Table 3 is shown in Figure 7.

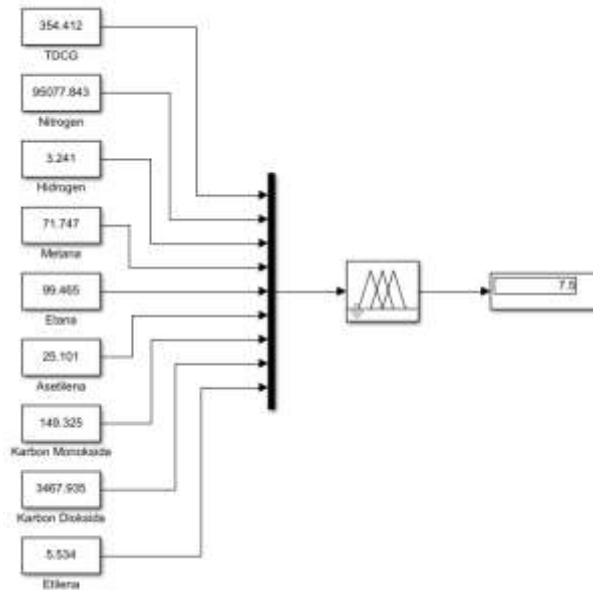


Figure 7. Fuzzy Logic Output Result for Power Transformer 3

The output in the form of a membership degree for the insulating oil condition of power transformer 3 is at "7.5". This output indicates that the insulating oil of power transformer 3 is classified as being in a normal condition and that there are no disturbance symptoms in the transformer insulating oil. This can also be seen from the DGA test output data where the concentration of each dissolved gas content is within the normal condition limit. The output result also indicates that periodic maintenance is not required to prevent transformer failure. Referring to the breakdown voltage characteristics data, power transformer 3 has a breakdown voltage test result of "100.1", where this value is classified as good. This breakdown voltage value is consistent with the output obtained through fuzzy logic, namely that the transformer insulating oil is in a normal condition.

#### 4. Conclusions

Based on the conducted research and completed data analysis, it can be concluded that the transformer insulating oil condition obtained through fuzzy logic in the Matlab simulation is consistent with the transformer insulating oil condition based on its breakdown voltage characteristics, namely that the transformer insulating oil is in a normal condition. Meanwhile, the gas contents that have a significant impact on the indication of failure in transformer insulating oil are the concentrations of TDCG (Total Dissolved Combustible Gas) and nitrogen. This is because when one or more of the TDCG or nitrogen concentration values are at a high or very high level, the transformer insulating oil condition is classified as dangerous or requiring maintenance.

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